Clutter Environment Analysis using Adaptive Processing (CLEAN-AP)

Sebastián Torres and David Warde

CIMMS/The University of Oklahoma
and National Severe Storms Laboratory/NOAA

NEXRAD TAC
Norman, OK
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we need your decision

Should the ROC proceed with the ***engineering evaluation*** *of* ***CLEAN-AP*** *on the RDA?*

what is CLEAN-AP?

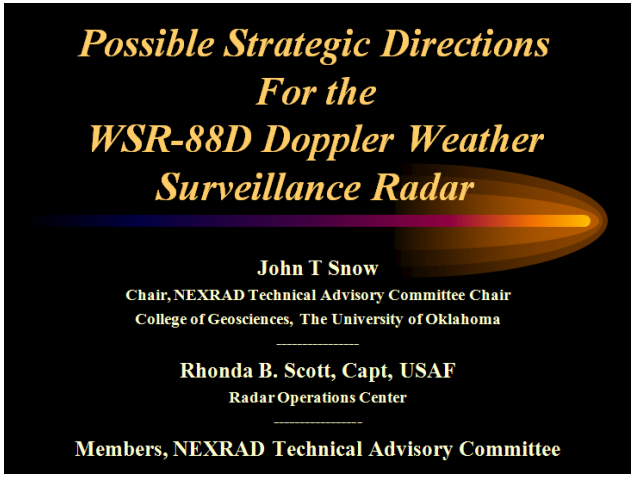
CLEAN-AP is a novel **real-time**, **automatic**, **integrated** technique for ground clutter **detection** and **filtering** that produces data with **better quality** while meeting NEXRAD technical **requirements**.

from research to operations

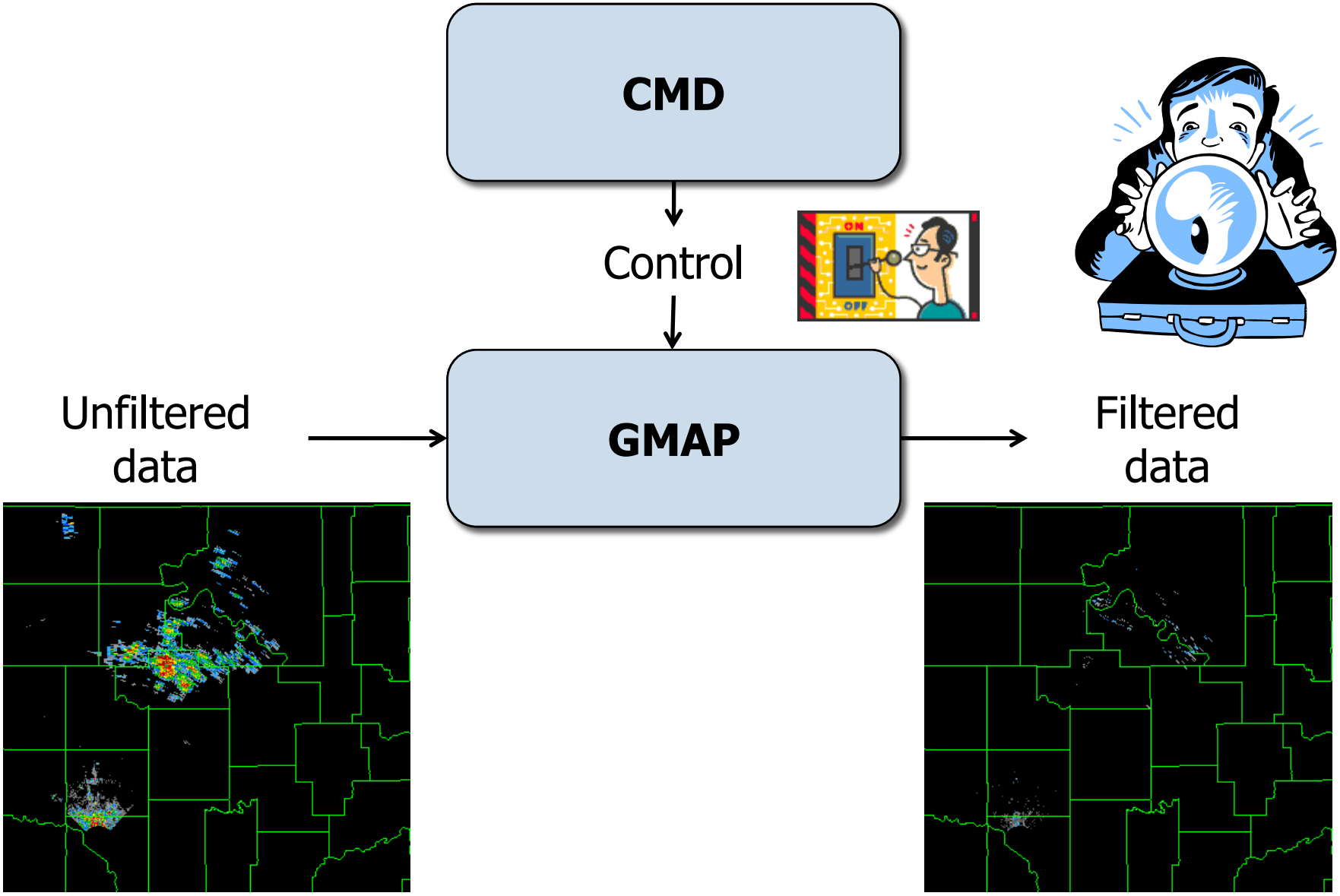
- Nov 2009 TAC meeting
  - initially presented CLEAN-AP
    - *"… the technique shows potential utility…", "… encouraged by early results…"*
    - *"… [have not] shown the scientific details behind the algorithm…"*
    - *"… [need] case comparisons with CMD…"*
- Fall 2010 ROC/NSSL/NCAR TIM
  - presented more technical details and data cases
  - received positive feedback from ROC eng and agency reps
- a catch-22 situation
  - science is ready for transition to operations
    - not enough funding/resources allocated for this
  - need endorsement of science to move forward
    - some operational questions can only be answered with a transition effort in place

you asked for it, you got it!

- "Produce the **best quality data** possible from the WSR-88D throughout the remainder of its service life."
  - "…these applications require that quality control/assurance be applied **automatically**."
  - "…signal processing could be improved to almost **completely mitigate ground clutter**…"

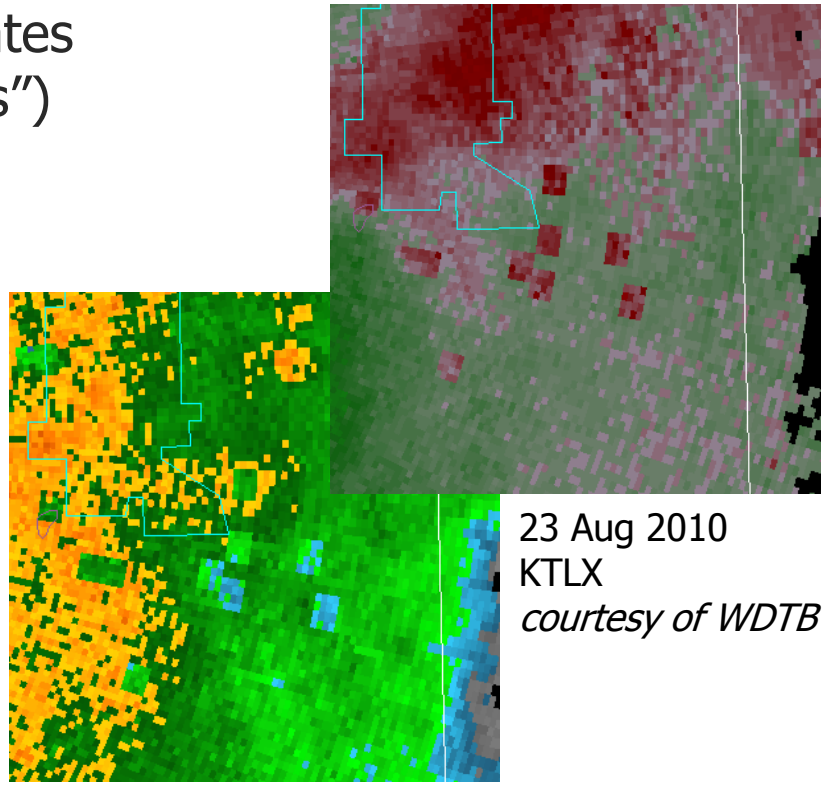


clutter mitigation at the RDA



reported data quality issues

- **false detections** along zero isodop
  - GMAP is applied on non-contaminated gates and reflectivity is biased low ("signal loss")
- **missed detections** for multiple clutter sources
  - GMAP is not applied on contaminated gates and reflectivity is biased high ("hot spots")
- **spatial irregularities** in data fields
  - GMAP applied/not applied on "patches" of data cause spatial discontinuities
  - Spatial map "growing" to minimize missed detections results in over-filtering

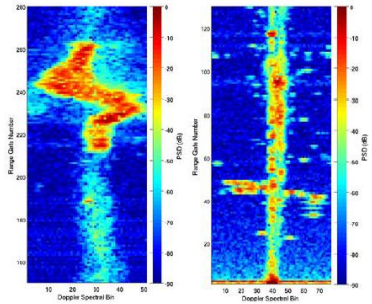


23 Aug 2010
KTLX
courtesy of WDTB

the CLEAN-AP filter (I)

- CLEAN-AP is **automatic**
  - no need for user intervention
  - real-time detection
  - no need for clutter maps
- CLEAN-AP produces data with **better quality**
  - adaptive data windowing finds a good compromise between clutter suppression and data quality
- CLEAN-AP meets NEXRAD **requirements**
  - improved suppression
  - requirements (Z) met with as few as 8 samples
- CLEAN-AP is **integrated**
  - one algorithm for ground clutter detection and filtering
  - gate-by-gate operation

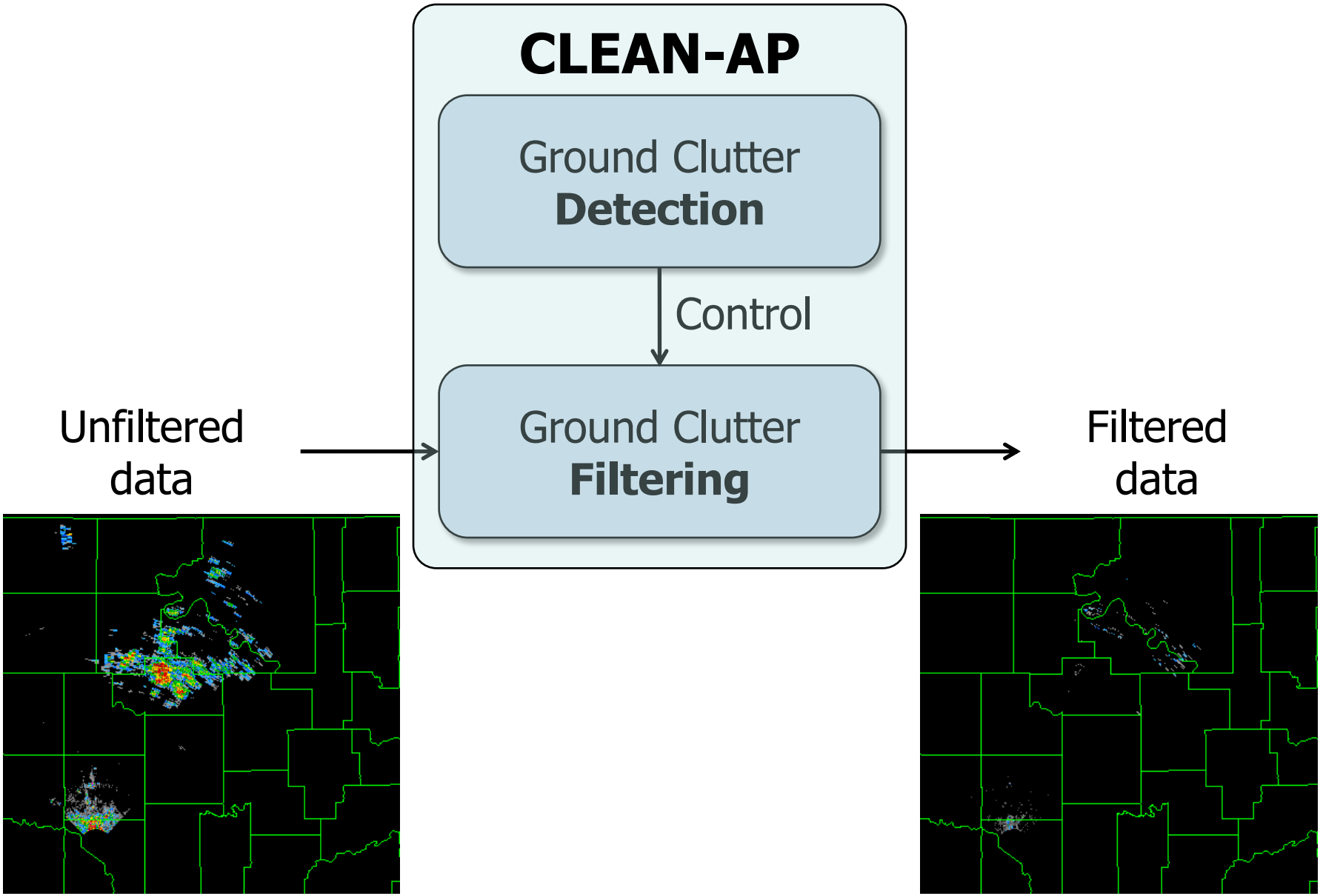
the CLEAN-AP filter (II)



- CLEAN-AP "sets the stage" for further **spectral processing**
  - phase information is not lost
  - immune to biases from circular convolution
- CLEAN-AP is **operational on the NWRT PAR**
  - running in real-time since Sep 2008
  - performance informally evaluated by meteorologists and forecasters (PARISE experiments)

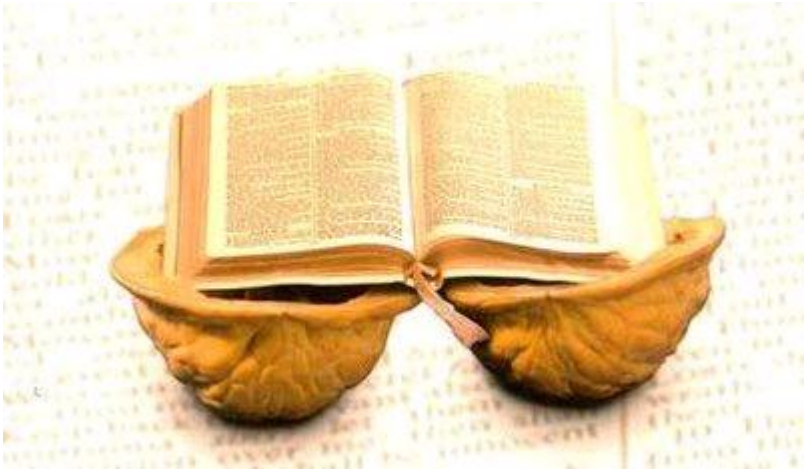
- CLEAN-AP consideration as an alternative clutter mitigation solution **makes sense now**
  - compatible with current and future upgrades
    - dual pol., SZ-2, SPRT, range oversampling, etc

CLEAN-AP clutter mitigation



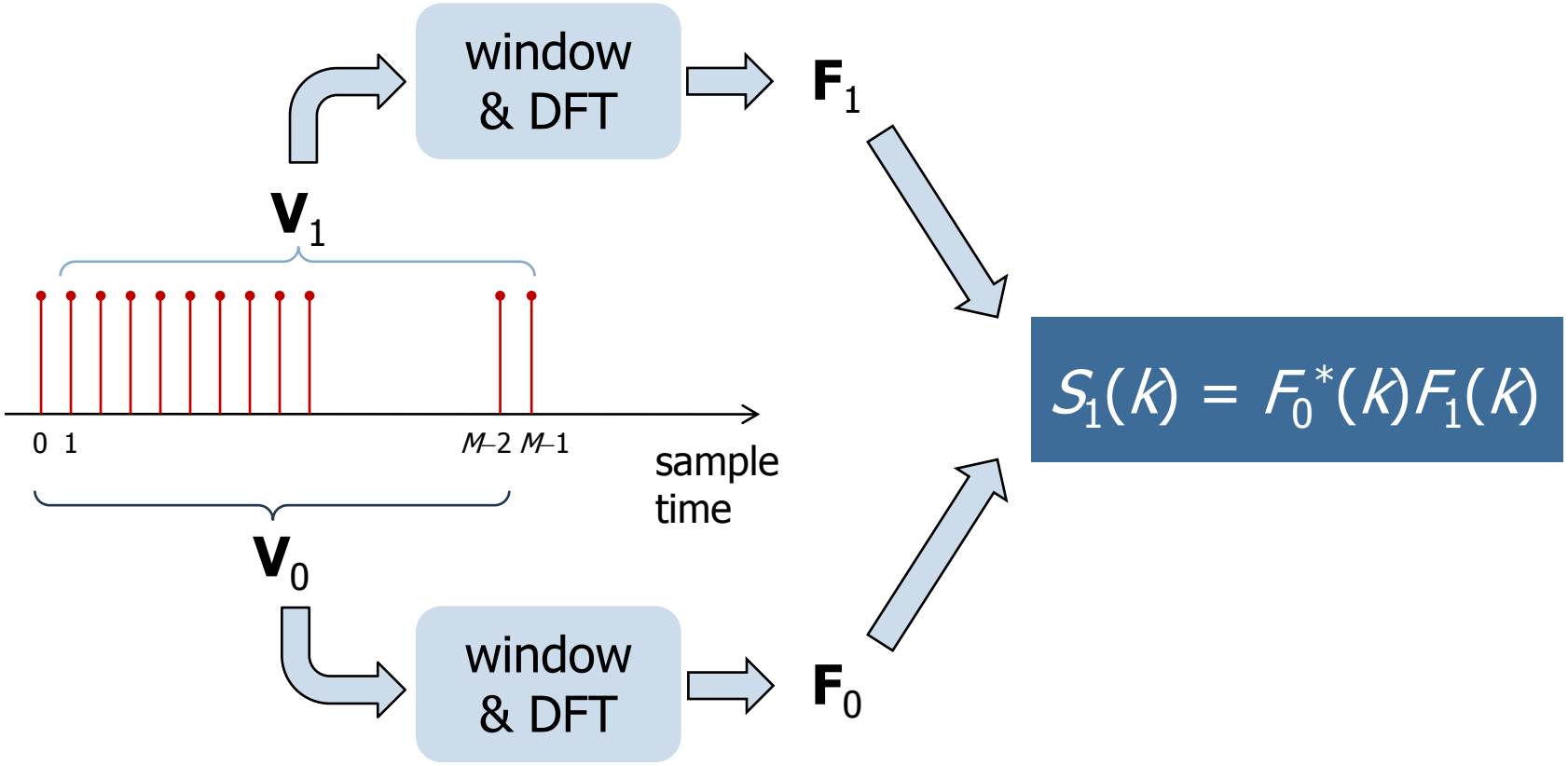
in a nutshell

- CLEAN-AP
  - selects a suitable data window
  - identifies contaminated spectral components
  - removes contaminated spectral components
  - reconstructs filtered spectrum



CLEAN-AP's core: the ASD

lag-1 **a**utocorrelation **s**pectral **d**ensity



- For <u>periodic</u> signals: $F_1(k) = F_0(k)\, e^{j2\pi k/M}$
  - $S_1(k) = F_0^*(k)\, F_0(k)\, e^{j2\pi k/M}$
  - the **ASD** is the **PSD** with linear phase

some ASD facts

- its computation requires 2 DFTs

$$S_1(k) = F_0^*(k)F_1(k) \quad ; \quad k = 0,1,\ldots,M-1$$

- its sum is the lag-1 autocorrelation

$$\sum_{k=0}^{M-1} S_1(k) = R(1)$$

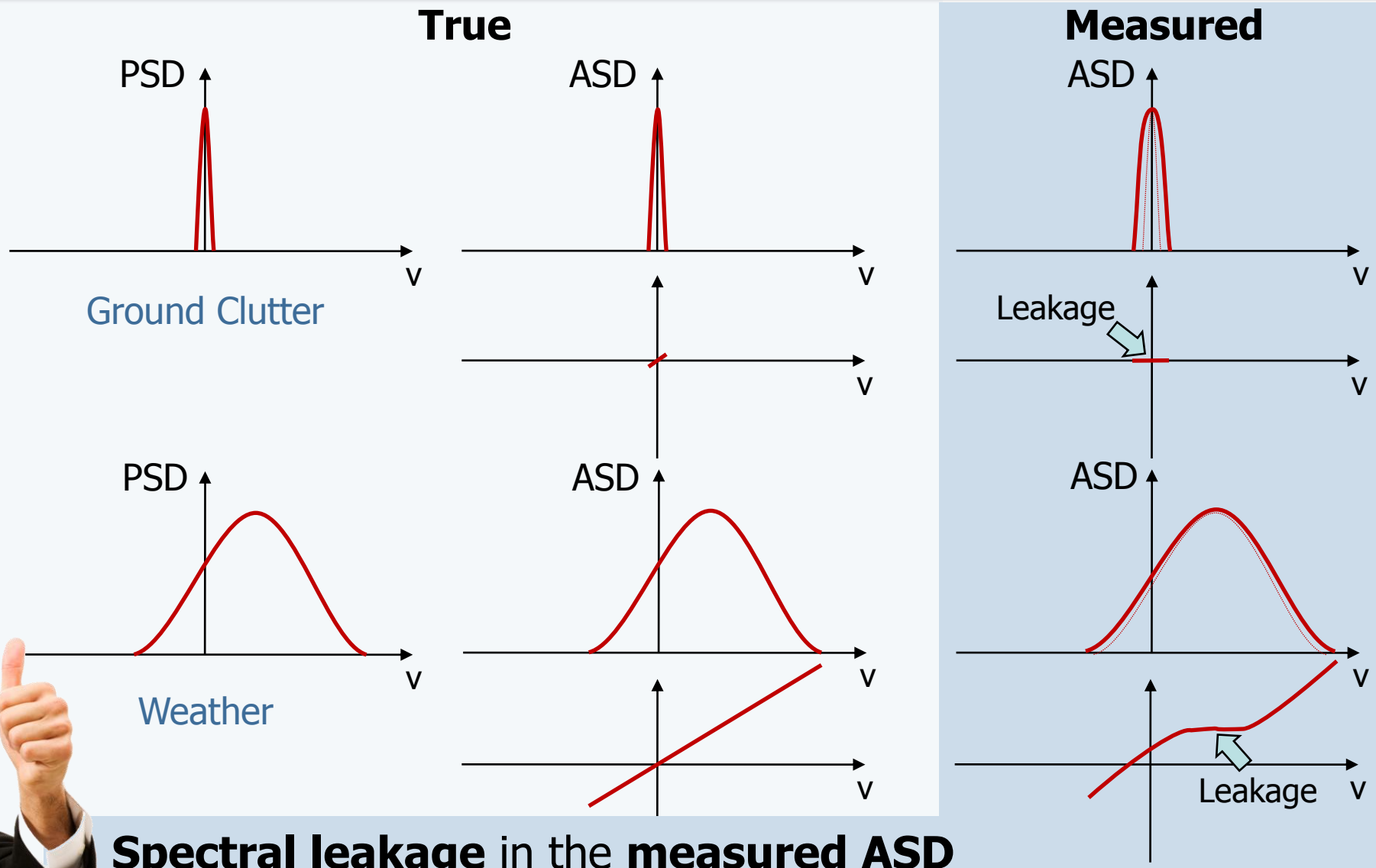
- its magnitude is the Doppler spectrum

$$\left|S_1(k)\right| = S(k)$$

- **ideally**, its phase is trivial

$$Arg\left[S_1(k)\right] = 2\pi k / M$$

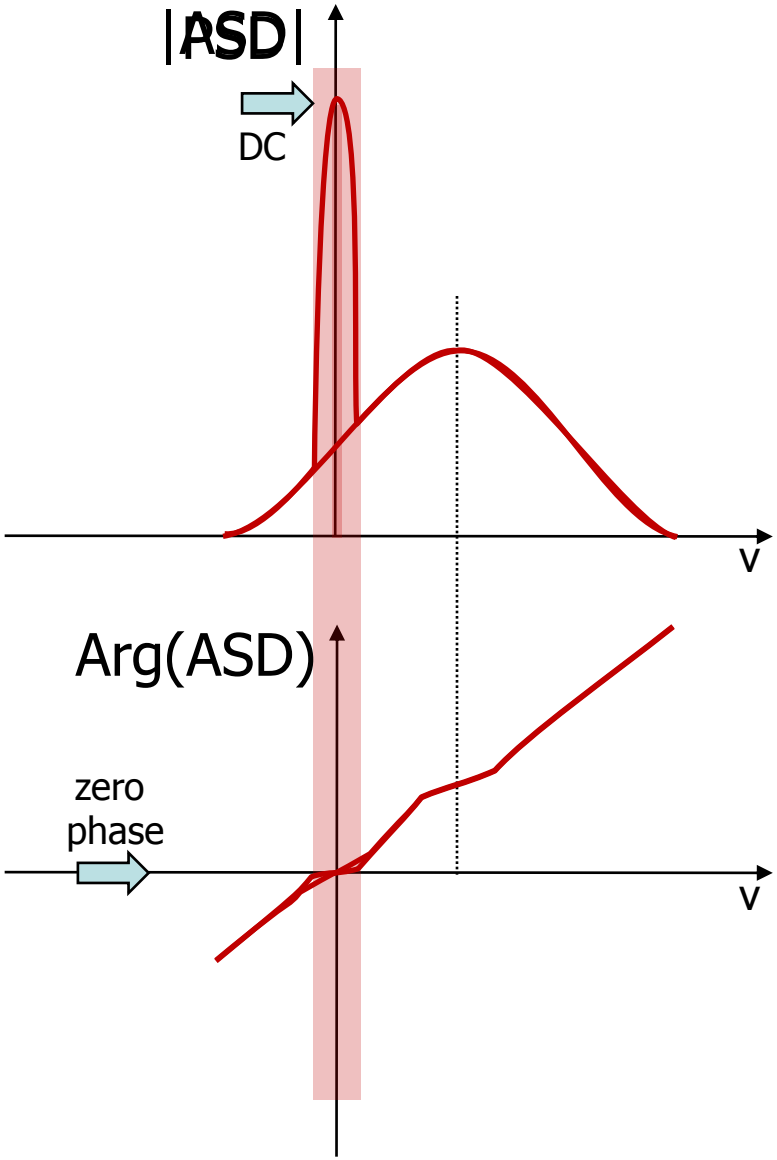
nothing is ideal…



Spectral leakage in the **measured ASD** is the basis for **clutter detection** in CLEAN-AP

how does CLEAN-AP work?

Integrated Detection and Filtering



Detection

- Estimate CNR
- Select appropriate data window
- Compute ASD
- Identify components with clutter contamination
  - Phase of ASD is near zero due to leakage effect

Filtering

- Remove clutter
- Reconstruct weather

- ASD is used to estimate meteorological variables

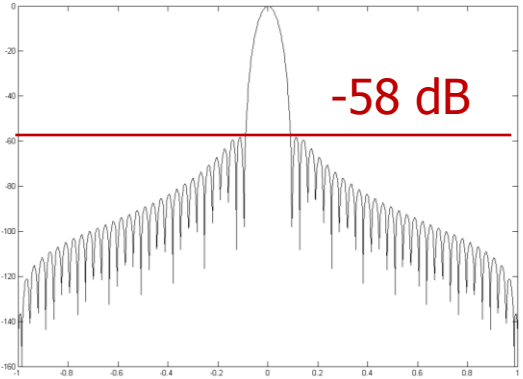
spectral leakage

data windows to the rescue!

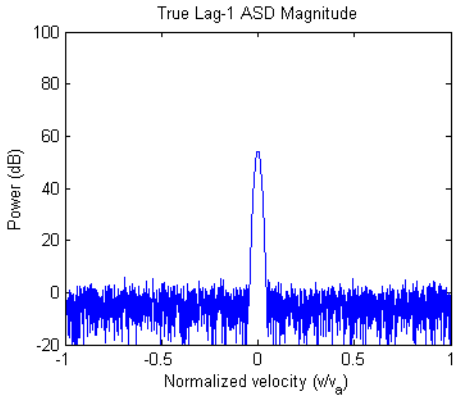
Data Window Spectra

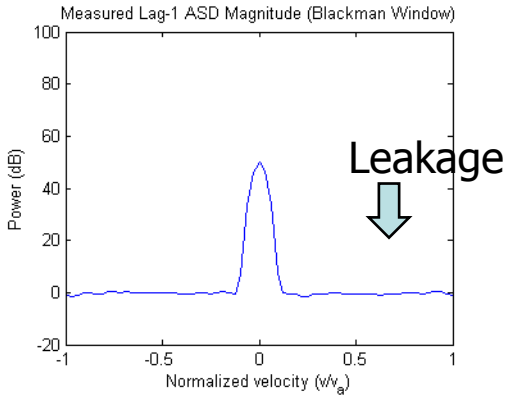
Rectangular

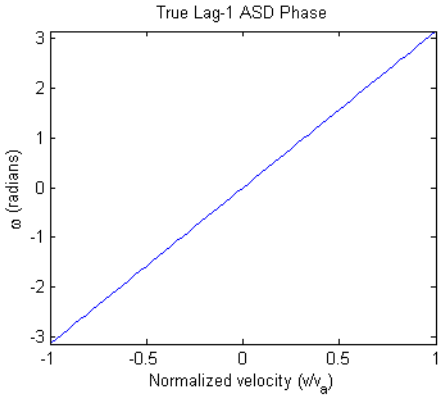
Blackman

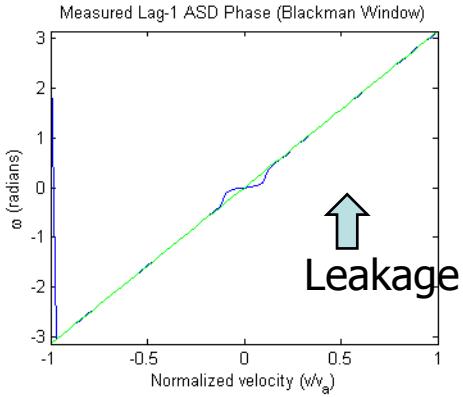


True and Measured ASD





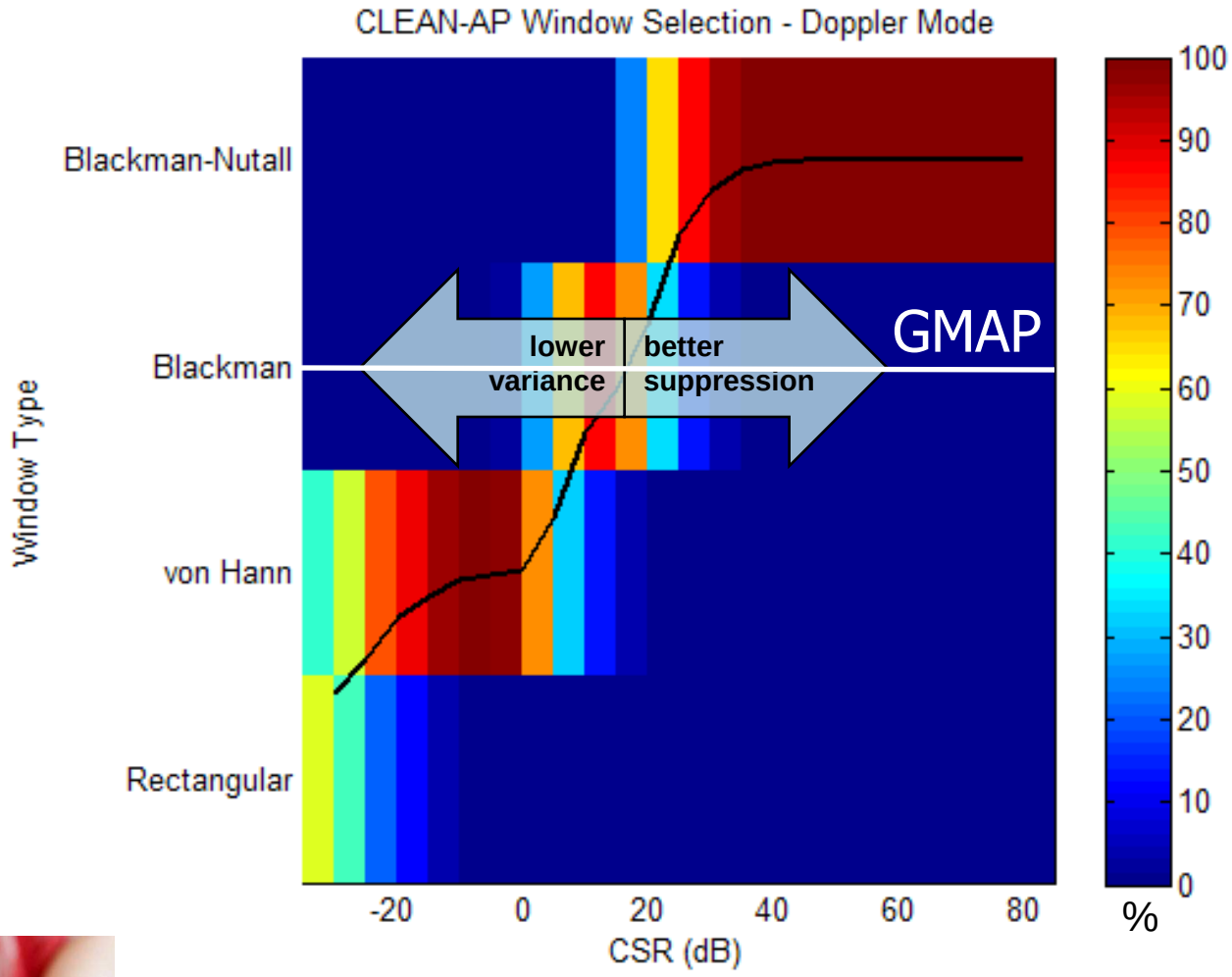




Tapered data windows are used to **contain spectral leakage**

data window selection

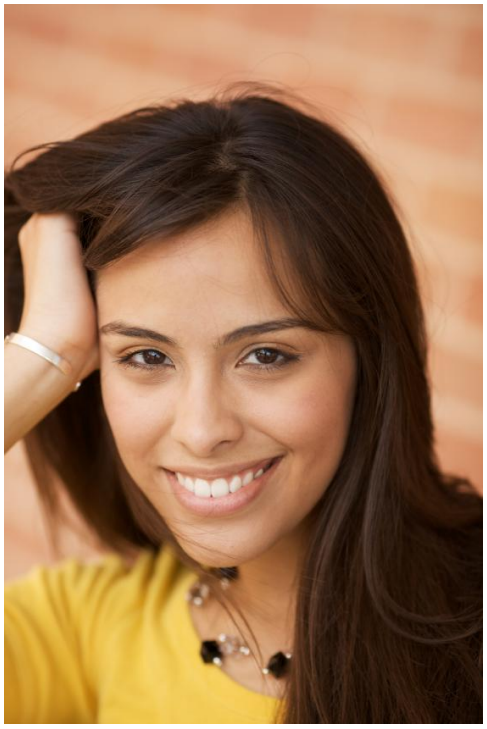
CLEAN-AP vs. GMAP



More **aggressive** data windows **contain** spectral leakage but **increase** variance of estimates

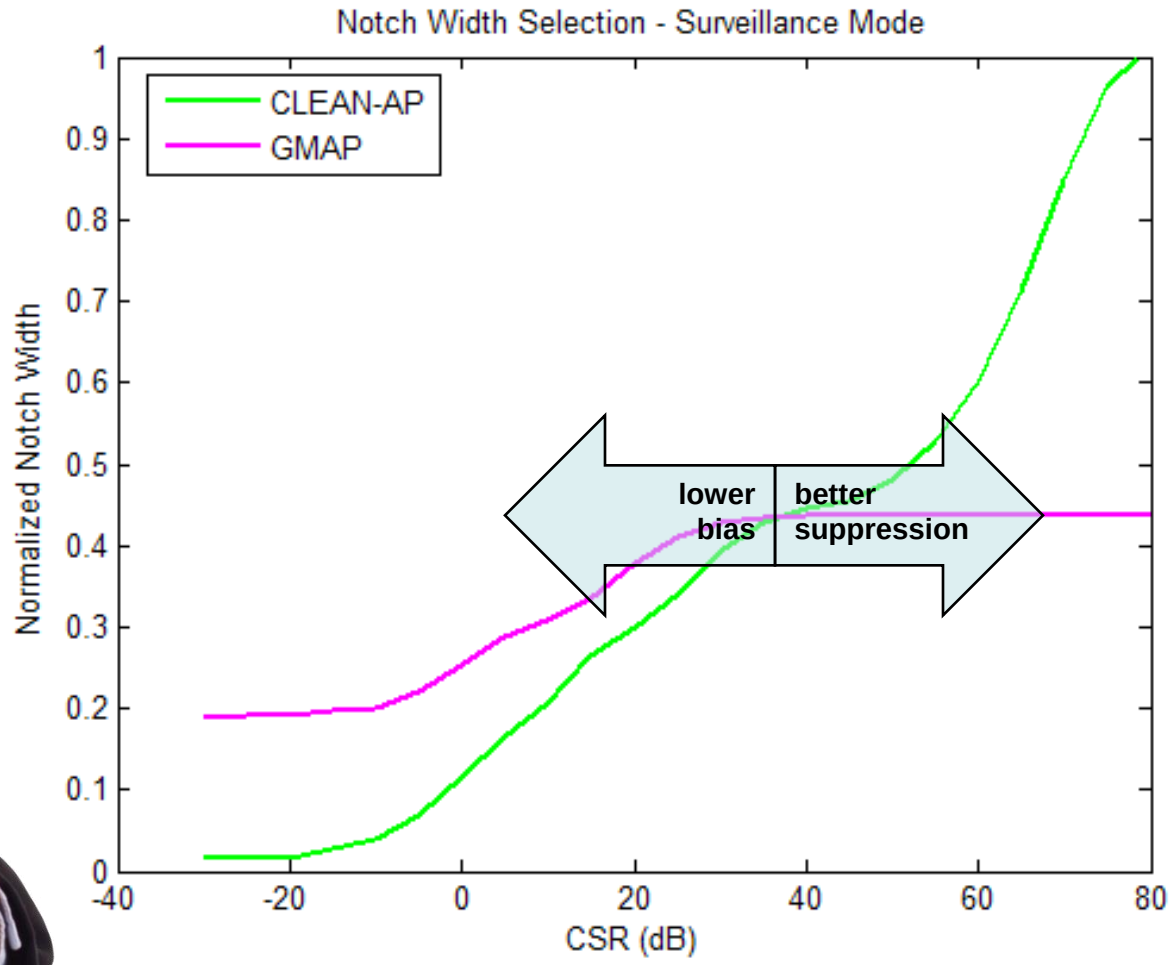
ground clutter model

- analogous to GMAP's model
  - single-parameter suppression control
- allows for automatic phase threshold adjustments for different sampling and processing conditions
  - PRT
  - number of samples
  - data window



notch width selection

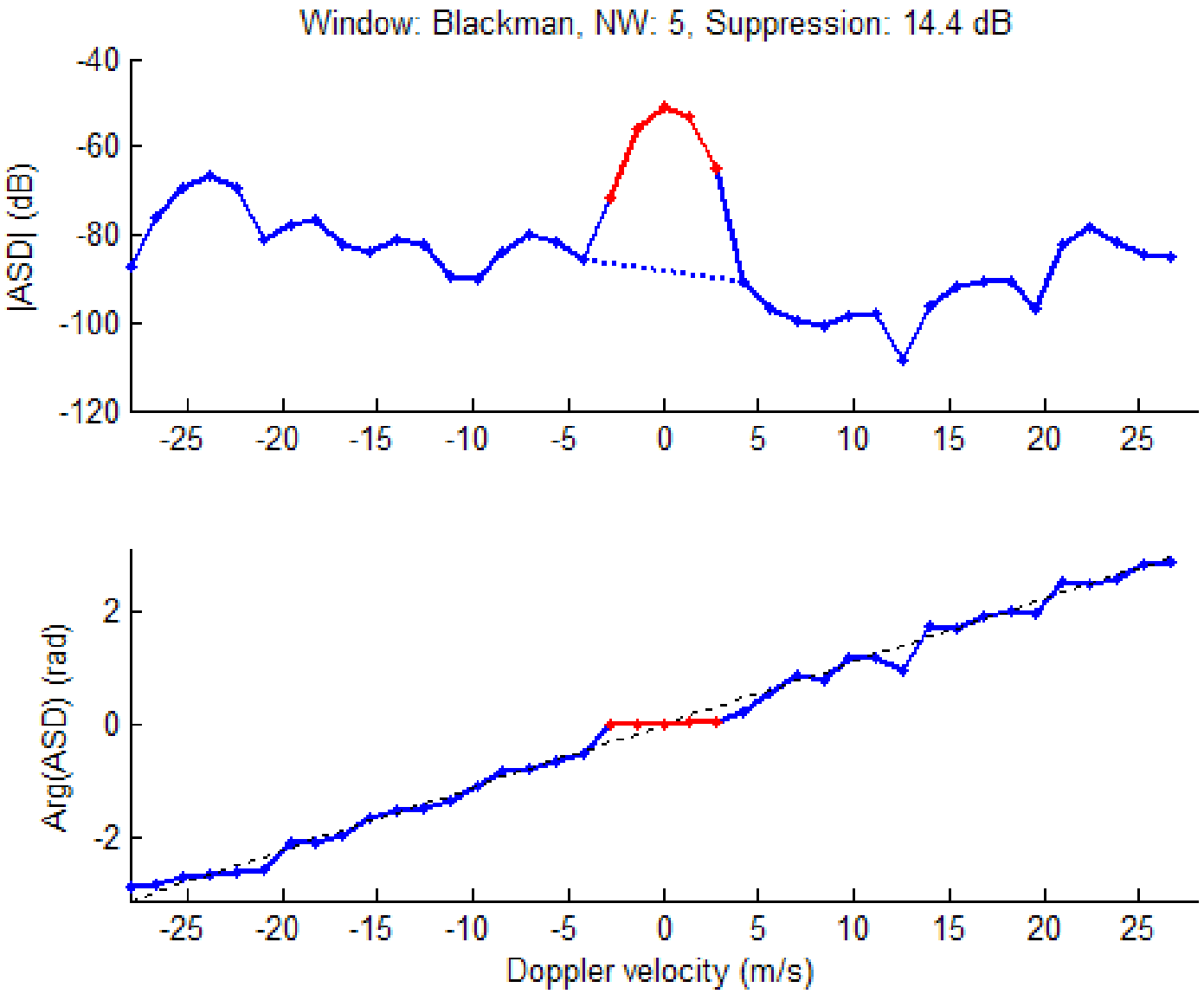
CLEAN-AP vs. GMAP



NW determination		
	mag	**phase**
GMAP	✓	
CLEAN-AP	✓	✓

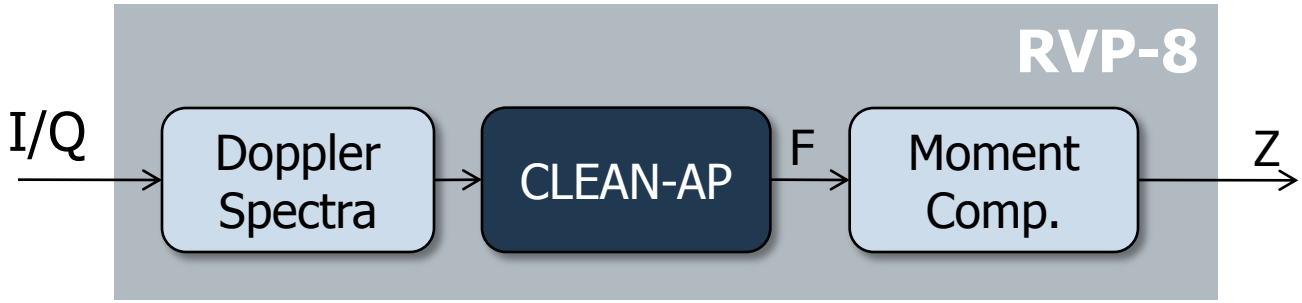
Use of **magnitude only** results in **poor notch width** determination

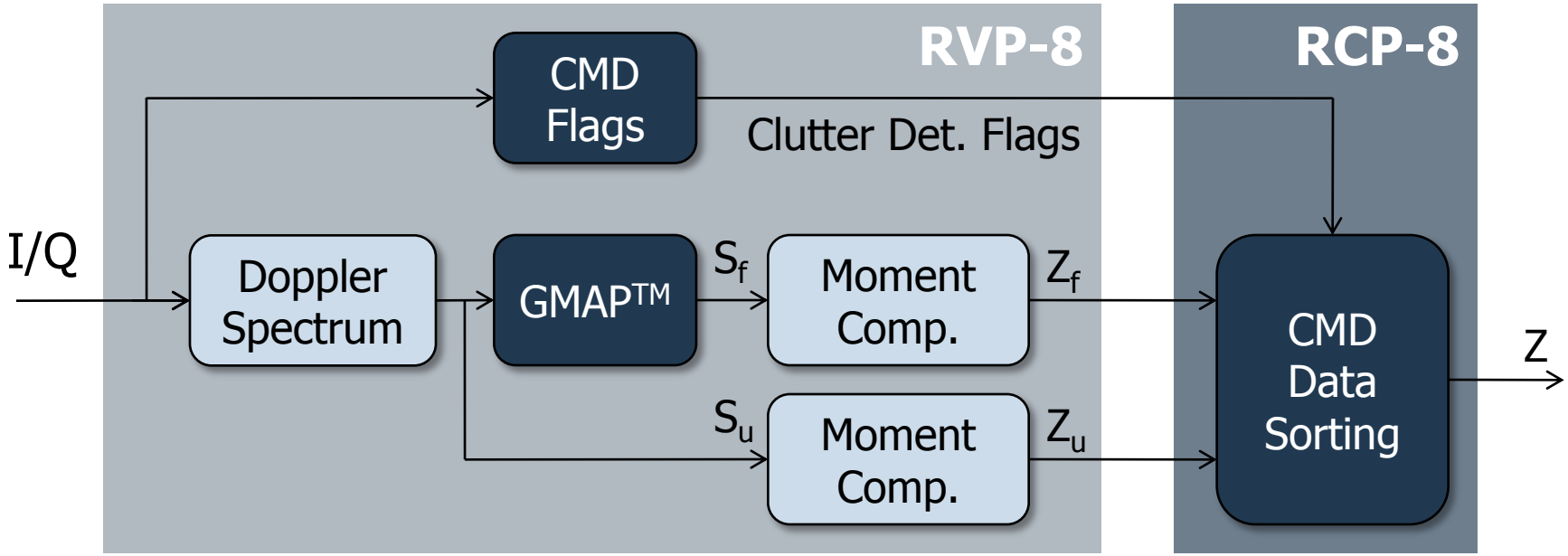
some real examples



KOUN:
VCP 12
T_s = 1 ms
M = 40

implementation
CLEAN-AP vs. CMD+GMAP





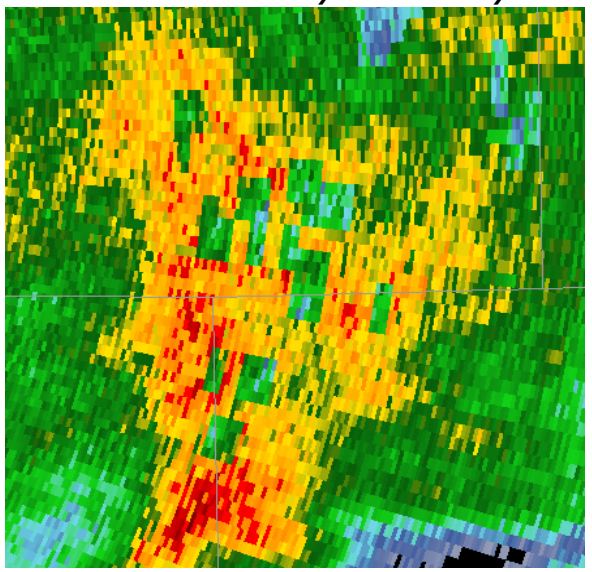
computational complexity
CLEAN-AP vs. CMD+GMAP

- Proposed solution will likely fit in current hardware without additional processing requirements
  - CLEAN-AP requires less processing time than GMAP
    - Code analysis, verified in MATLAB implementation
  - RVP8 has processing power to run "all bins" clutter filtering with GMAP

filter application
CLEAN-AP vs. CMD+GMAP

- CLEAN-AP is an "all-bins" approach
  - full performance can be characterized with simulations
  - spatially consistent
- CMD+GMAP is an on/off approach
  - filter performance can be characterized with simulations
  - full performance must be characterized with real data
  - spatially inconsistent
- CMD and GMAP are good but not perfect
  - price to pay for detection mistakes is significant due to GMAP's performance

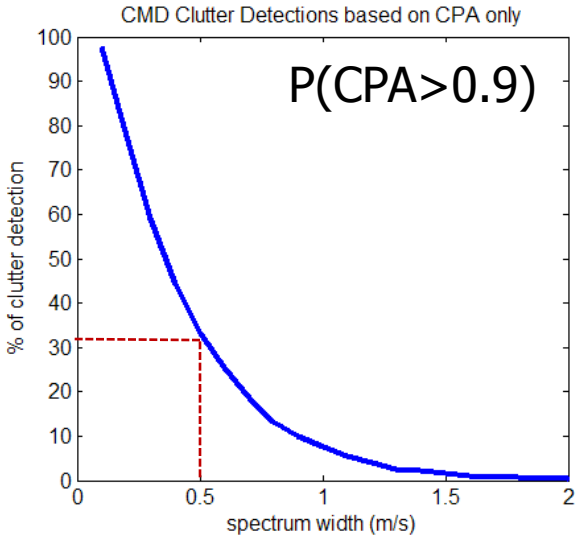
KGRR Reflectivity - 22 July 10



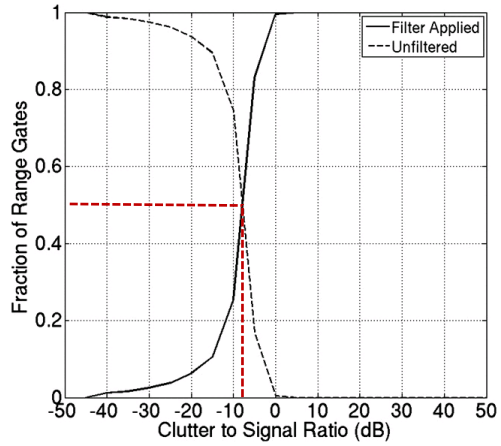
CMD detection performance

and the price of making mistakes

- zero-isodop case
  - based on CPA only, CMD makes a **false detection** 30% of the time for a weather signal with σ_v = 0.5 m/s
  - at σ_v = 0.5 m/s
    - GMAP introduces a reflectivity bias of ~23 dB
    - CLEAN-AP introduces a reflectivity bias of ~5 dB



- weak-clutter case
  - based on published data, CMD **misses a detection** more than 50% of the time for CSR < -8 dB
    - could be operationally significant in terms of overlaid echo recovery

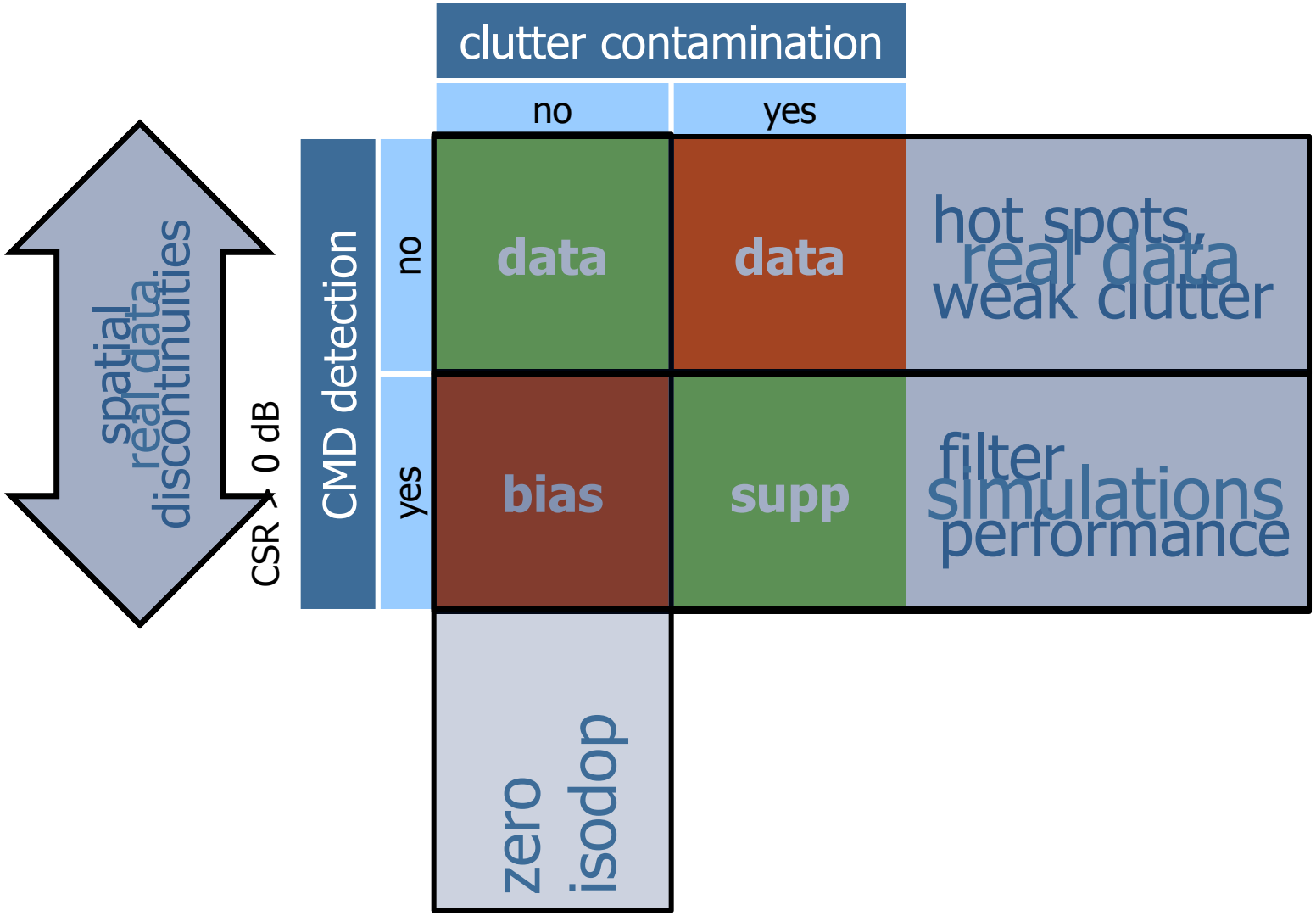


from Hubbert et al. (2009)

GMAP's misapplication leads to **degraded data quality**

performance evaluation

CLEAN-AP vs. CMD+GMAP



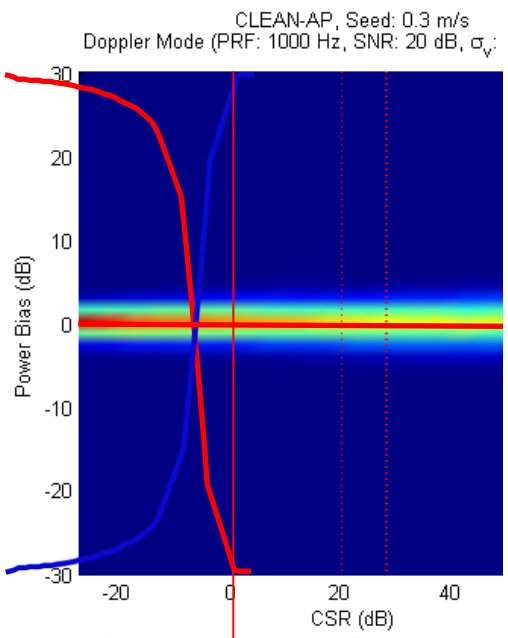
Clutter Suppression

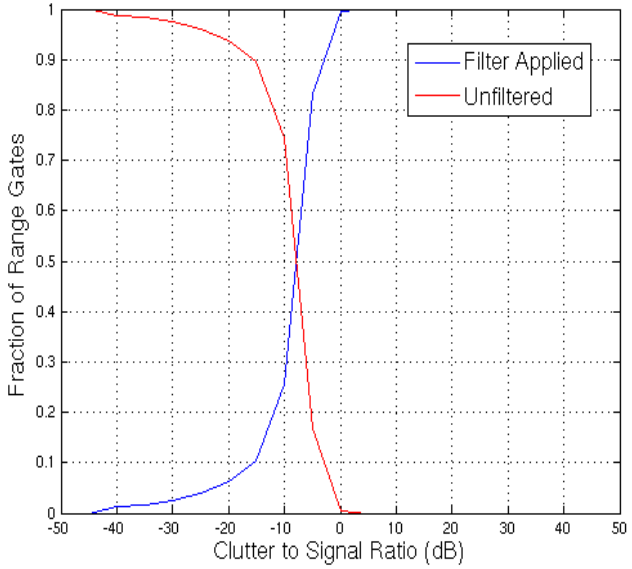
Doppler Mode (20, 28, and 50 dB)

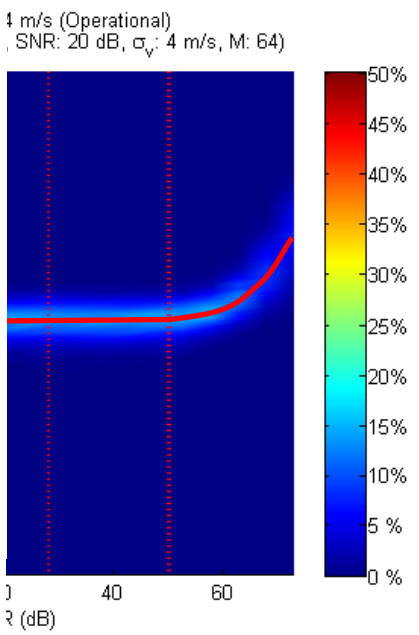
CLEAN-AP

GMAP

CMD







Hubbert et al. 2009

Clutter Filter Toggled ✗ | Clutter Filter Always On ✓

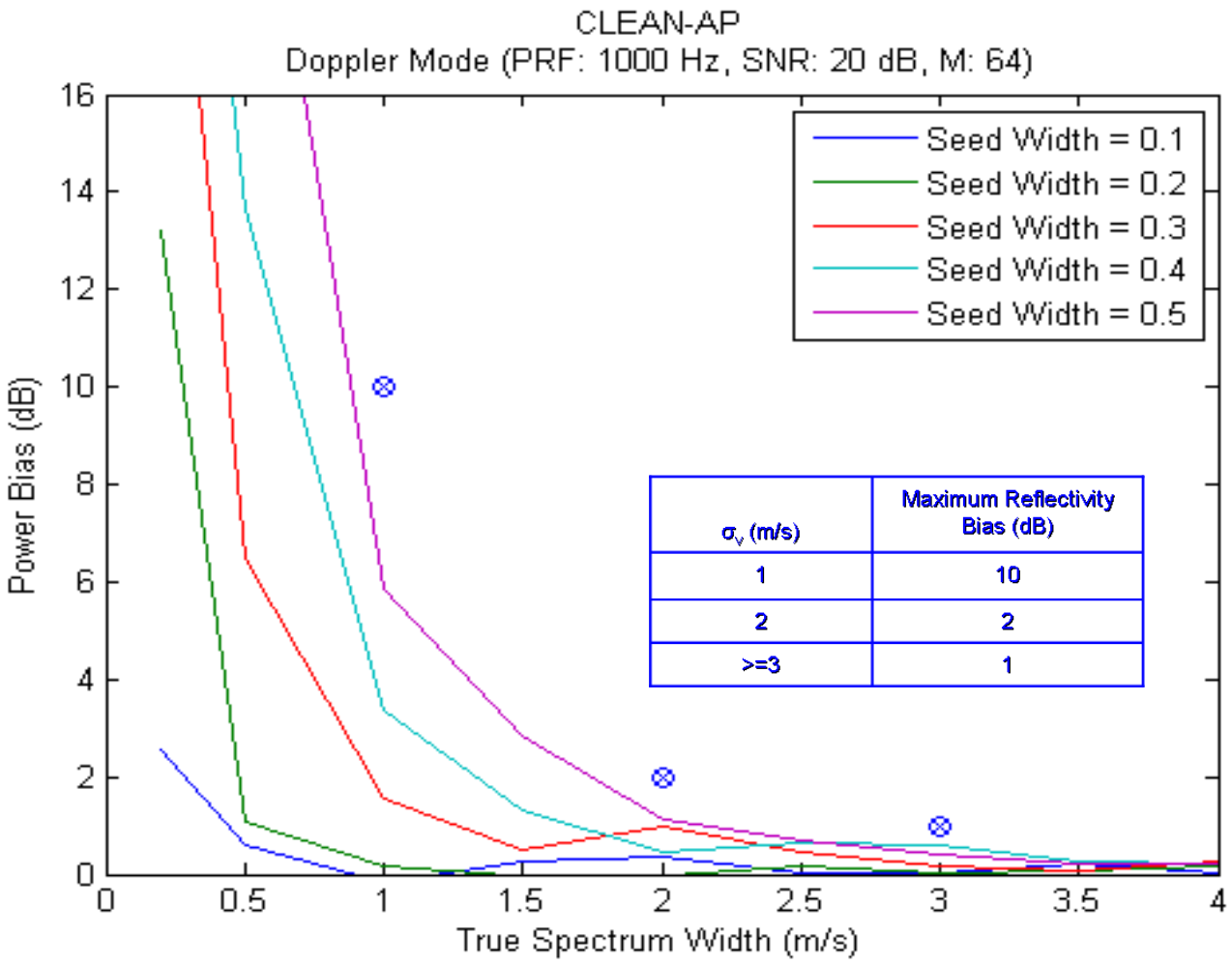
Clutter Filter Toggled ✗ | Clutter Filter Always On ✓

CLEAN-AP has **more clutter suppression** and **less variance of estimates**

CMD detection	clutter contamination: no	clutter contamination: yes
no	data	~~data~~ ✗
yes	bias	supp ✓

Reflectivity (Power) Bias

Doppler Mode



σ_v (m/s)	Maximum Reflectivity Bias (dB)
1	10
2	2
>=3	1

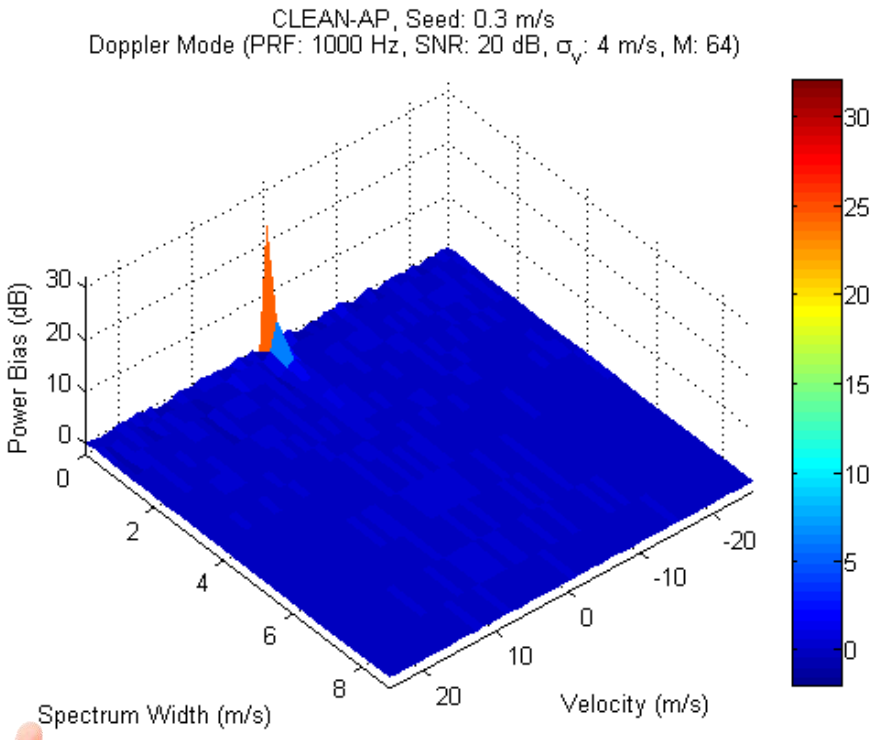
Clutter **model** allows for control of **clutter suppression**

CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias ✓	supp

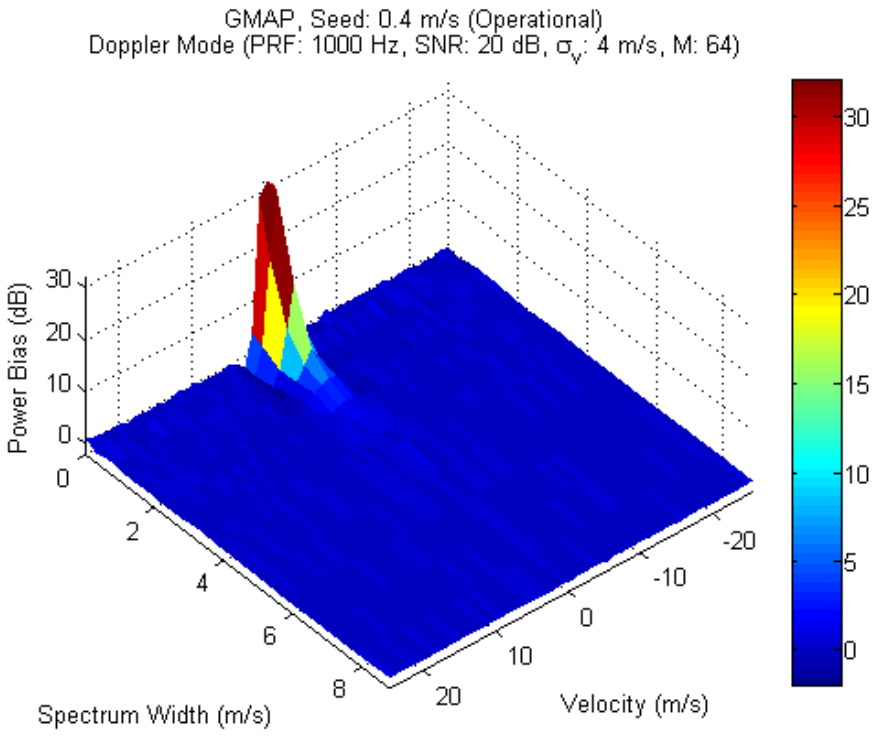
Reflectivity (Power) Bias

Doppler Mode

CLEAN-AP



GMAP



CLEAN-AP has a more **robust notch width determination** that results in **smaller biases**

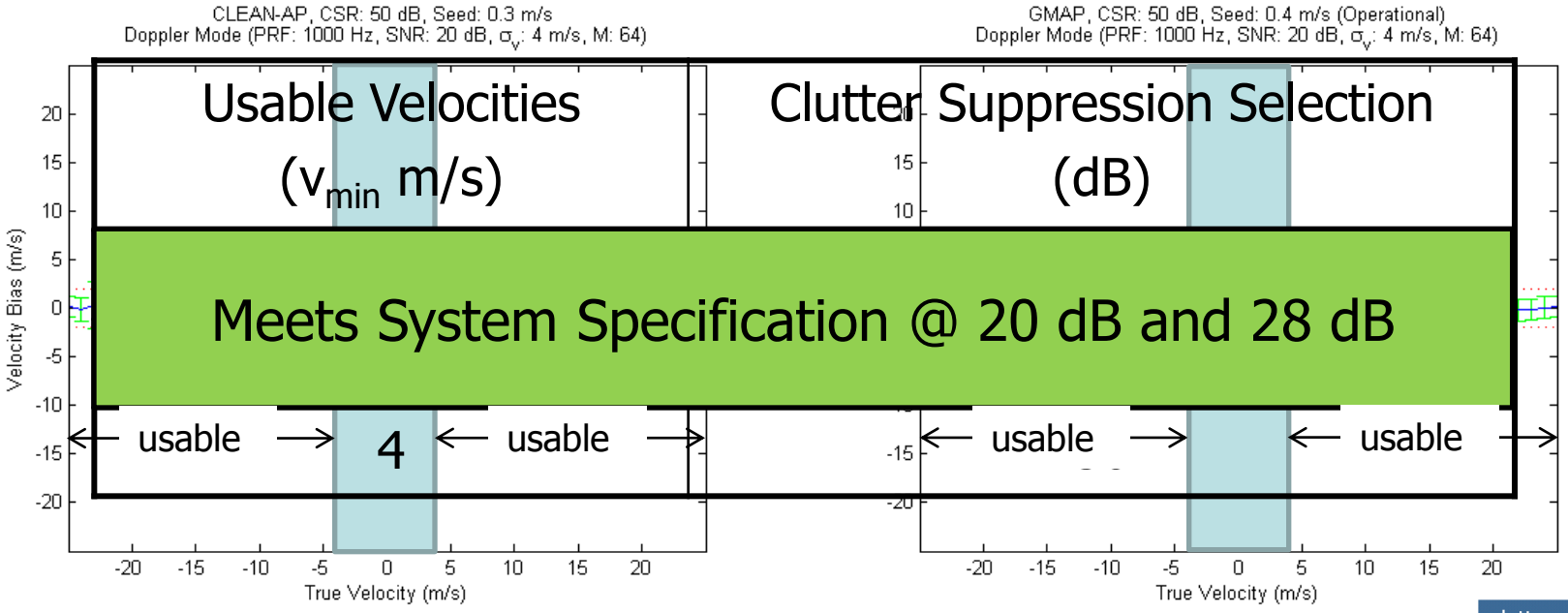
CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias ✓	supp

Velocity Bias

Doppler Mode

CSR = 50 dB

CLEAN-AP **GMAP**



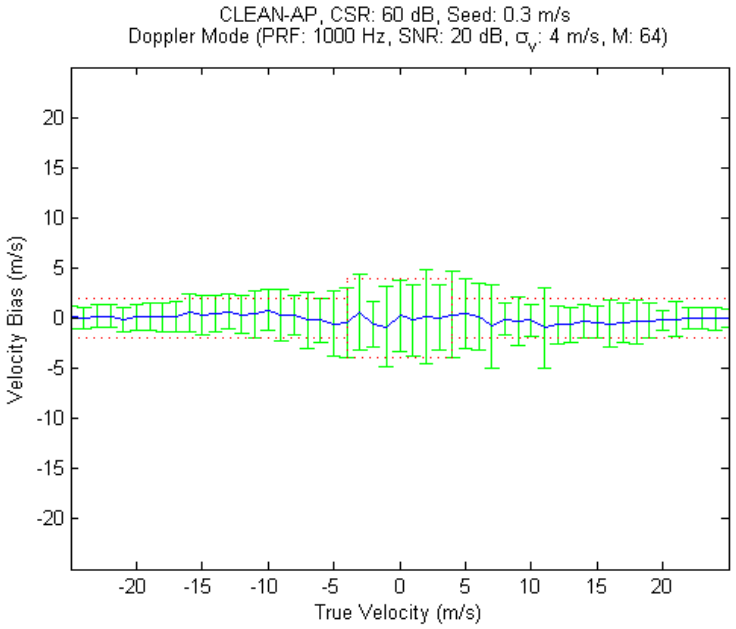
CMD detection \ clutter contamination	no	yes
no	data	data
yes	bias ✓	supp

Velocity Bias

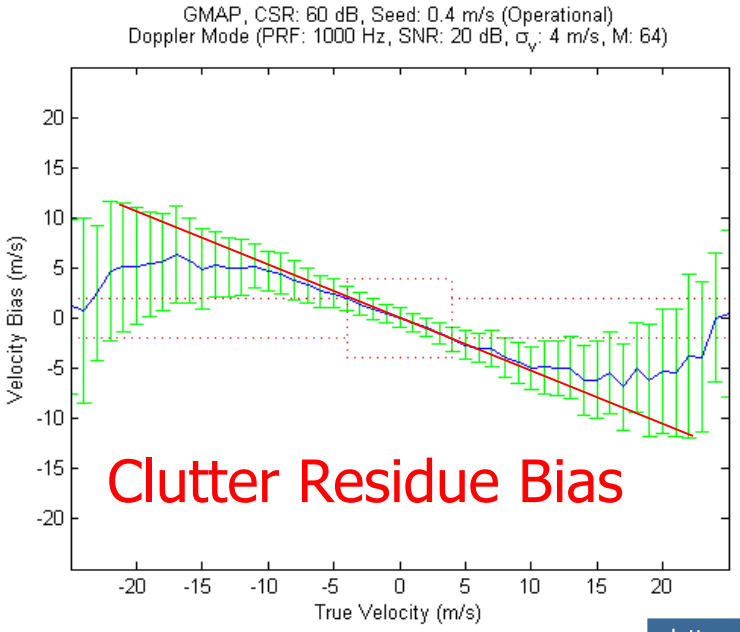
Doppler Mode

CSR = 60 dB

CLEAN-AP



GMAP



CLEAN-AP allows **more clutter suppression** and exhibits **smaller biases**

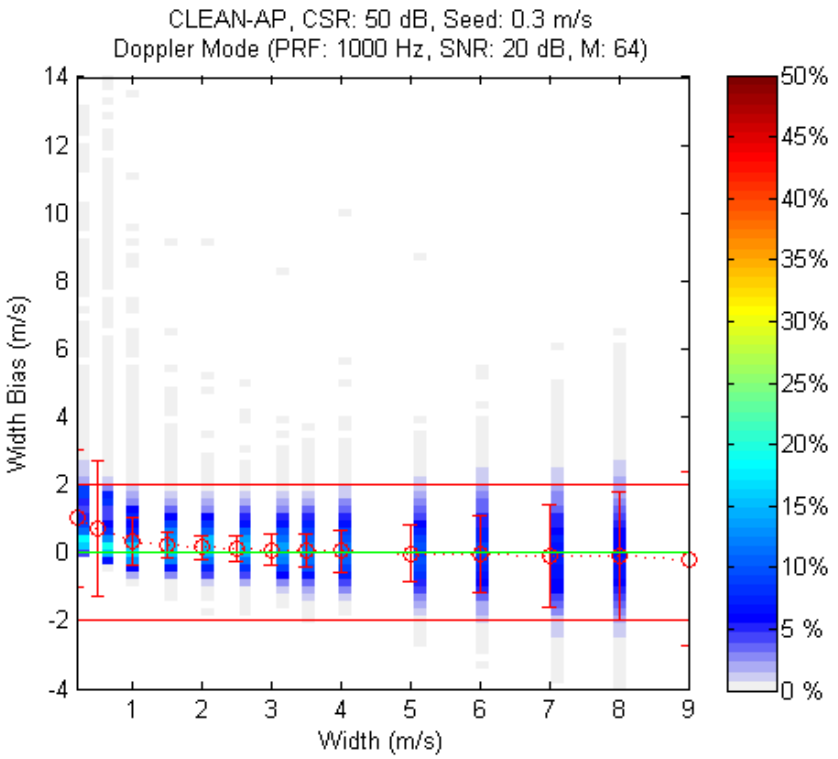
CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias ✓	supp

Spectrum Width Bias

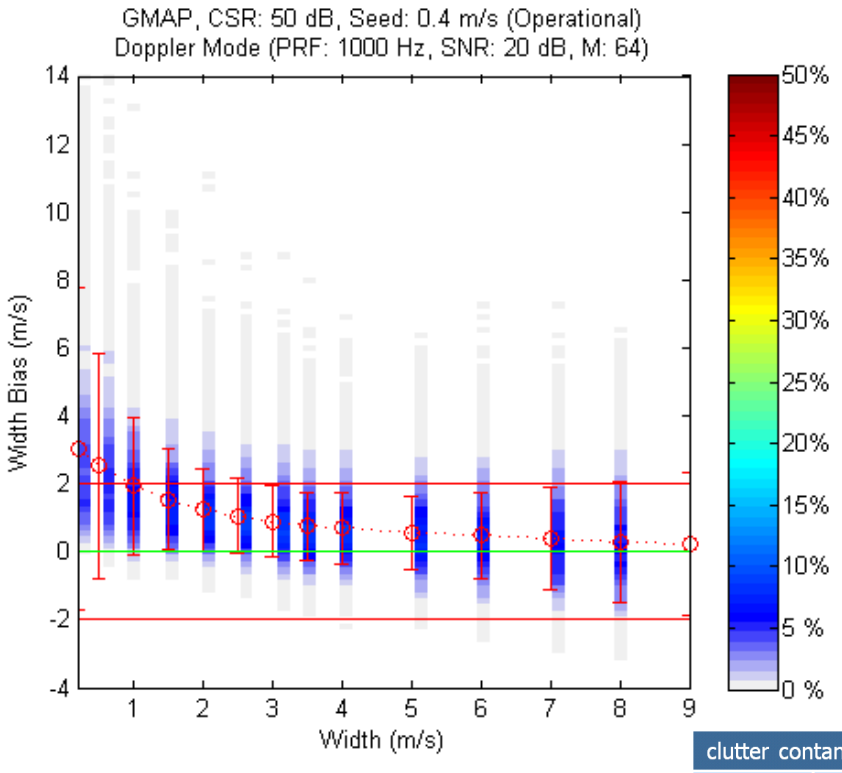
Doppler Mode

CSR = 50 dB

CLEAN-AP



GMAP



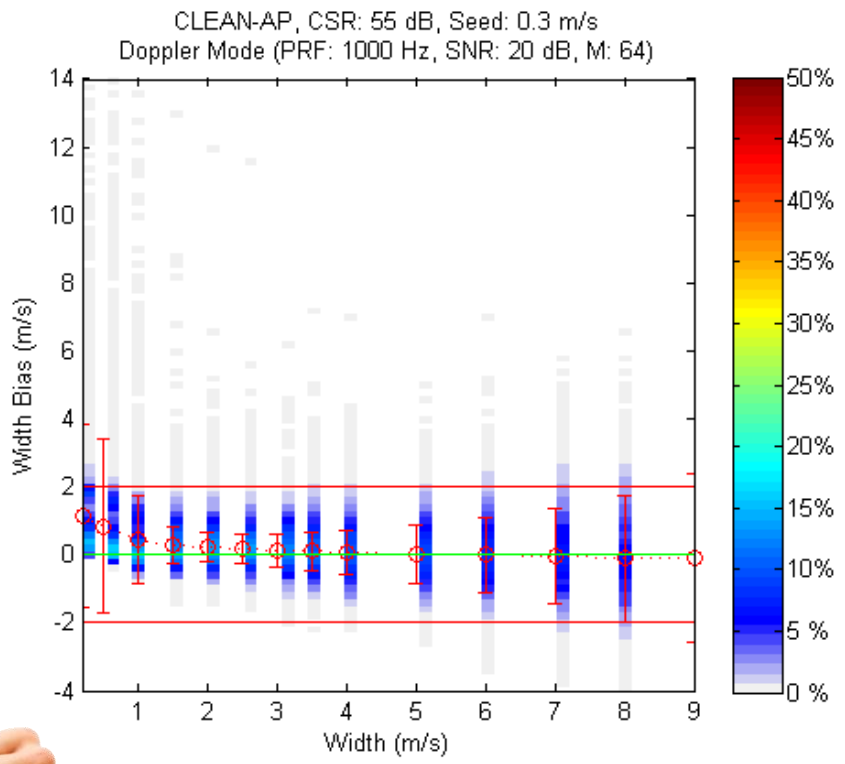
CMD detection \ clutter contamination	no	yes
no	data	data
yes	bias ✓	supp

Spectrum Width Bias

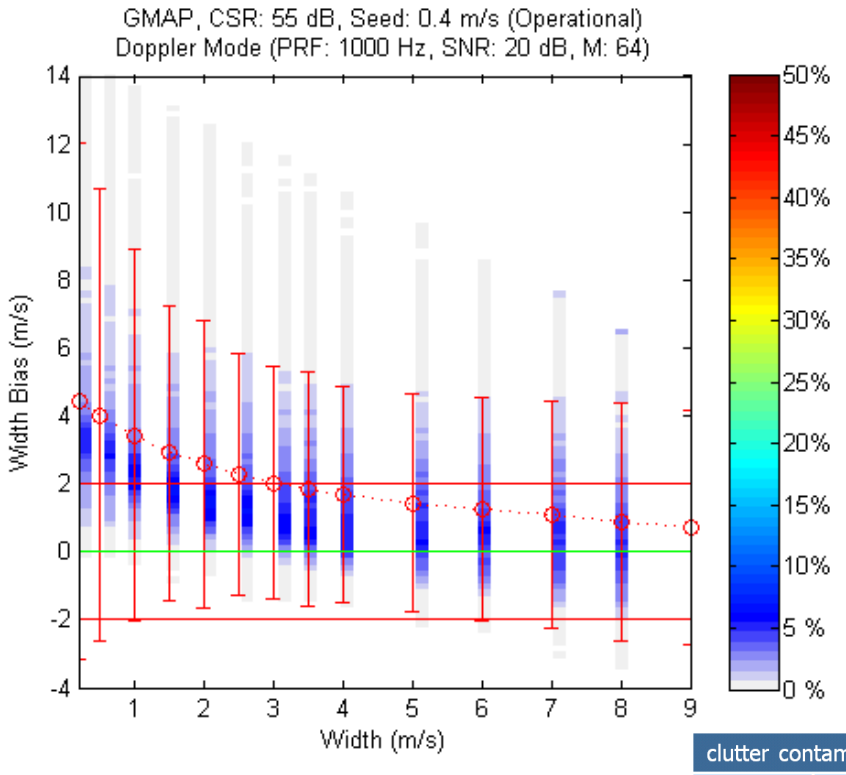
Doppler Mode

CSR = 55 dB

CLEAN-AP



GMAP



CLEAN-AP allows **more clutter suppression** and exhibits **smaller biases**

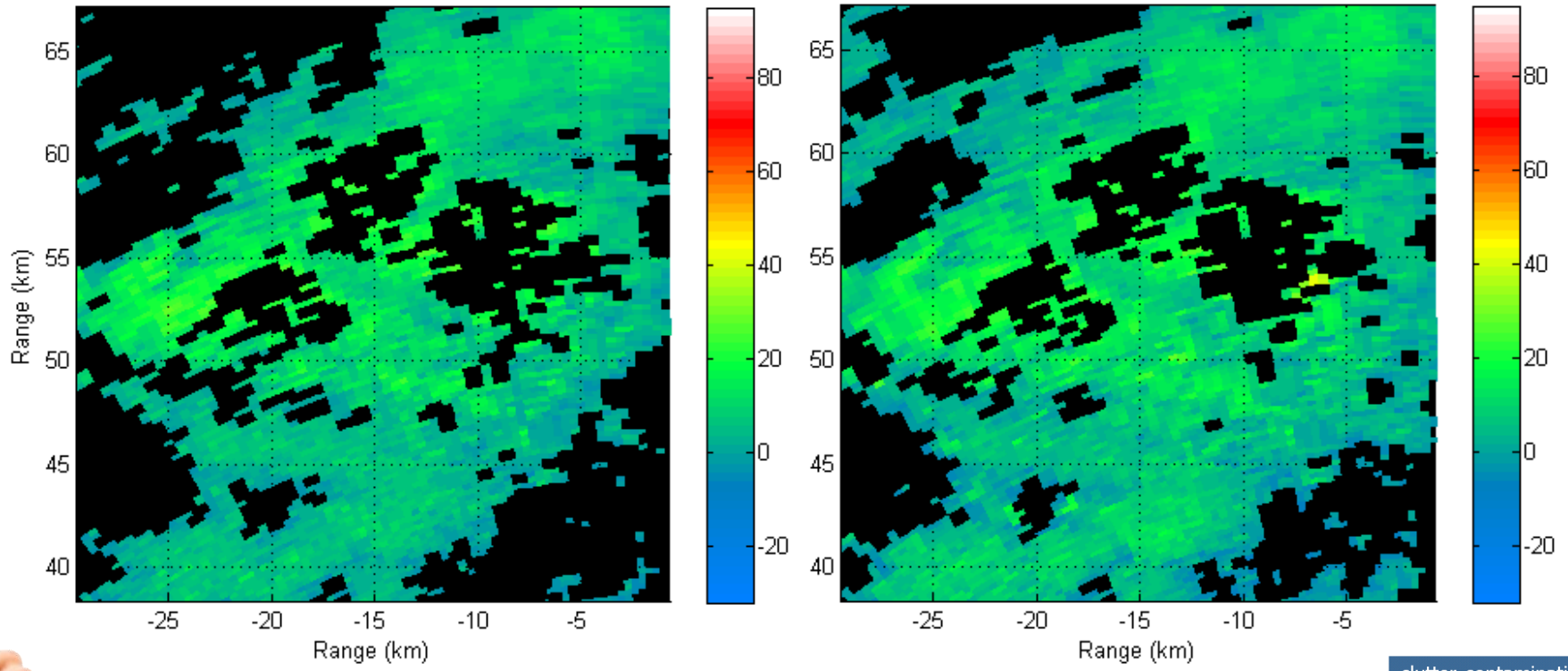
CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias ✓	supp

KEMX Tucson, AZ

Can you see the mountains?

CLEAN-AP

CMD+GMAP



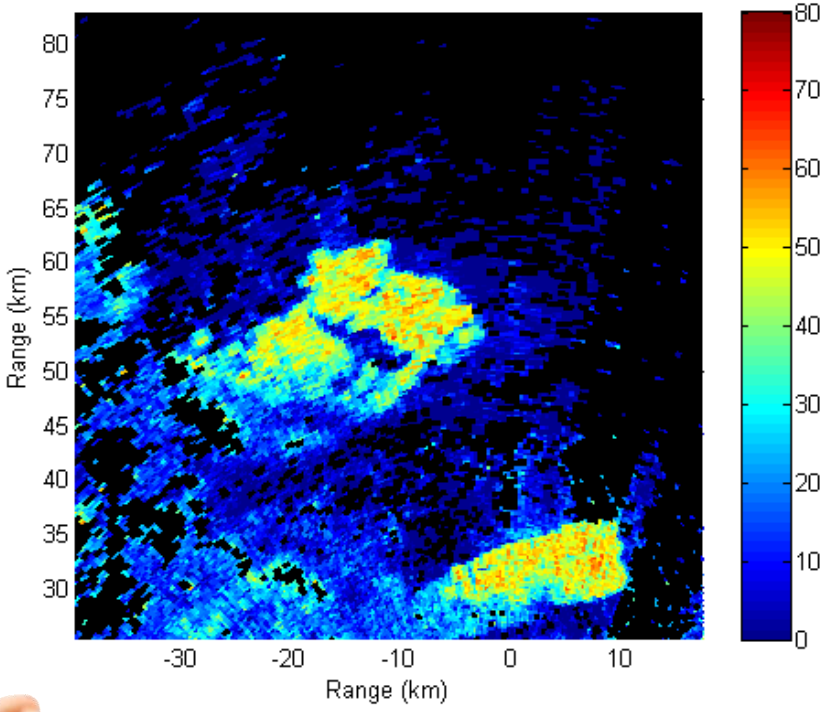
CLEAN-AP mitigates both **weak and strong clutter** contamination

CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data ✓
yes	bias	supp

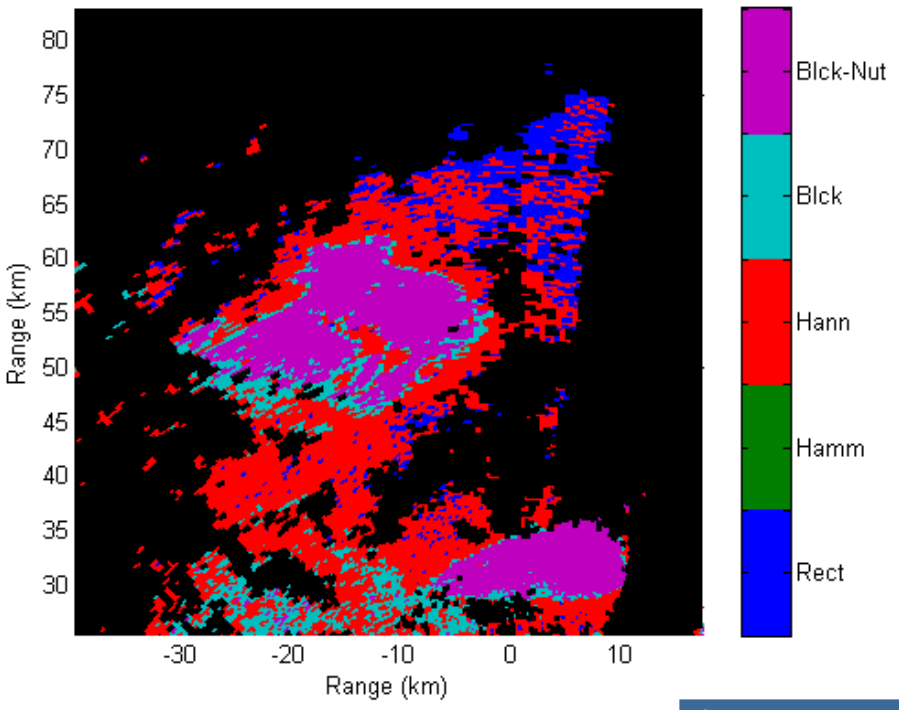
KEMX Tucson, AZ

What is CLEAN-AP doing?

Power Removed



Window Used



CLEAN-AP **adapts** to clutter environment

CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data ✓
yes	bias	supp

KCRI (ROC Testbed) Norman, OK

What happened to the zero-isodop?

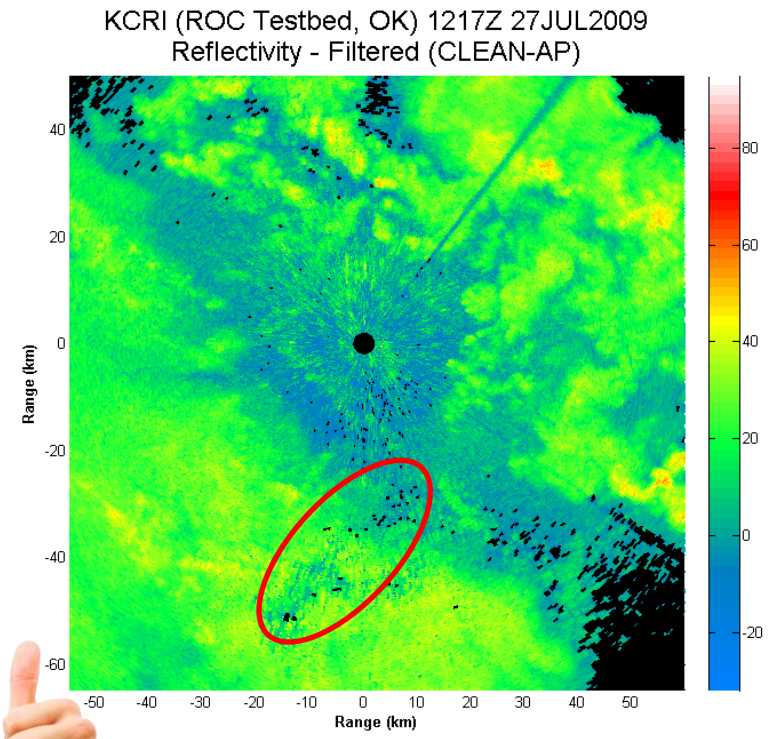
- Zero-isodop loss
  - Weather with narrow spectrum width and near zero velocity has nearly the same spectrum as clutter

if it looks like a duck…

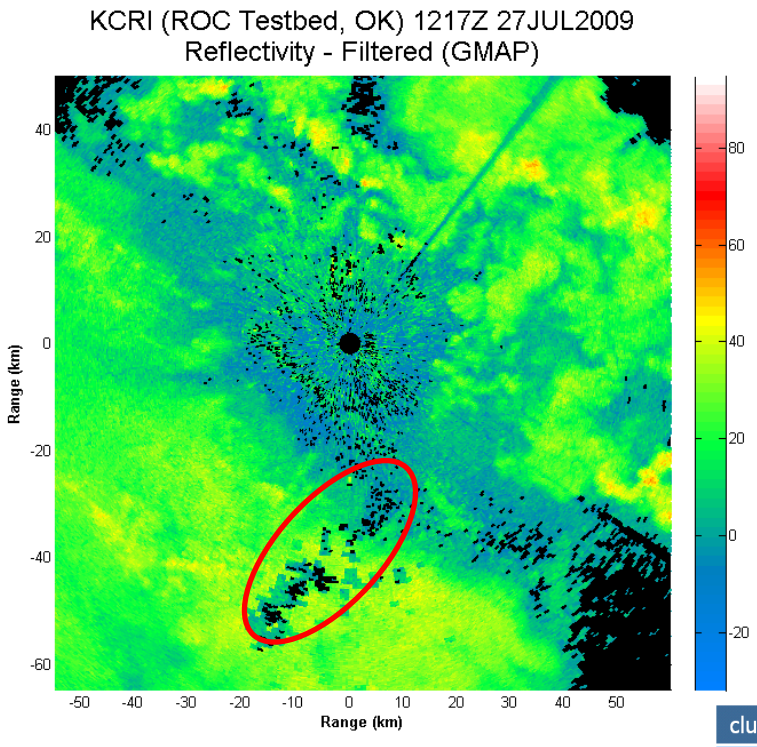
KCRI (ROC Testbed)

Reflectivity

CLEAN-AP



CMD+GMAP



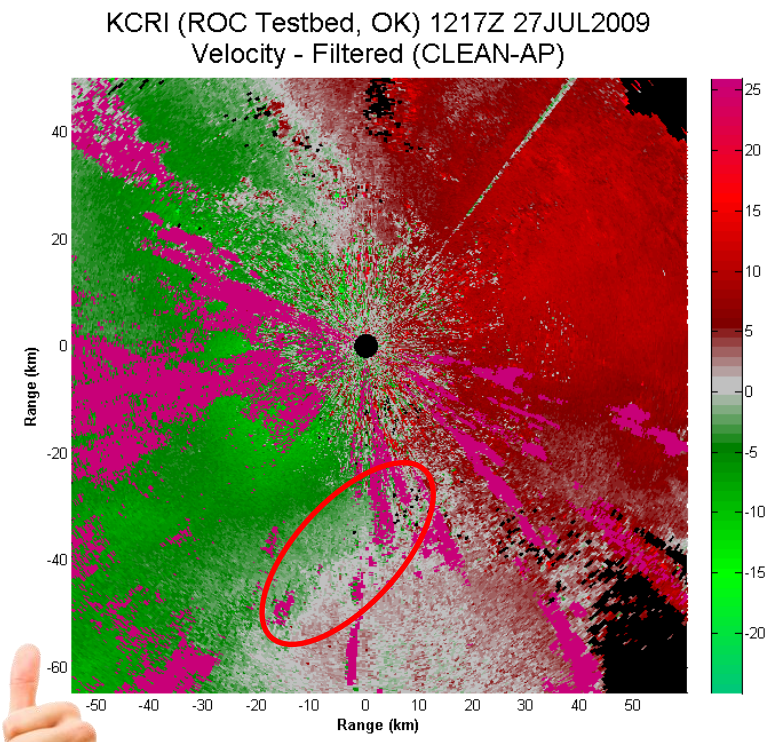
CLEAN-AP better **preserves** the **zero isodop**

CMD detection \ clutter contamination	no	yes
no	data	data
yes	bias	supp

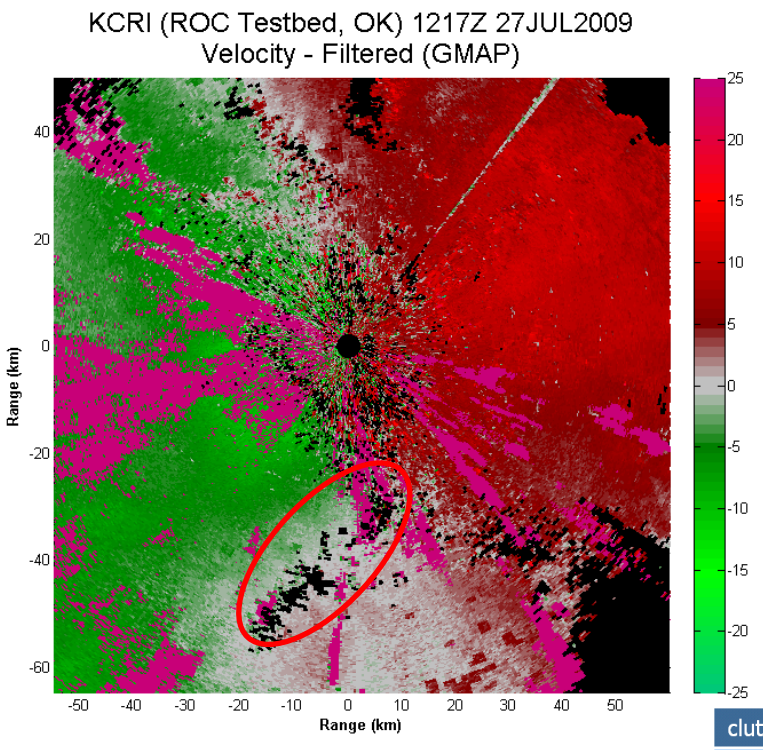
KCRI (ROC Testbed)

Velocity

CLEAN-AP



CMD+GMAP



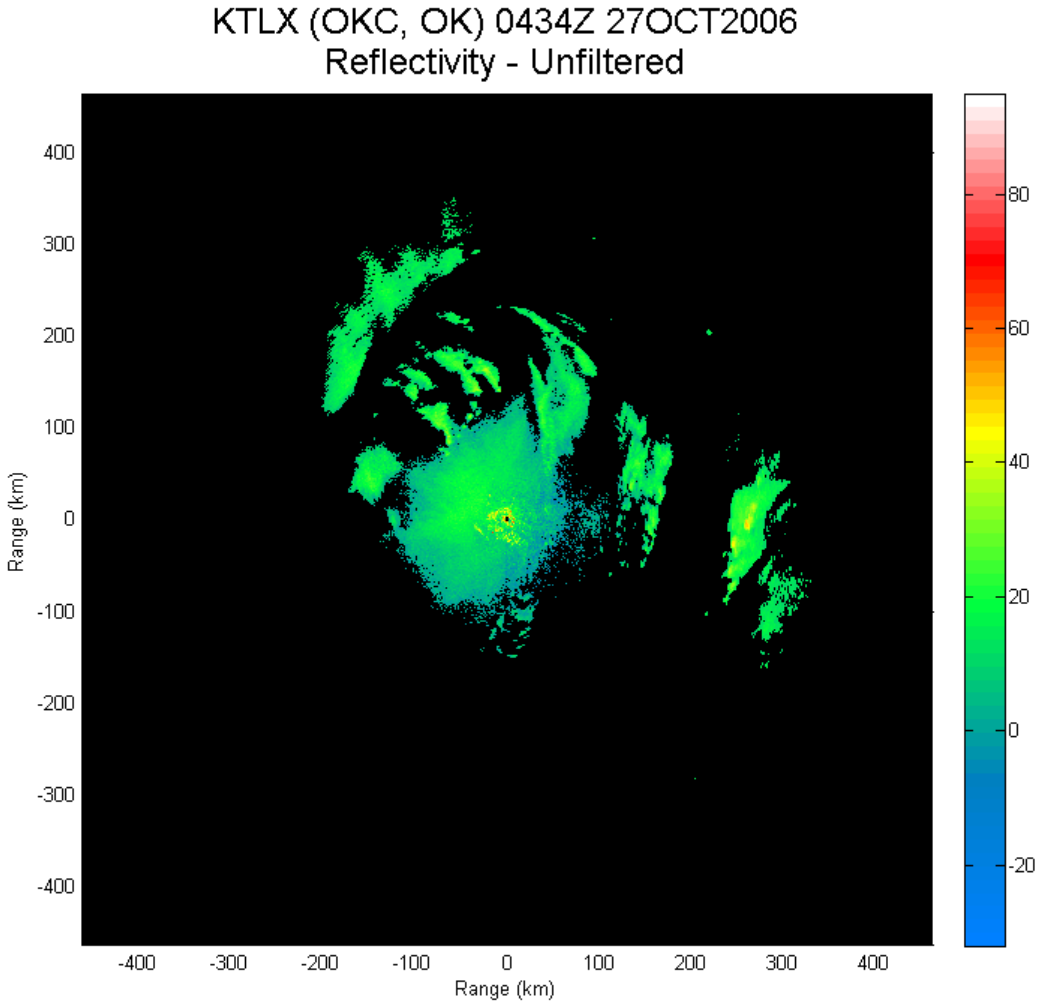
CLEAN-AP better **preserves** the **zero isodop**

CMD detection \ clutter contamination	no	yes
no	**data**	**data**
yes	**bias**	**supp**

KTLX Oklahoma City, OK

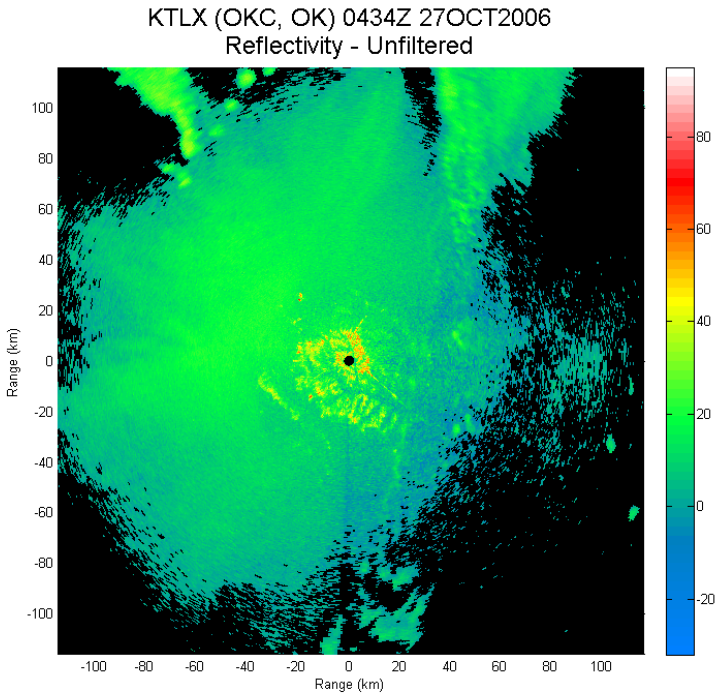
Where is the zero?

- Snow event with embedded storms

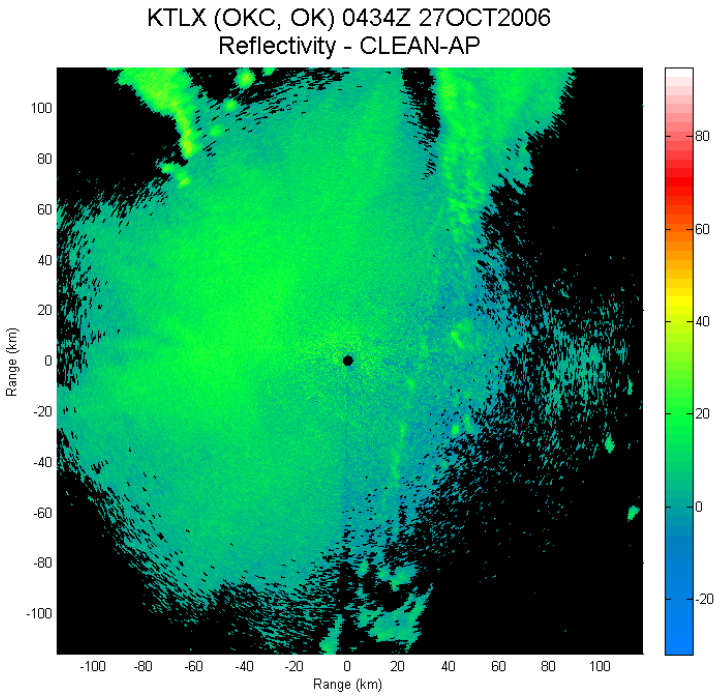


KTLX
Reflectivity

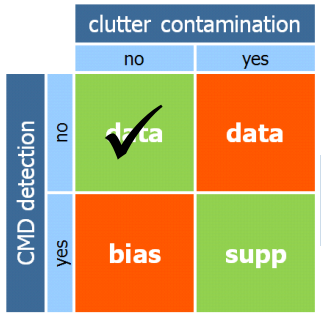
Unfiltered



CLEAN-AP

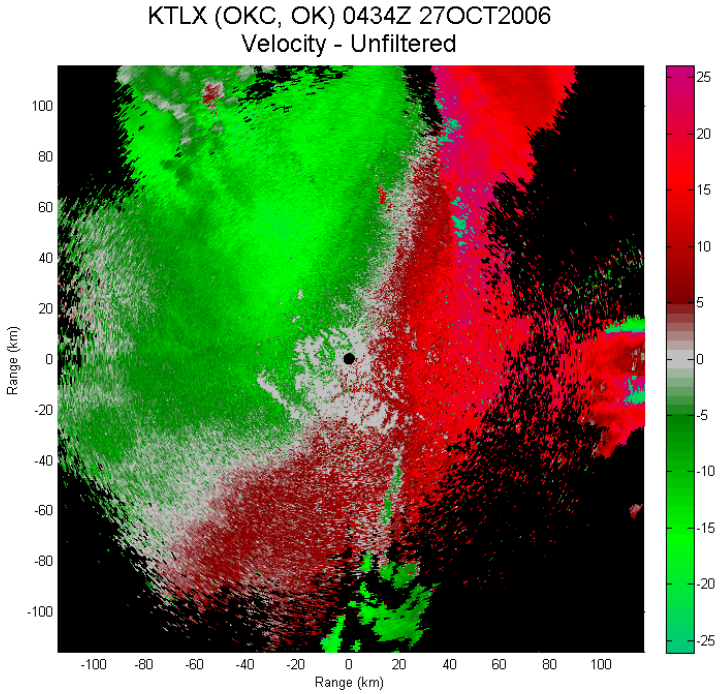


Where is the zero isodop?

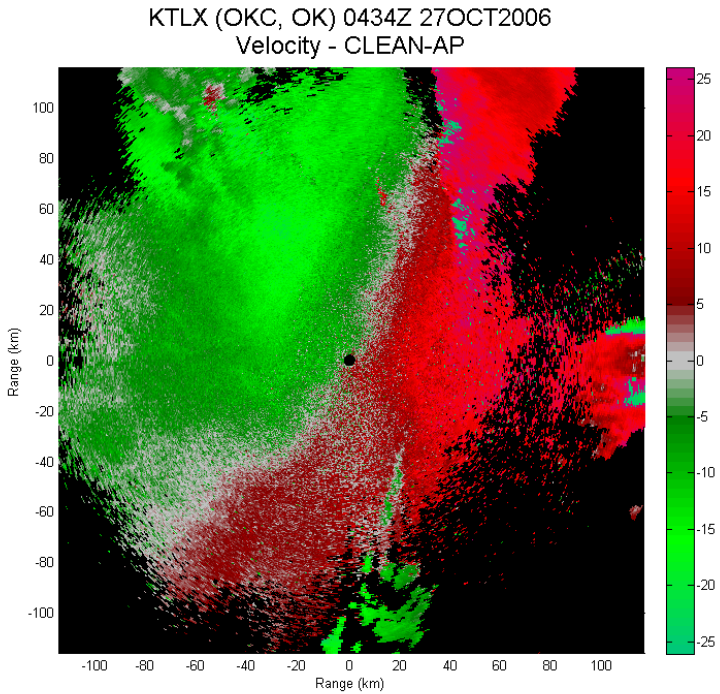


KTLX
Velocity

Unfiltered



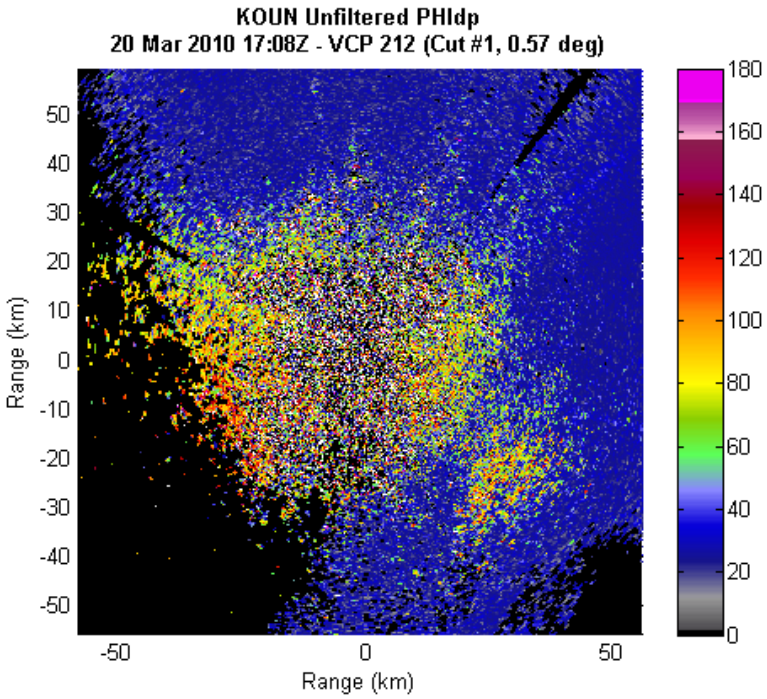
CLEAN-AP

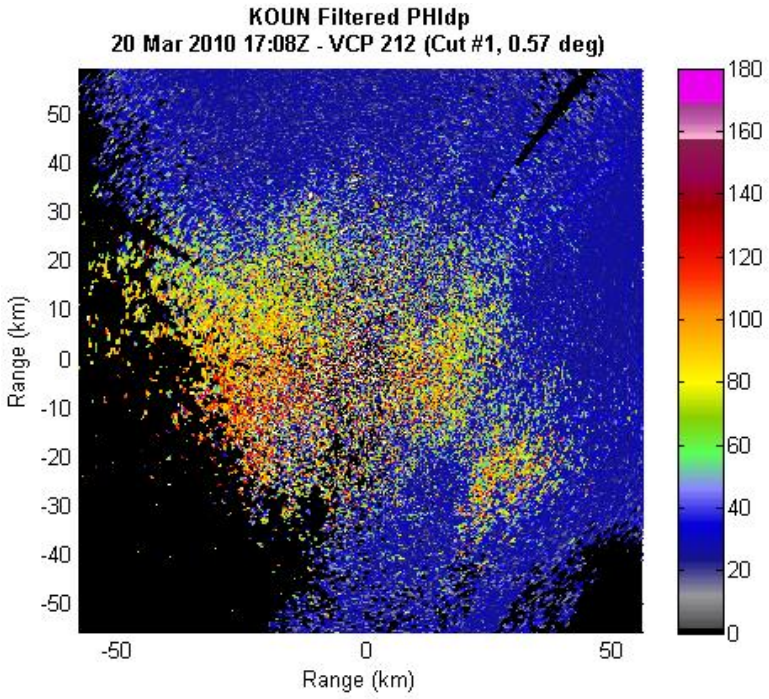


No detectable **zero isodop loss**

KOUN

What about dual polarization?





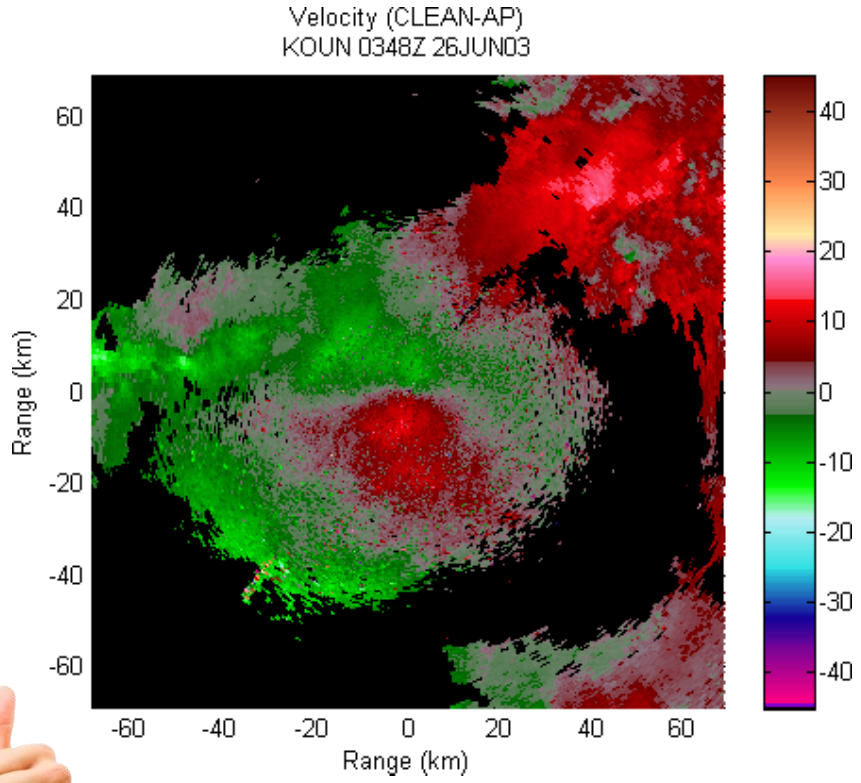
Differential Phase

CLEAN-AP is **compatible** with **dual polarization**

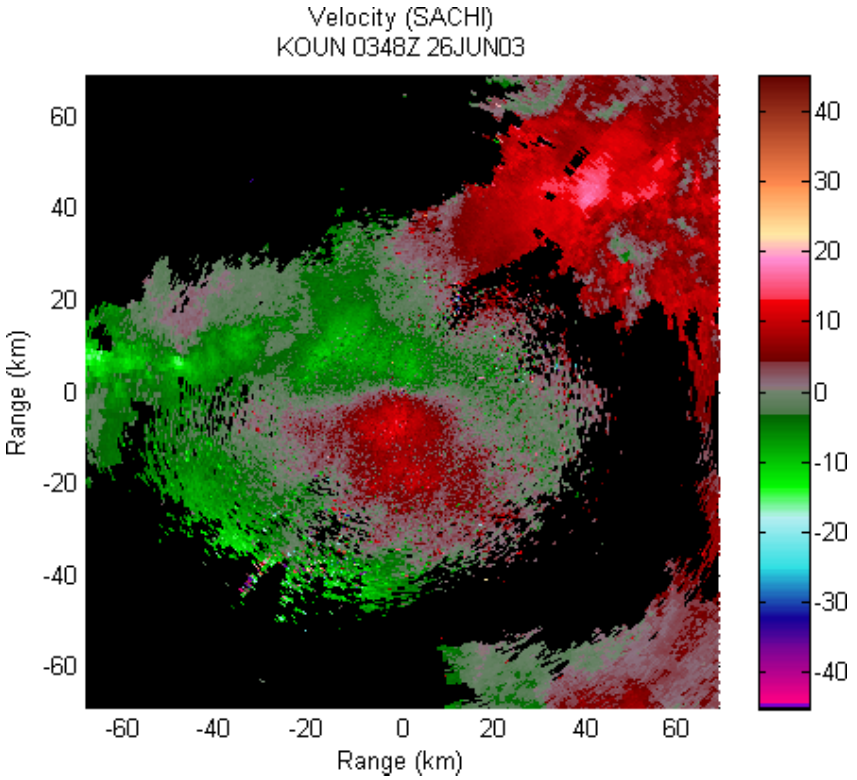
KOUN

What about staggered PRT?

CLEAN-AP



SACHI



CLEAN-AP is **compatible** with **staggered PRT**

milestones

- Developed concept (Spring '08)
- Evaluated performance using simulations (Spring '08)
- Implemented in real time on the NWRT PAR (Fall '08)
- Compared with current WSR-88D clutter mitigation (Fall '09)
  - KEMX (Tucson, AZ), KTLX (Oklahoma City, OK), KABX (Albuquerque, NM), KCRI (ROC testbed)
- Extended to **dual-polarization** (Spring '10)
  - KOUN (S-band)
  - OU' (C-band)
- Developed clutter model (Spring '10)
  - Form/Function/Fit for RVP8
- Extended to staggered PRT (Fall '10)
  - Integrates into general PRT-ratio framework
- Presented at DQ TIMs (last time: Fall '10)
  - Task added to current DQ MOU with ROC

now you know what CLEAN-AP is

CLEAN-AP is a novel **real-time**, **automatic**, **integrated** technique for ground clutter **detection** and **filtering** that produces data with **better quality** while meeting NEXRAD technical **requirements**.

we need your decision

Should the ROC proceed with the ***engineering evaluation*** *of* ***CLEAN-AP*** *on the RDA?*

back up slides

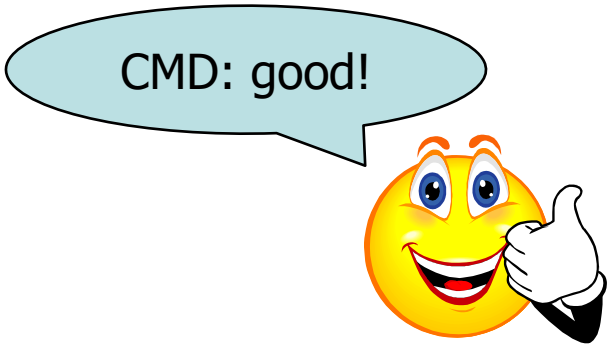
what is CLEAN-AP **not**?

While CLEAN-AP can deal with normal- (NP) and anomalous-propagation (AP) clutter, it is *not* a mitigation technique for moving clutter such as **airplanes**, **cars**, or **wind turbines**.

ground clutter filter control

Past, Present, and Future

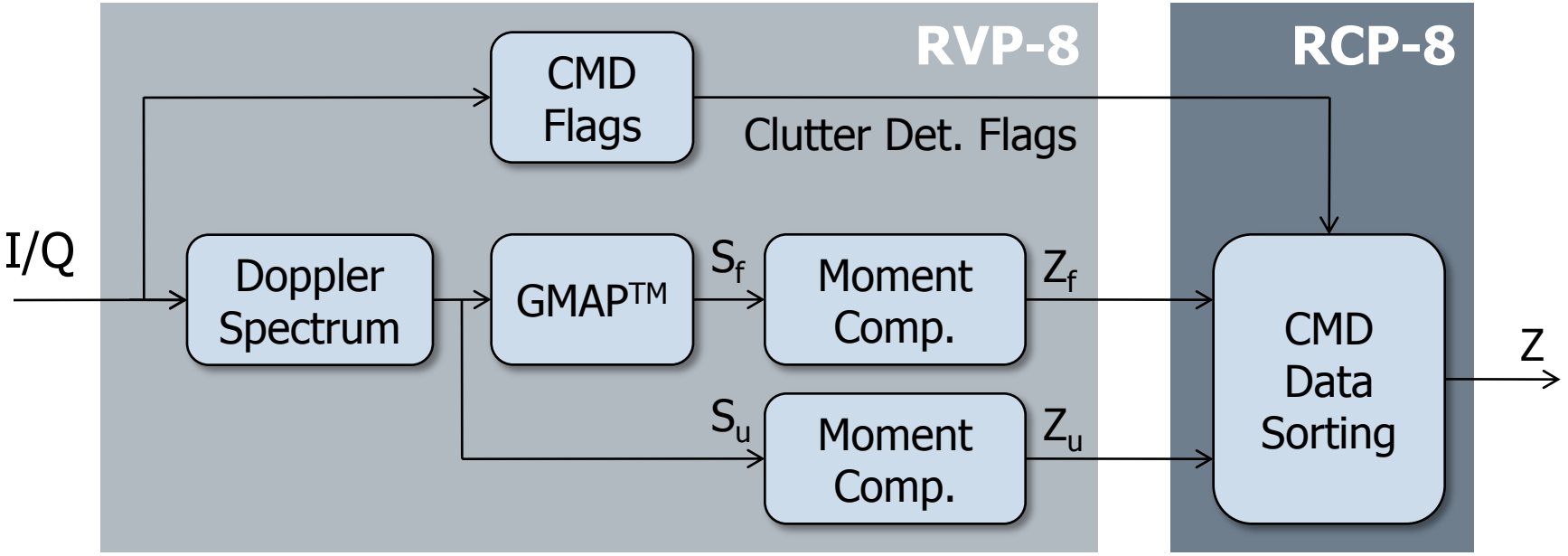
- ORDA Build 10 **& 12**
  - Static ground clutter maps (BYPASS map)
  - Operator-defined Clutter Censor Zones (CCZ)
- ORDA Build 11
  - Lower tilts (split cuts)
    - Clutter Mitigation Decision (CMD)
  - Upper tilts
    - Static ground clutter maps (BYPASS map)
  - Operator-defined Clutter Censor Zones (CCZ)



ground clutter filter control

B11 Clutter Mitigation Decision (**CMD**)

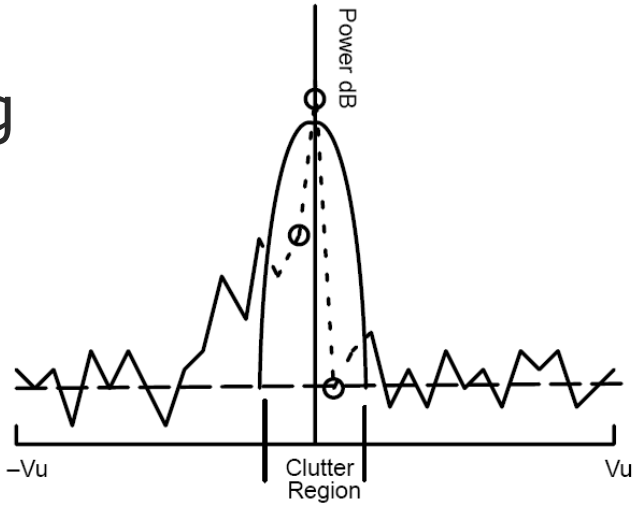
- Uses temporal and spatial features in a fuzzy-logic system to automatically detect ground clutter contamination in real time
  - Detections are "filled-in" by spatial filter
  - Detections are "extended" by map growing
  - Requires filtered and unfiltered data
  - Functionality split between RVP-8 and RCP-8



ground clutter filtering

Gaussian Model Adaptive Processing (**GMAP**™)

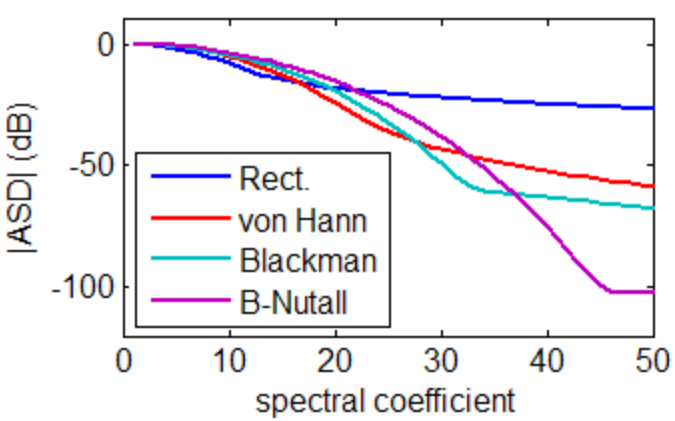
- Uses Gaussian model for clutter to determine notch width
  - Suppression is limited by maximum notch width
- Needs Blackman window to achieve required suppression
  - Does not produce data with best possible quality
- Uses iterative process to reduce reflectivity bias
  - Computationally intensive
- Needs at least 16 samples to achieve required suppression
  - Imposes limit on faster updates
- Not conducive to more spectral processing
  - Phase is lost from filtered signal
  - Affected by circular convolution biases
- Algorithm is under Vaisala control

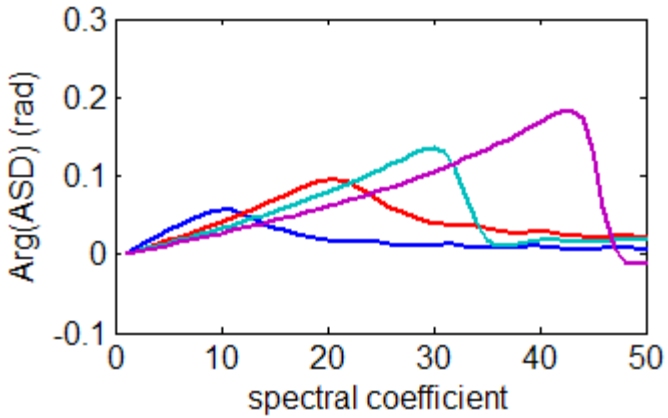


Source: Siggia and Passarelli (2004)

Supporting charts

	Current CMD+GMAP			Proposed CLEAN-AP	
	DFT	GMAP	CMD	DFTs	CLEAN-AP
Surveillance mode	all	all	all	all	all
Doppler mode	all	all	none	all	all

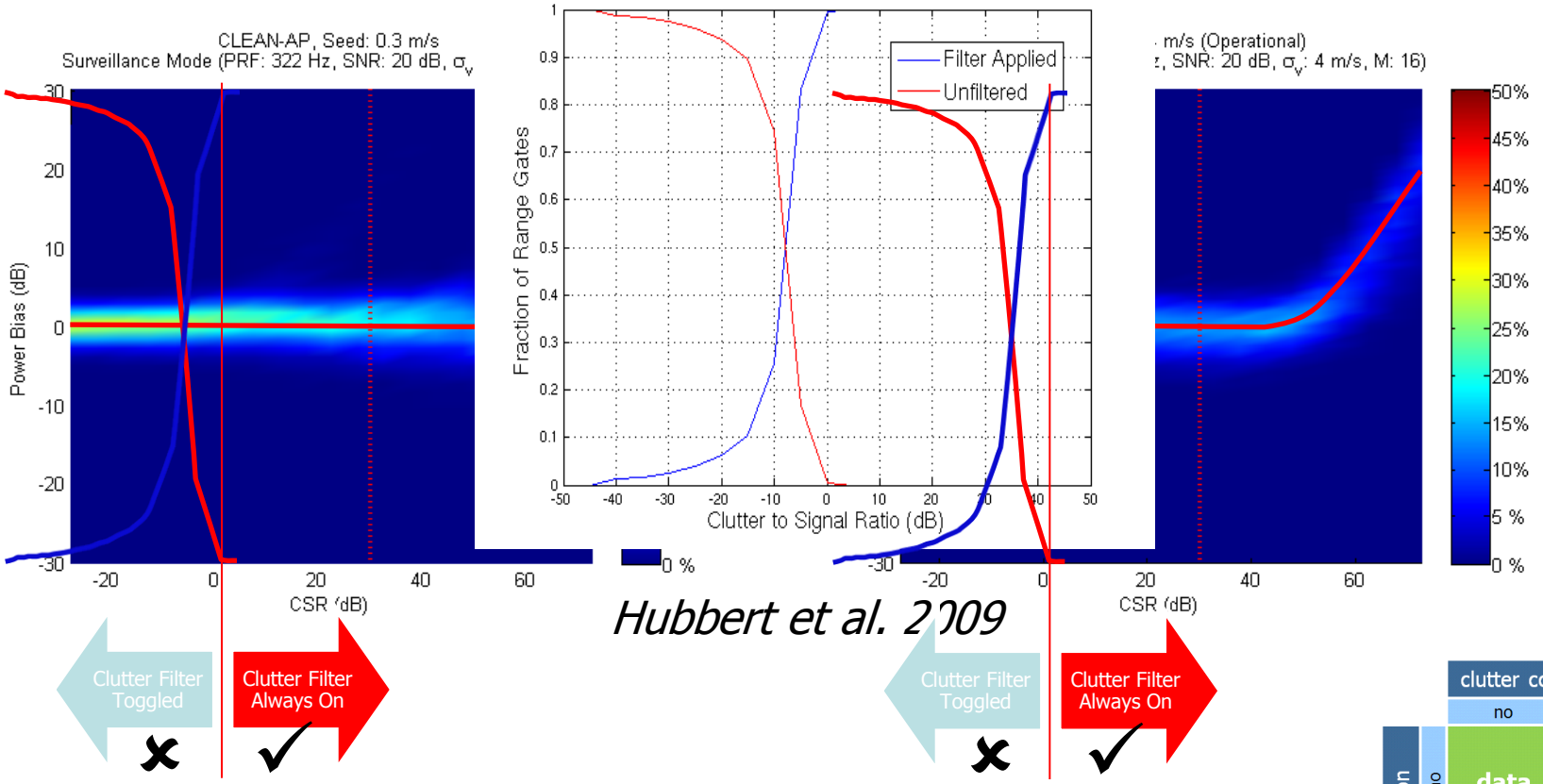




Clutter Suppression
Surveillance Mode (30 dB)

CLEAN-AP | **GMAP**

CMD

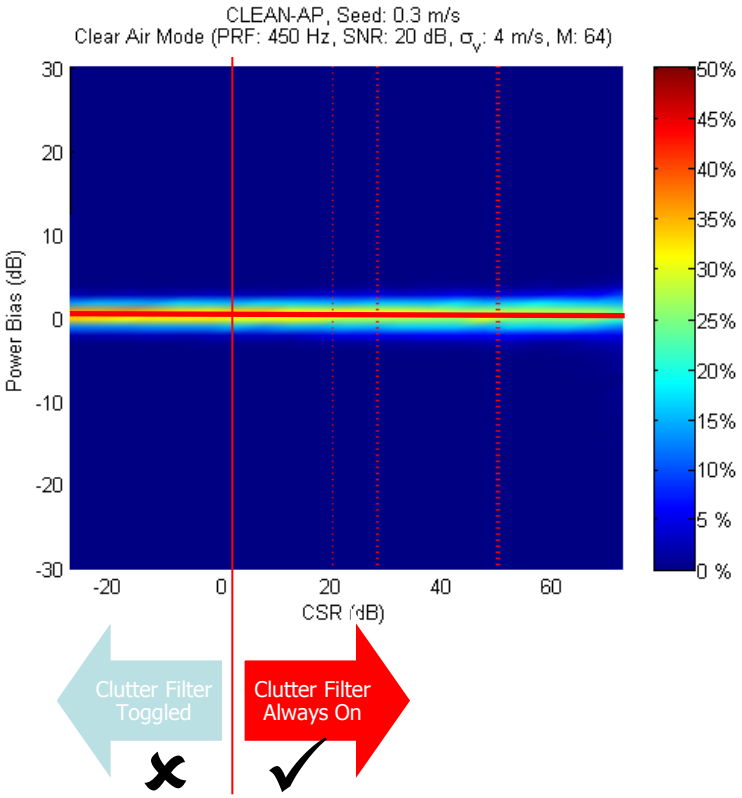


Hubbert et al. 2009

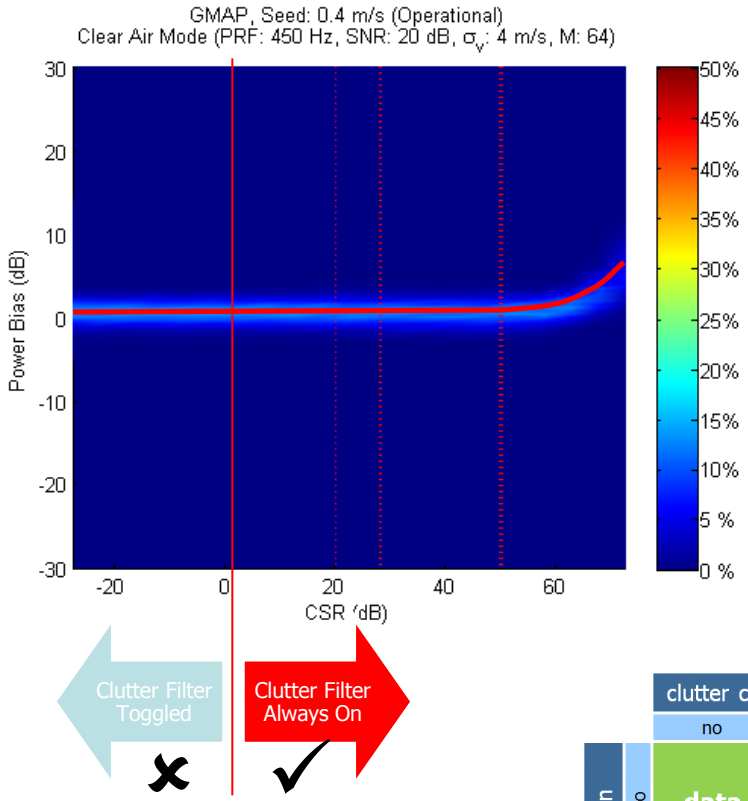
CMD detection \ clutter contamination	no	yes
no	data	data ✗
yes	bias	supp ✓

Clutter Suppression
Clear Air Mode (20, 28, and 50 dB)

CLEAN-AP



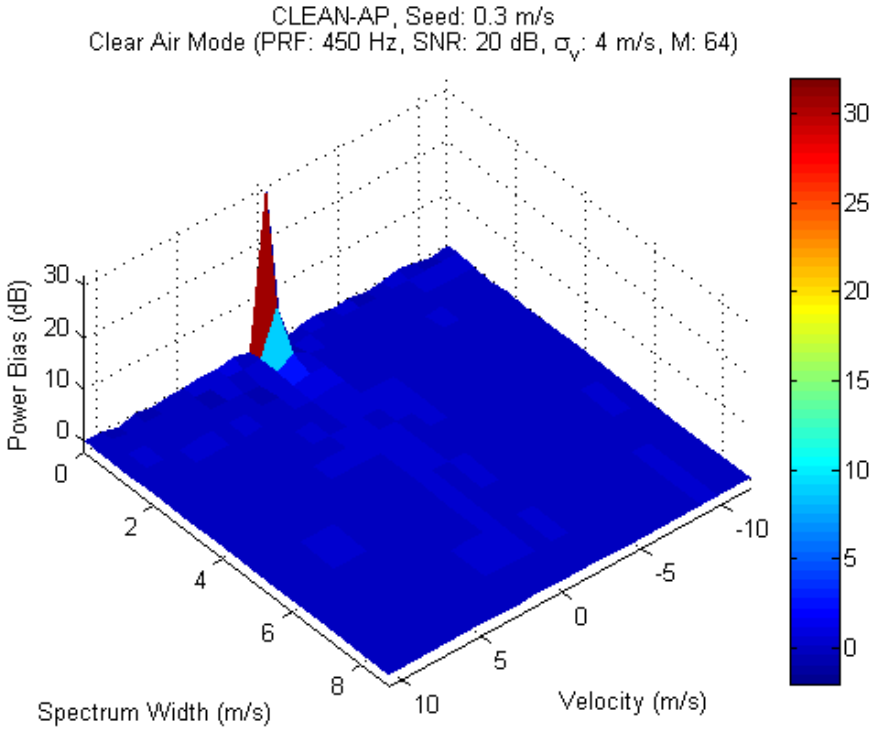
GMAP



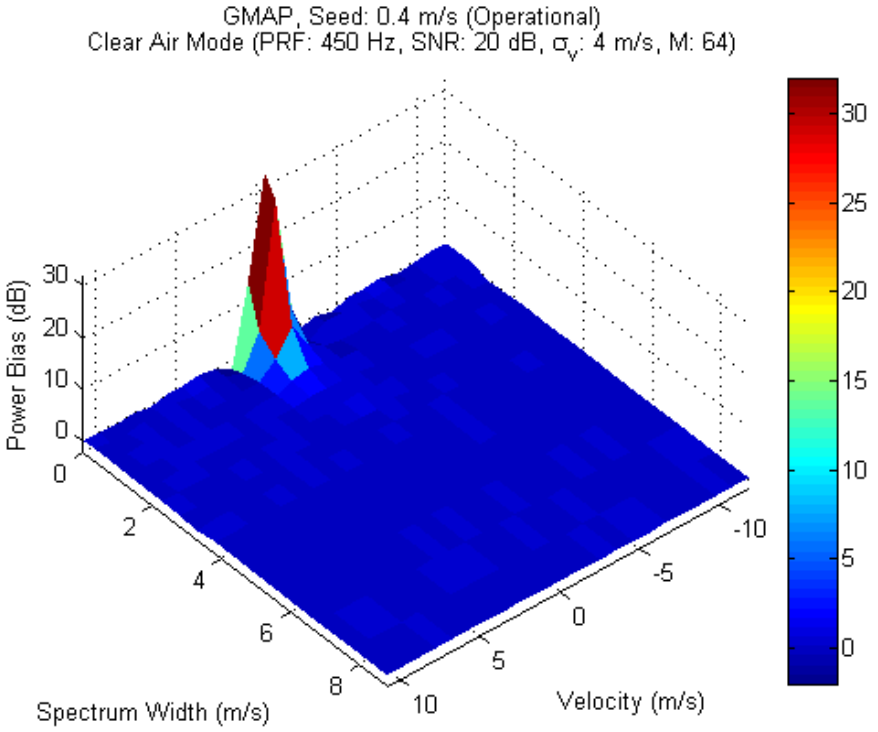
CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias	supp

Reflectivity (Power) Bias
Clear Air Mode

CLEAN-AP

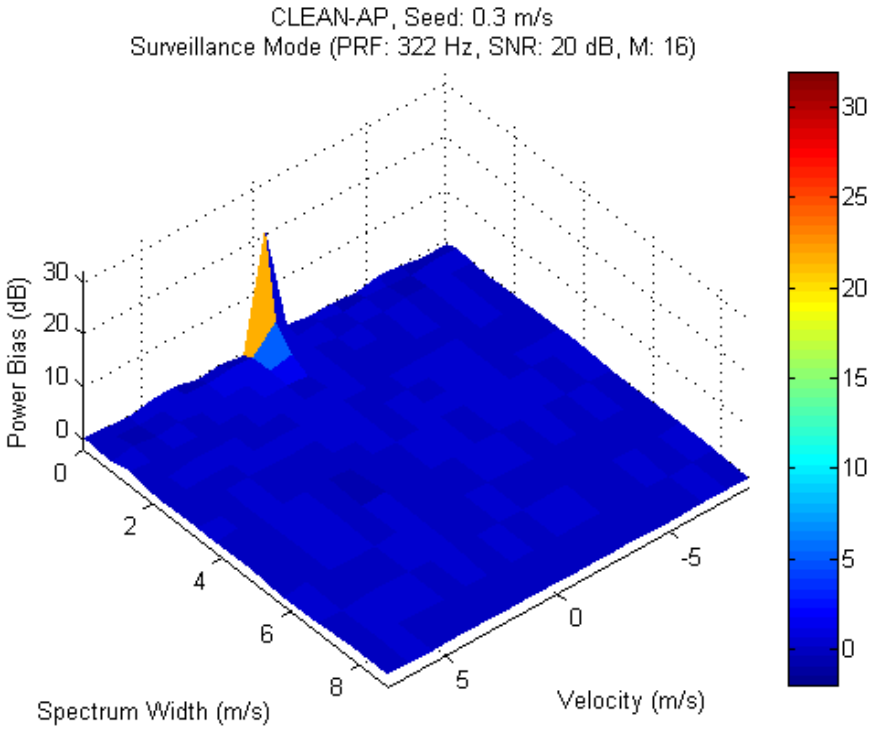


GMAP

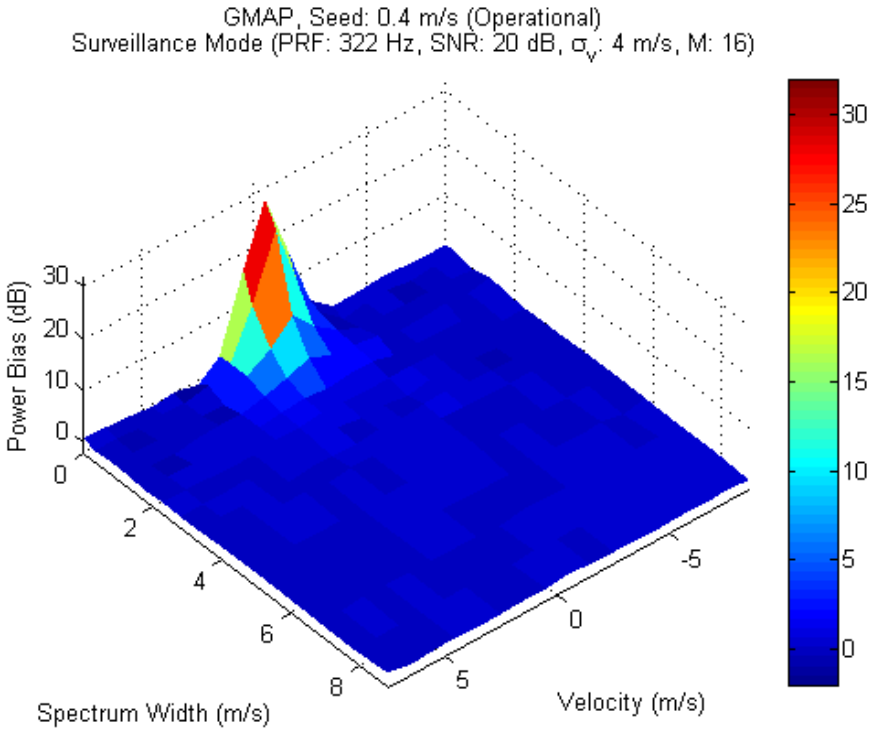


Reflectivity (Power) Bias
Surveillance Mode

CLEAN-AP



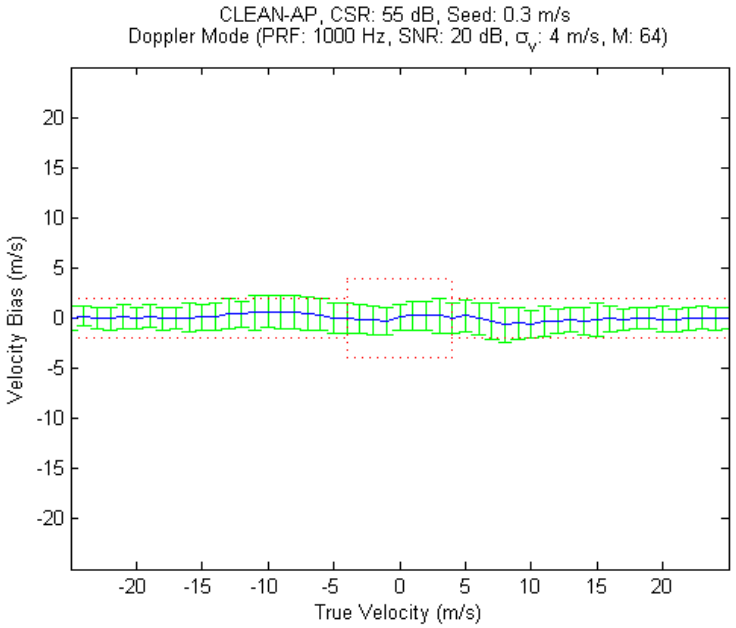
GMAP



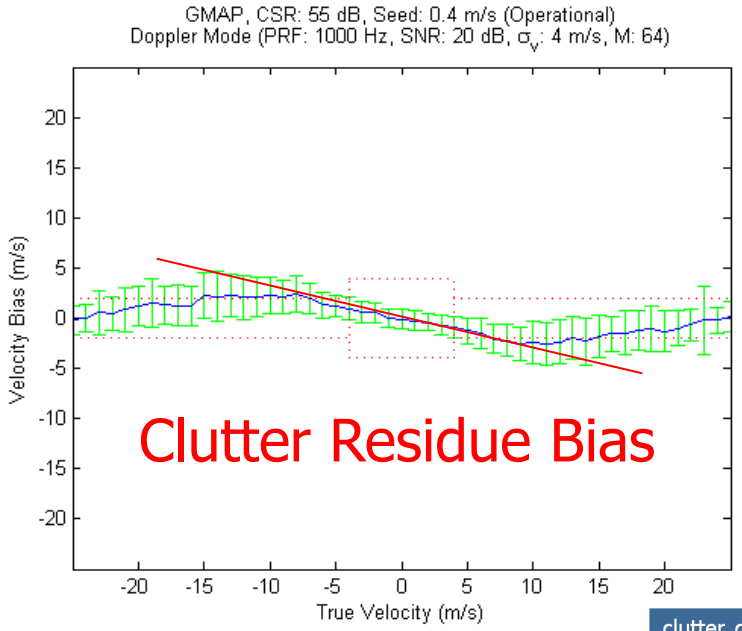
Velocity Bias
Doppler Mode

CSR = 55 dB

CLEAN-AP



GMAP



CMD detection	clutter contamination: no	clutter contamination: yes
no	data	data
yes	bias ✓	supp

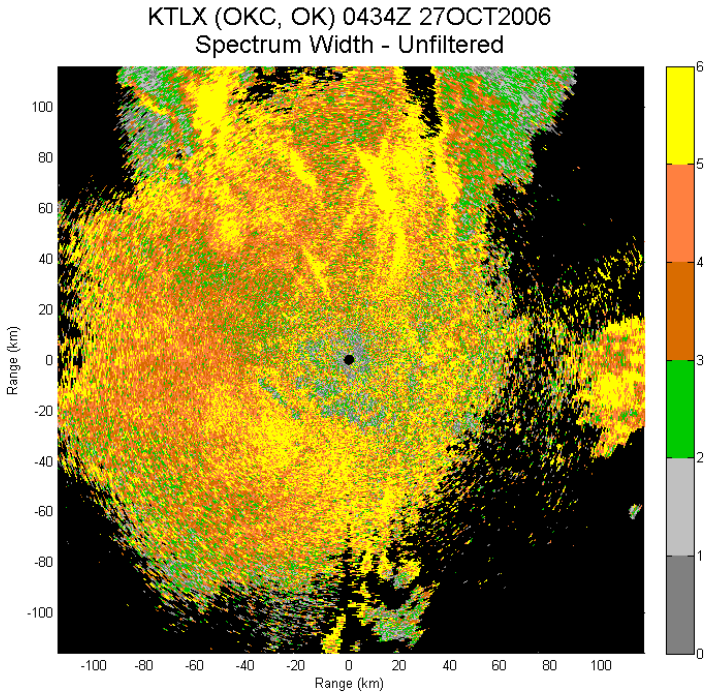
KEMX Tucson, AZ

Can you see the mountains?

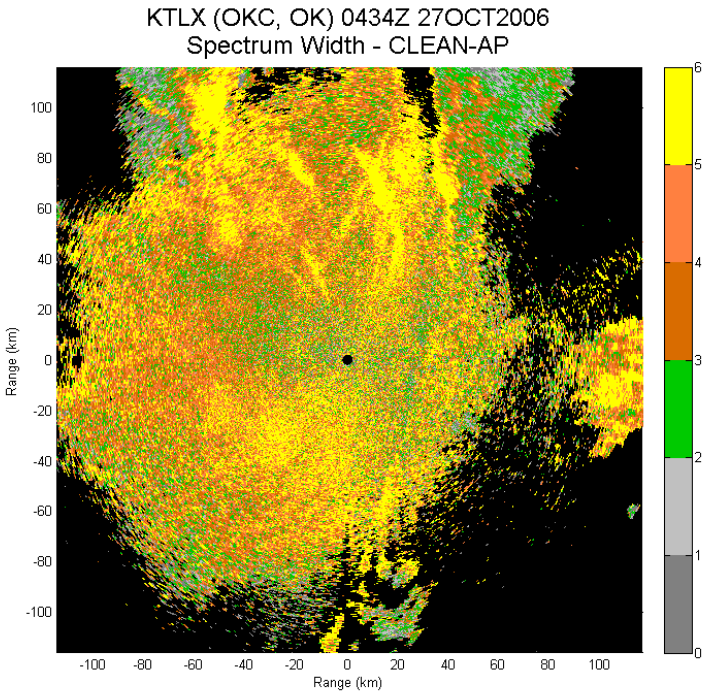
- RDA Build 11.0 Beta Test (CMD implemented)
  - Missed CMD detections in RDA Build 11.0
    - Level-I data indicated that, at times, two distinct targets were captured by the moving antenna
    - Phase and power changes between clutter targets caused low CPA values
  - Mitigated CMD missed detections in RDA Build 11.1 (only for super resolution)

KTLX
Spectrum Width

Unfiltered



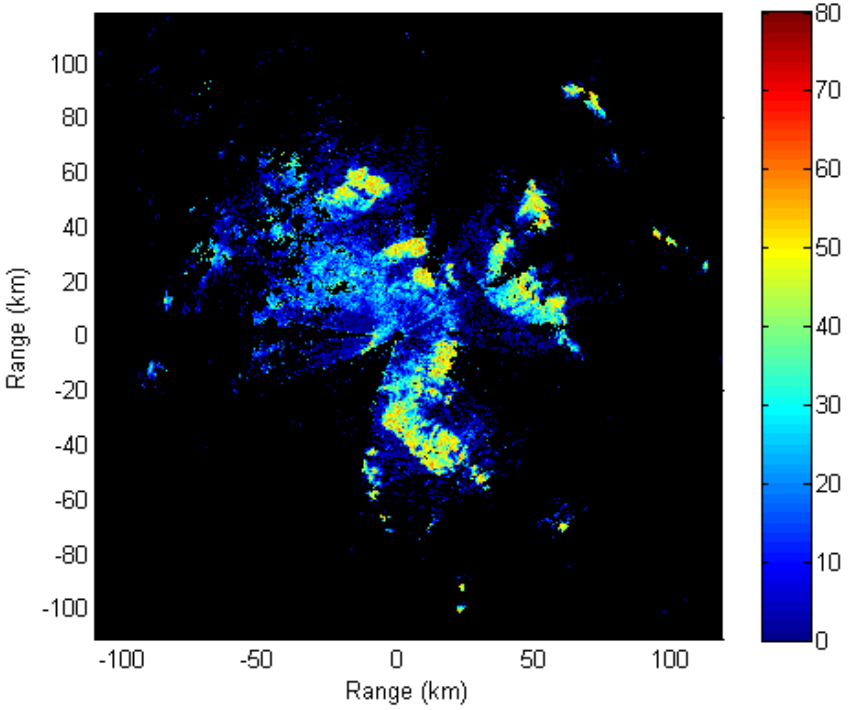
CLEAN-AP



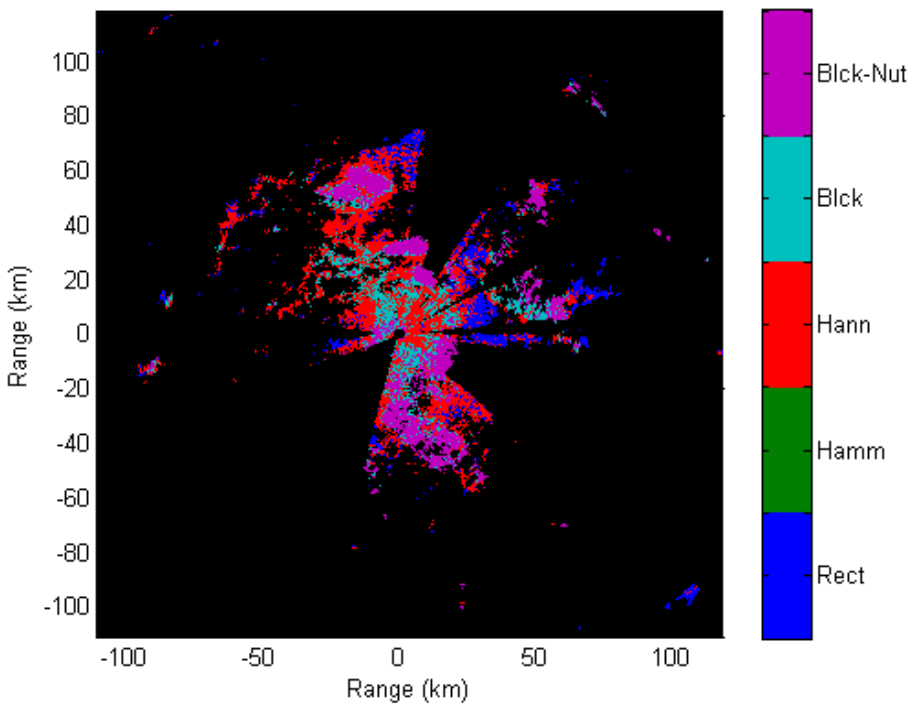
KEMX

What is CLEAN-AP doing?

Power Removed

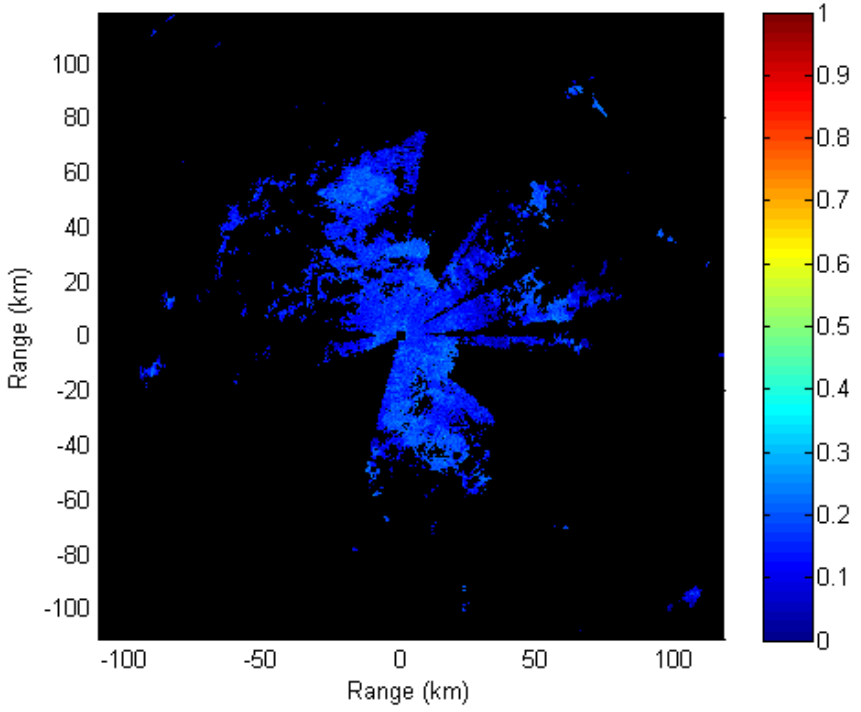


Window Used

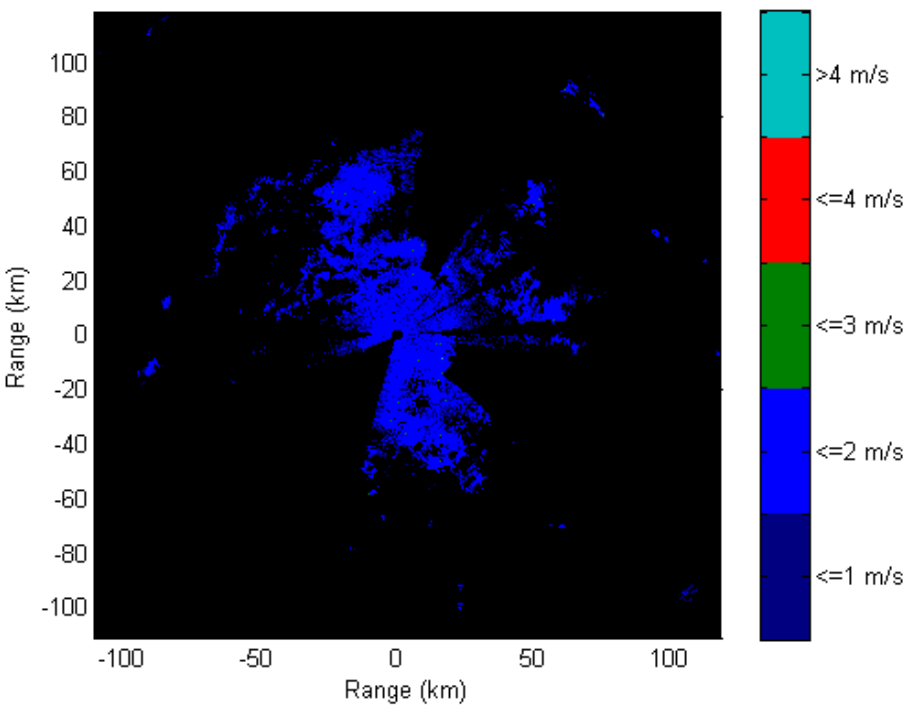


KEMX

Percent of Notch

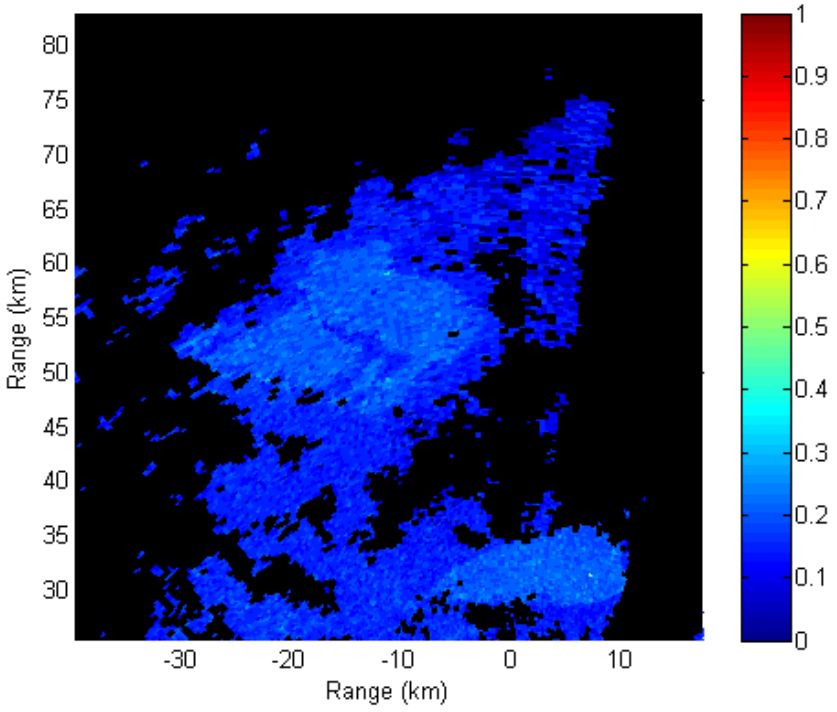


Usable Velocities

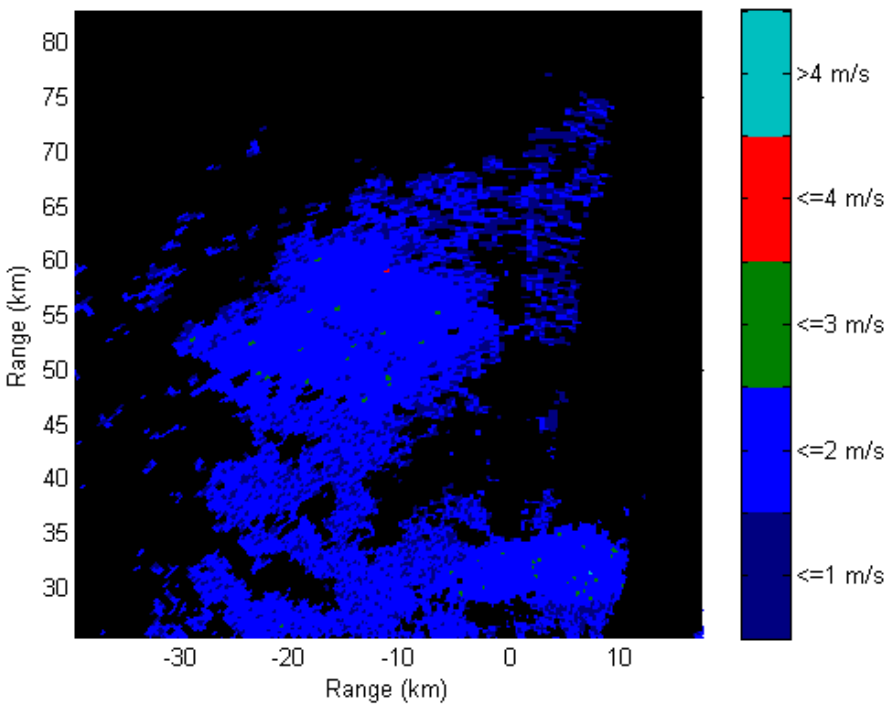


KEMX

Percent of Notch



Usable Velocities



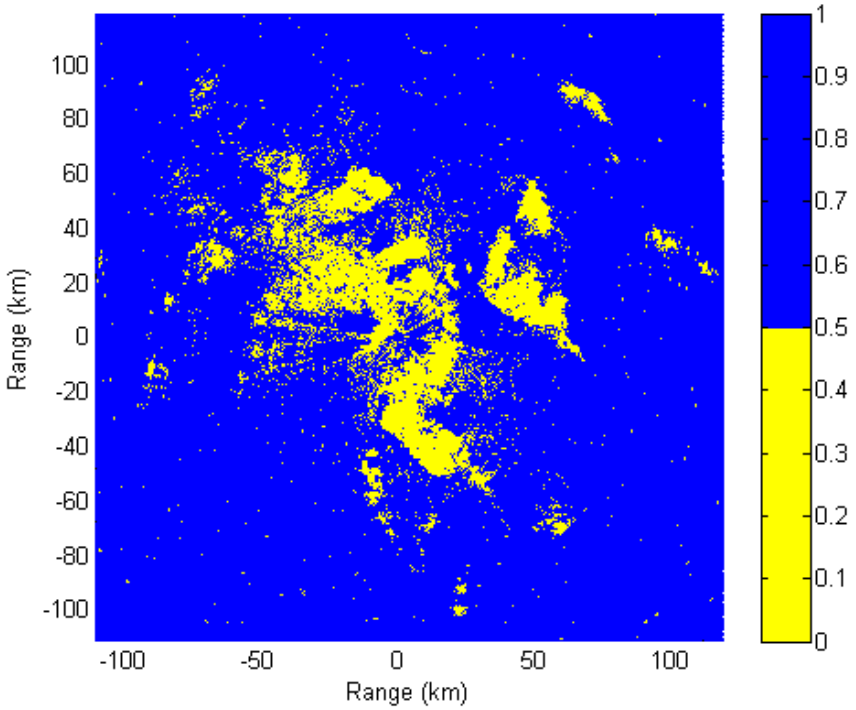
Operational Considerations

What about Clutter Maps?

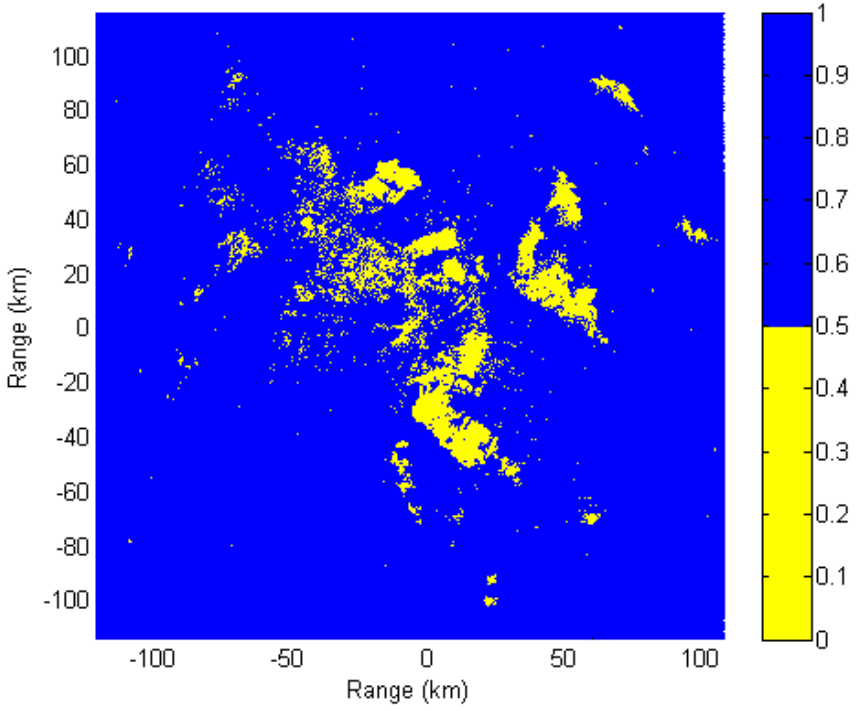
- WSR-88D Operational Clutter Maps
  - 5 elevation (el.) segments transitions in Volume can be changed.
    - VCP-12
      - Segment 1: el. < 1.05
      - Segment 2: 1.05 < el. < 1.65
      - Segment 3: 1.65 < el. < 4.05
      - Segment 4: 4.05 < el. < 6.45
      - Segment 5: el. > 6.45
  - Resolution = 1 km (resolution of base data = 1/4 km)
  - Static
  - Dynamic
- CLEAN-AP runs on all bins
  - Clutter Maps?

KEMX

Clutter Map (Pwr Rmvd > 10 dB)

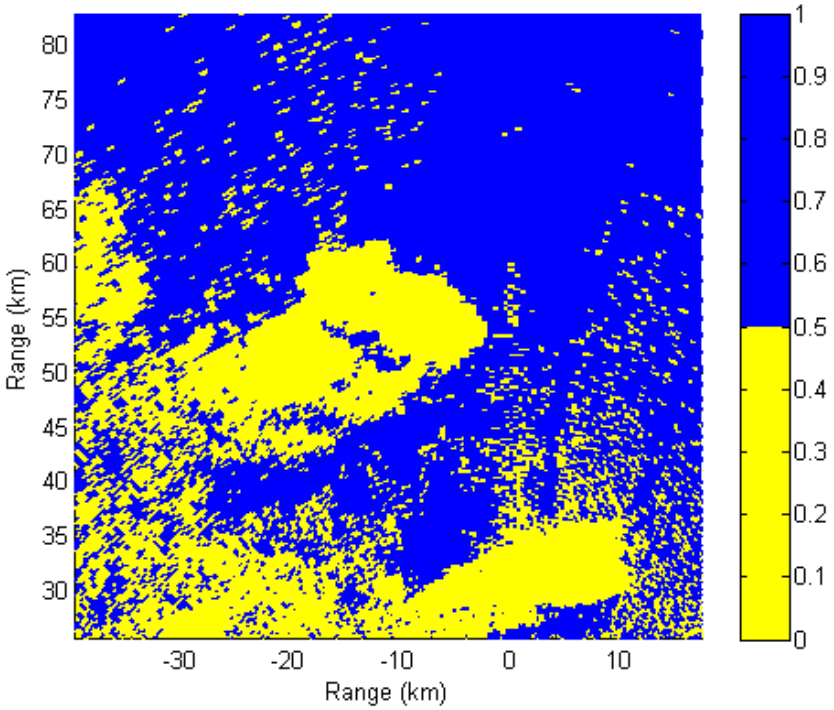


Clutter Map (Pwr Rmvd > 20 dB)



KEMX

Clutter Map (Pwr Rmvd > 10 dB)



Clutter Map (Pwr Rmvd > 20 dB)