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A Knowledge-Aided STAP Architecture

William L. Melvin, Gregory A. Showman and Daren J. Zywicki

Georgia Tech Research Institute (GTRI)

Sensors & Electromagnetic Applications Laboratory

bill.melvin@gtri.gatech.edu, Ph. 770-528-3274

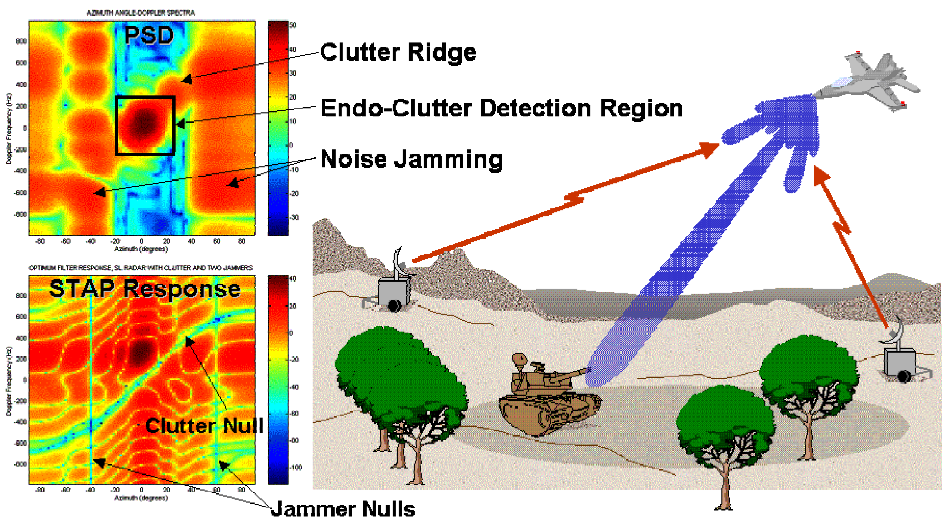
Outline

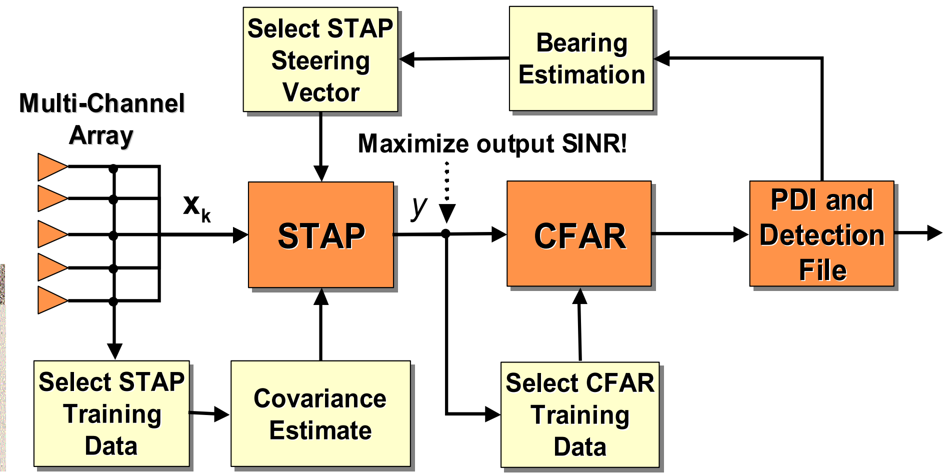
- Goals of ground moving target indication (GMTI)
  - Adaptive detection
  - Minimum detectable velocity (MDV)
- Impact of complex, heterogeneous clutter on front-end adaptive algorithm performance
  - Taxonomy of clutter heterogeneity
  - Simulated and measured data examples
- Knowledge-Aided STAP (KA-STAP)
  - KA training, KA pre-filtering, KA covariance estimation
- Multi-resolution processing
- Overview: A KA-STAP processing architecture
- Summary

GMTI Goals

- Detect slow moving targets in the presence of clutter and jamming signals
  - Angle-Doppler properties of target and clutter are very similar
    - Endo-clutter detection
- Space-time adaptive processing (STAP) is a key technology
  - As a member of the class of super-resolution techniques, greatly overcomes diffraction-limited clutter spread
  - Supports high area coverage rate (ACR)
- Minimum detectable velocity (MDV) and ACR are key metrics
- GMTI radar must operate effectively in complex, heterogeneous clutter environments
  - DARPA's Knowledge-Aided Sensor Signal Processing and Expert Reasoning (KASSPER) Program addressing front-end signal processing architecture improvement

STAP Detection Block Diagram & Metrics

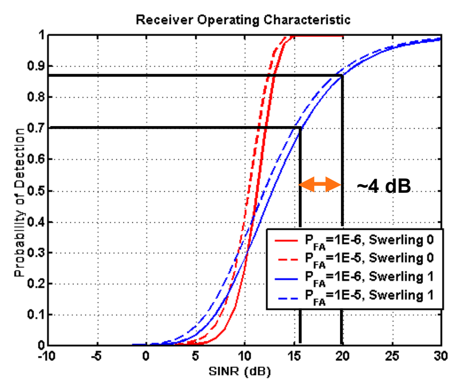




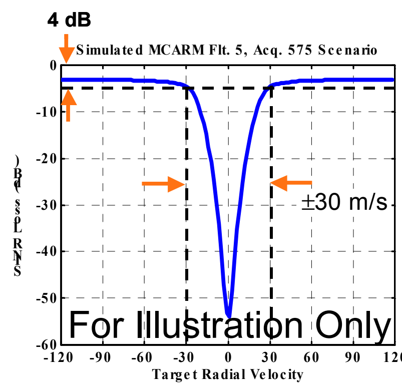
Key Metrics:

- Minimum Detectable Velocity (MDV)
- False alarm rate
- Area Coverage Rate (ACR)

E.g.,

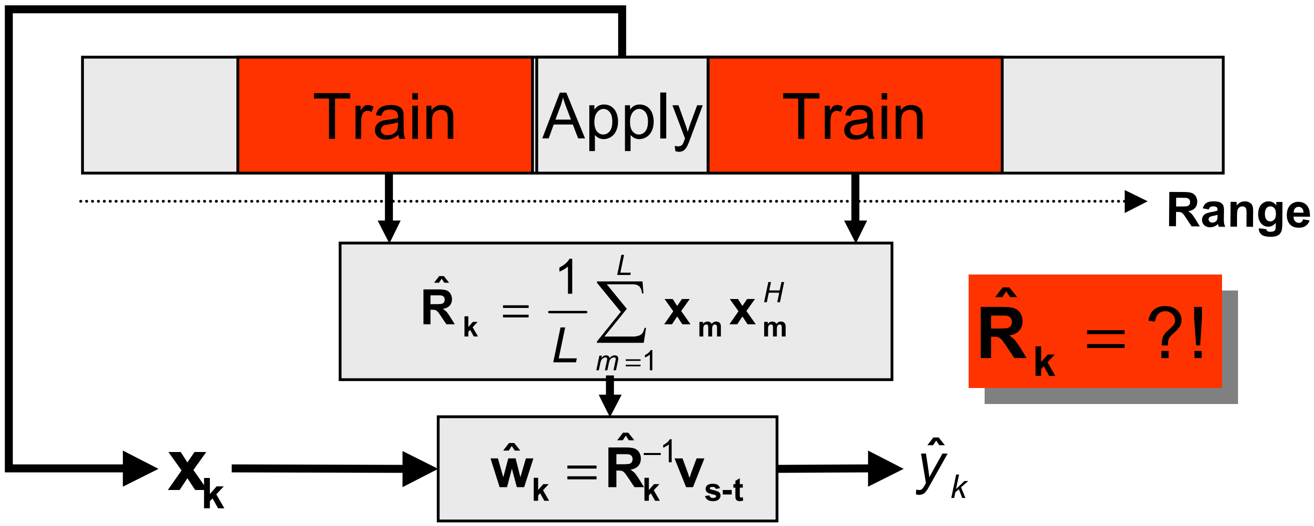


MDV



Training the Adaptive Filter

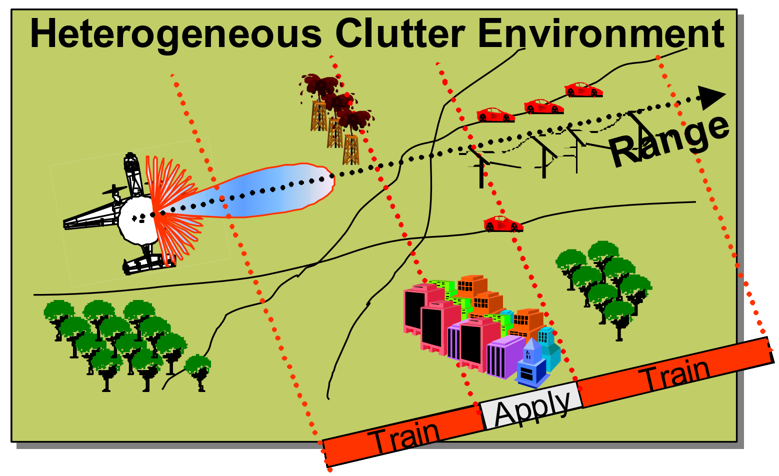
Adaptive: Generally assumes IID training data



$$SINR = SNR \times \underbrace{\left(\frac{SINR_o}{SNR}\right)}_{L_{s,1}} \times \underbrace{\left(\frac{SINR_{a/iid}}{SINR_o}\right)}_{L_{s,2}} \times \underbrace{\left(\frac{SINR_{a/het}}{SINR_{a/iid}}\right)}_{L_{s,3}}$$

$\mathbf{R}_k$ = known

iid × heterogeneous

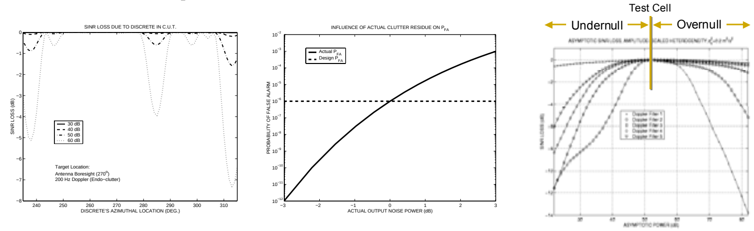


Heterogeneous Clutter Affects STAP

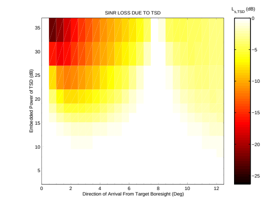
Taxonomy of Clutter Heterogeneity

Type	Some Causes	Impact
Amplitude	Spatially varying clutter reflectivity, shadowing, edges	Inadequately nulled clutter, increased Pfa
Spectral	Variable ICM (e.g., windswept fields, undulation of waves)	Inappropriately set filter notch, uncancelled clutter, degraded MDV
CNR-Dependent Spectral	CNR's influence on spectral spreading mechanisms	Inadequately nulled clutter, degraded MDV
Moving Scatterers	Ground/air traffic, weather	Signal cancellation, distorted beam, exhausts DoF
Angle-Doppler Misalignment	Sensor geometry induces non-stationary behavior (e.g., bistatics, canted or forward-looking arrays, conformal arrays)	Combination of above

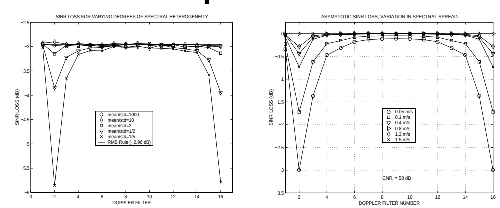
Amplitude & CNR-Induced



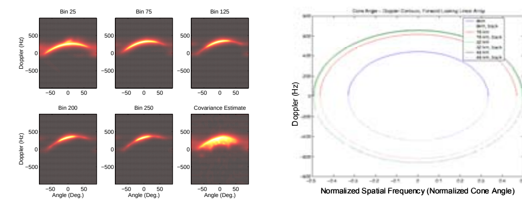
TSD

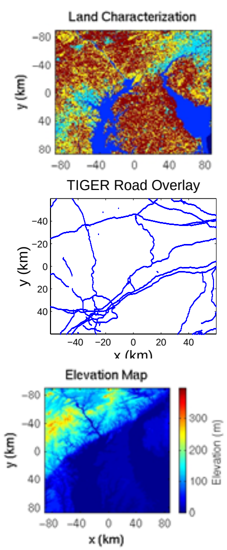


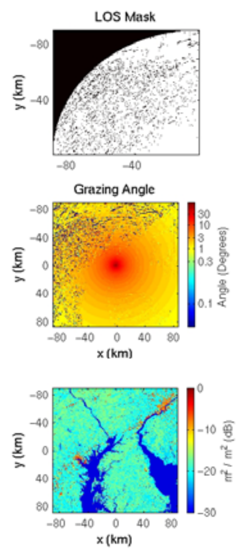
Spectral



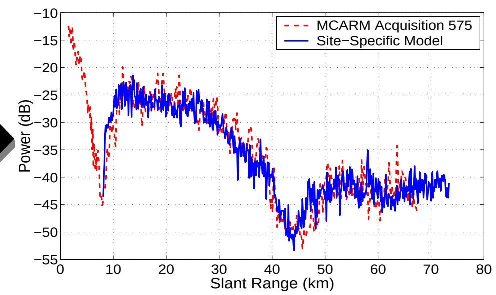
Geometry-Induced

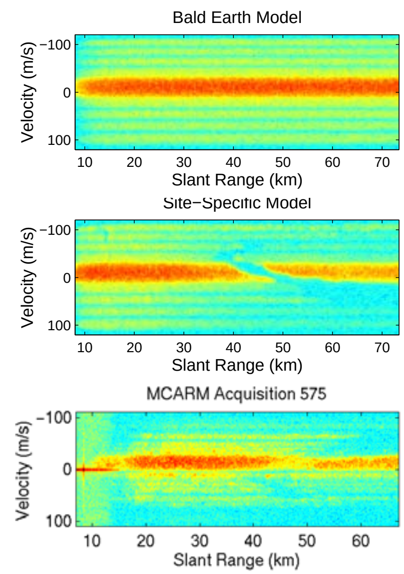






Site Specific Analysis





Knowledge Sources

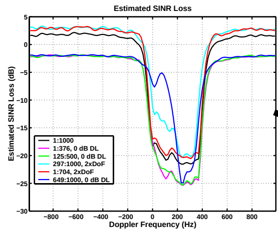
What we know…	How we know it…
Platform velocity and attitude	INU/GPS
Array normal and antenna characteristics	INU/GPS and calibration
Road locations	Mapping data
Predominant clutter type	Mapping data, prior missions and other sensors
Location of discretes	Mapping data, prior missions and other sensors
Predominant angle-Doppler clutter behavior	INU/GPS and simulation
Estimated clutter amplitude and spread	Scattering/EM codes, prior data collections

Adaptivity required due to imperfect knowledge, incorrect models, system errors…

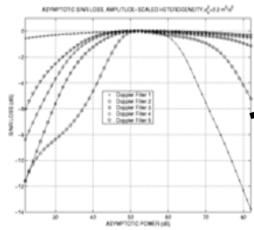
KA-STAP Overview

- Consider the application of *a priori* knowledge to enhance STAP implementation and improve GMTI detection performance

KASSPER Datacube

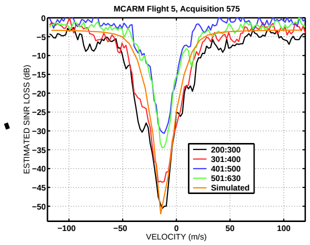


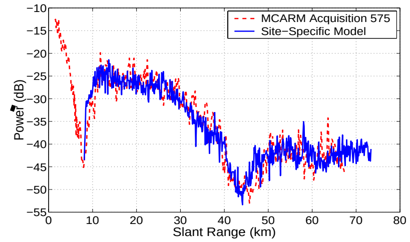
Heterogeneous Clutter Models



Traditional STAP

$$\hat{\mathbf{R}}_k = ?$$





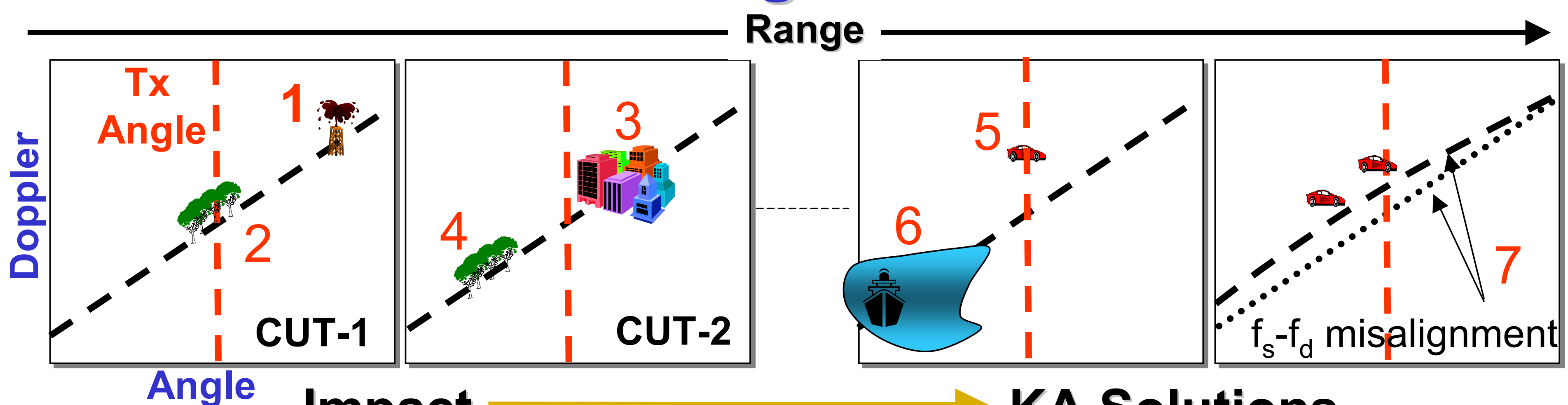
Measured MCARM Data

KA-STAP

e.g.,

$$\min_{KA} E\left[\left\|\boldsymbol{\varepsilon}\right\|_2\right] = \min_{KA} \left\|E\left[\hat{\mathbf{w}}_k\right] - \mathbf{w}_k\right\|_2$$

Detection Challenges & KA Solutions



Impact → KA Solutions

Impact

1) Discrete in CUT-1 – raises P_{FA}.
2) "Soft" scatters in mainbeam – Notch width too narrow to accommodate ICM.
3) Overnull in CUT-1, potential signal whitening. Increased clutter residue in CUT-2, target masked (CFAR maintains acceptable P_{FA}).
4) Slight increase in clutter residue in CUT-1. No impact for CUT-2.
5) TSD leads to target whitening in CUTs 1&2.
6) Leads to undernulled clutter in CUTs 1&2.
7) Increased clutter residue, increased P_{FA}.

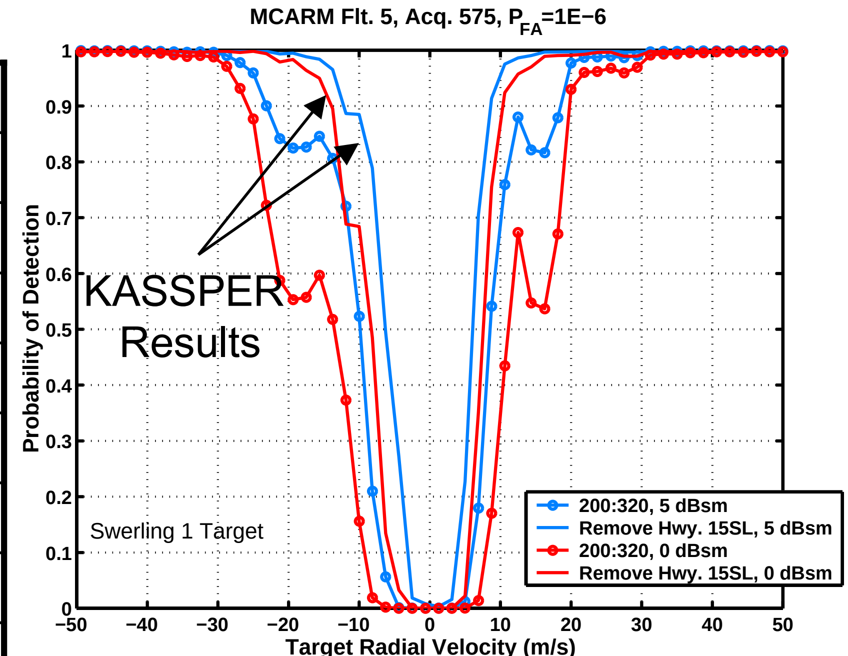
KA Solutions

1) Cultural database identifies regions with discretes; data-dependent screening (train or blank); multi-resolution.
2) Cultural database suggests CMT; modify training region; KA filter bank adjusts filter width.
3) Cultural database aids in training selection; KA constraints to pre-null; KA pre-whiten/filter bank.
4) Cultural database aids in training selection
5) Screen training region using cultural database; data-dependent screening; KA constraints.
6) Cultural database aids in training; KA pre-whitening; KA filter bank.
7) Use INU/GPS to compensate training set; KA filter bank.

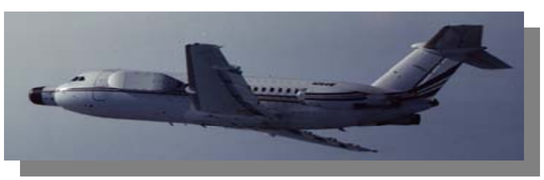
A KA-STAP Example

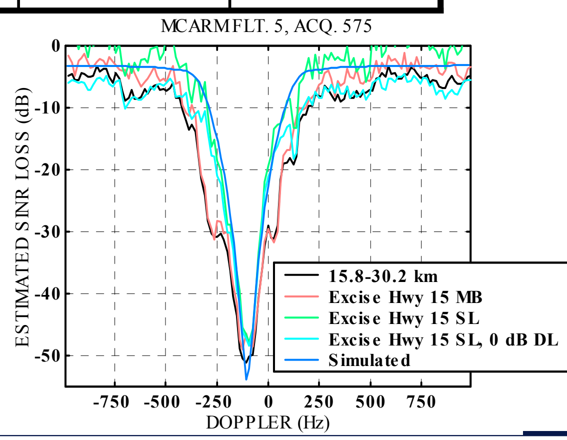
Measured Data Results

	0 dBsm	0 dBsm	5 dBsm	5 dBsm
Velocity	P_D	$P_{D/KASSPER}$	P_D	$P_{D/KASSPER}$
-20 m/s	0.56	0.98	0.83	0.99
-15 m/s	0.56	0.93	0.83	0.98
-10 m/s	0.16	0.68	0.53	0.88
-5 m/s	0	0.06	0.02	0.34
5 m/s	0	0.02	0.01	0.23
10 m/s	0.35	0.87	0.69	0.96
15 m/s	0.55	0.97	0.82	0.99
20 m/s	0.93	0.99	0.97	0.999



Exploit Map Data





TIGERLine Data

Knowledge-Aided Training

- Objective: select best possible training set to enhance target detection performance and minimize false alarms
- Employ *a priori* information in selection procedure
  - Knowledge sources…
    - Databases, such as land use, roadway, cultural indicators
    - Data-derived, such as nonhomogeneity detector (NHD) and power-selected training (PST), as well as higher resolution data
- Key challenge: effectively extracting and using information in a consistent manner

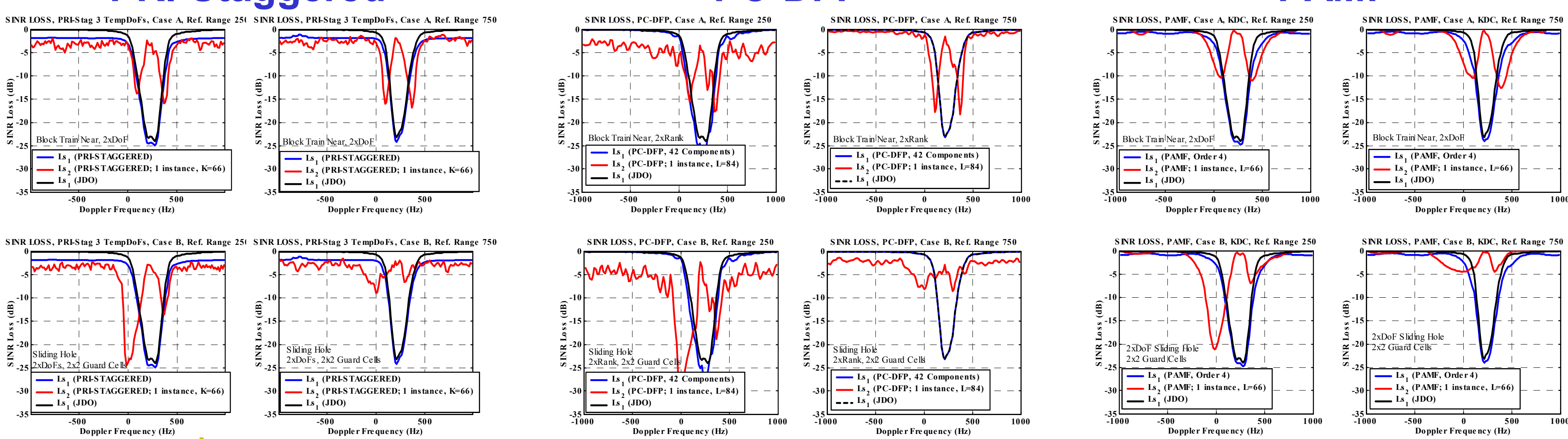
Note: Localized training is not a complete answer to this challenge…

Localized Training

- Premise: range-angle behavior of clutter similar in local region
  - Reasonable for distributed clutter
- Training on discretes
  - Local: increase null depth, but near mainbeam may greatly degrade MDV
- Disastrous when targets in secondary data
- Increased sensitivity to changing features ➔ $\left[\frac{\partial p}{\partial K}\right]_{Local} \geq \left[\frac{\partial p}{\partial K}\right]_{Global}$

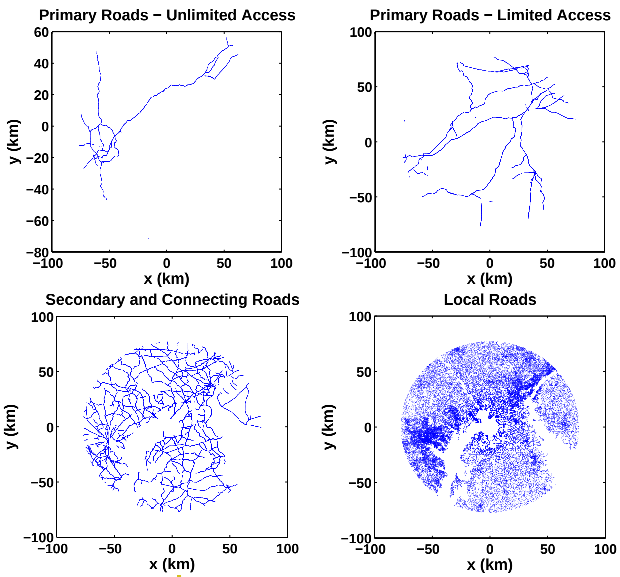
- Using KASSPER Data Cube from 2002 KASSPER Conference…
- Case A: Block Train (top row); Case B: Localized Sliding Hole (bottom row)

PRI-Staggered **PC-DFP** **PAMF**



KA Training Strategies

- Thresholding
  - Based on threshold, range is either a candidate or not
  - Mainlobe vs. sidelobe violations
- Rank Ordering
  - Based on weighted rule violation score, rank order candidate cells
  - Additional weighting may be applied based on proximity to range of interest (i.e., local cells score better than far cells)
- Based on candidate cells, may also compare with properties of cell of interest
  - Data-dependent test
- Search with permutations of candidate training cells for filter with “best” properties



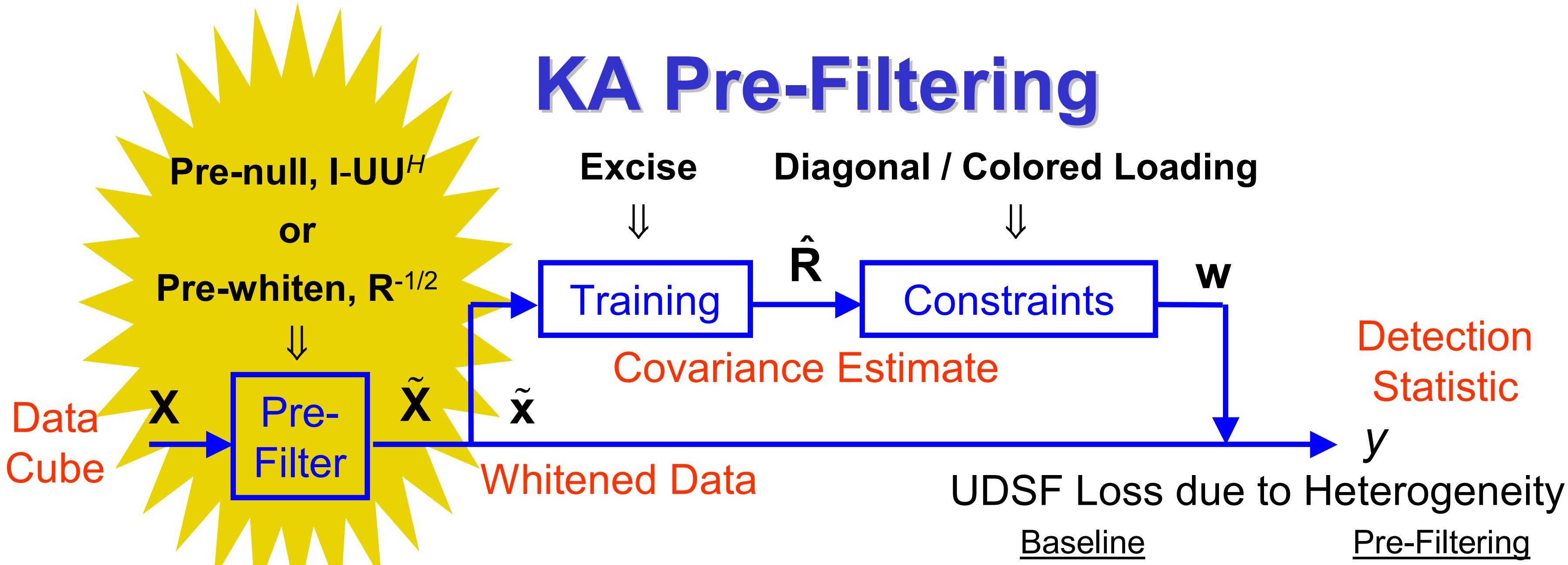
	Rules	Weights
Road Orientation (Doppler)	<5° <10° etc.	f(expected Doppler)
Road Type	< A29 (major highways) < A39 (plus secondary) < A49 (plus local)	f(type) f(expected traffic density)
Array Pattern	Mainlobe (ML) ML + 1st Sidelobe (SL) ML + 1st two SL’s Entire 360°	f(array pattern gain)

How can we effectively exploit *a priori* knowledge?

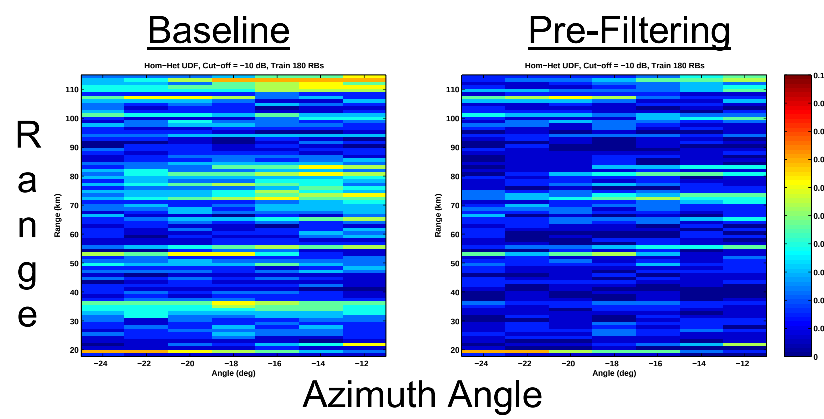
Pre-Filter Rationale

- Ground clutter angle-Doppler coupling is deterministic
  - To within limits of INU/GPS measurement system
  - Neglecting near-field scattering
- Clutter signal amplitude, spectral spread unknown
- Certain "nuisance" effects expand interference subspace
  - Angle-Doppler response of TSD mismatched to ground clutter
- Cultural database identifies certain "trouble spots"
- Construct a pre-filter to enhance clutter mitigation while constraining filter response
  - Range-varying
    - Employ site-specific clutter response prediction
  - Fixed response over range segment
    - E.g., null urban center in near sidelobe region

KA Pre-Filtering



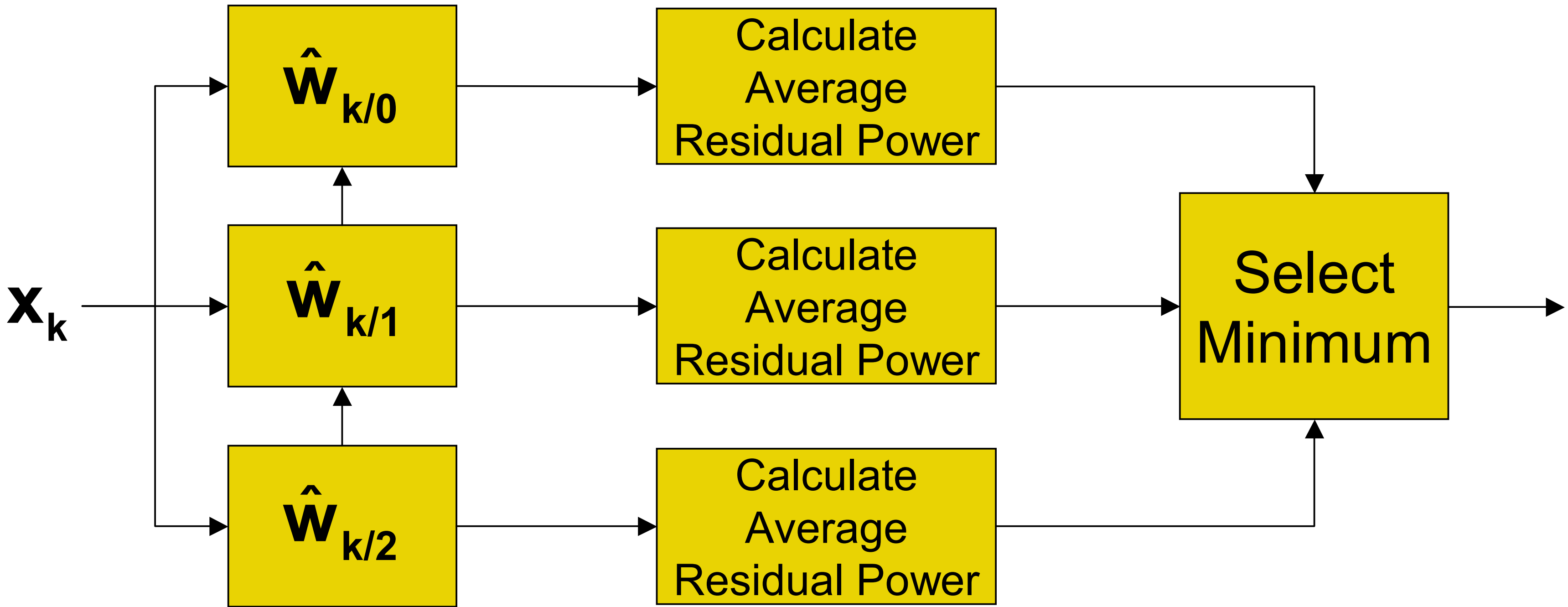
UDSF Loss due to Heterogeneity



- Data ⇑ snapshot pre-filtering
  - Filter is different for each range bin
  - Filter is derived from *site-specific* clutter predictions
- Benefits
  - *A priori* (known) heterogeneity removed from data prior to STAP
  - Smaller MDV, larger UDSF ⇒

Pre-filtering reduced the loss in usable Doppler space fraction (UDSF) due to clutter heterogeneity at some range-angle positions

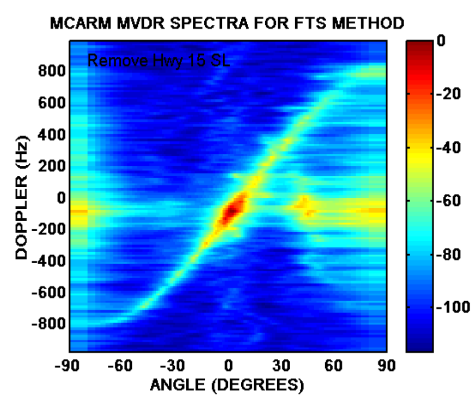
KA Covariance Estimation/Filtering



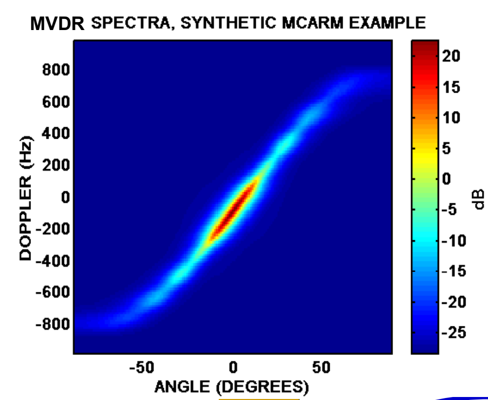
A Priori Info.

- Slope
- Calibration
- Amplitude
- Spectral width

Measured

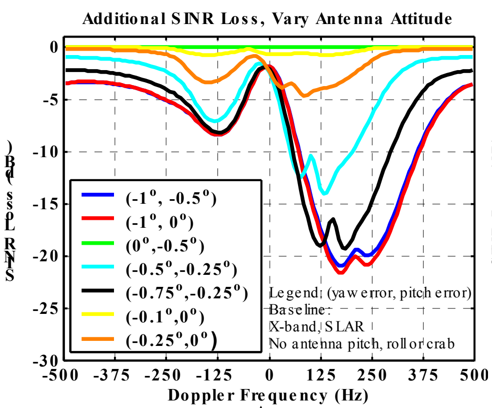


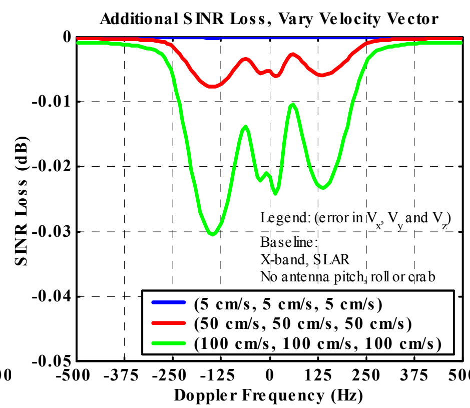
Simulated

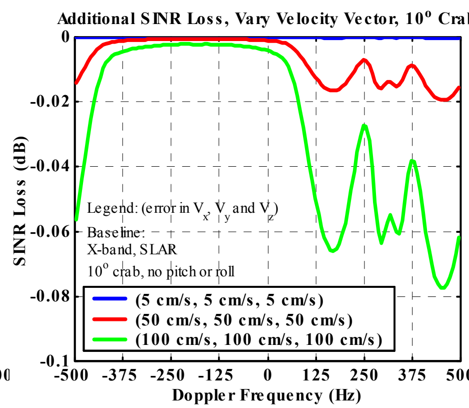


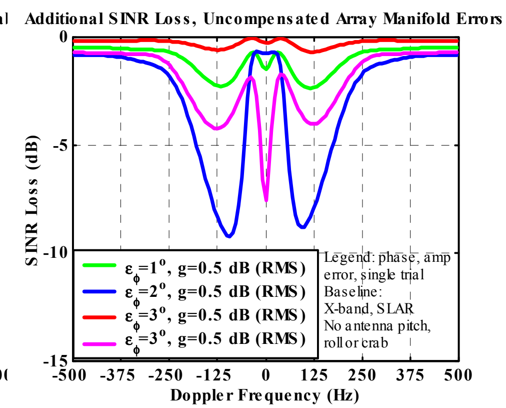
KA Covariance Estimation/Filtering Continued

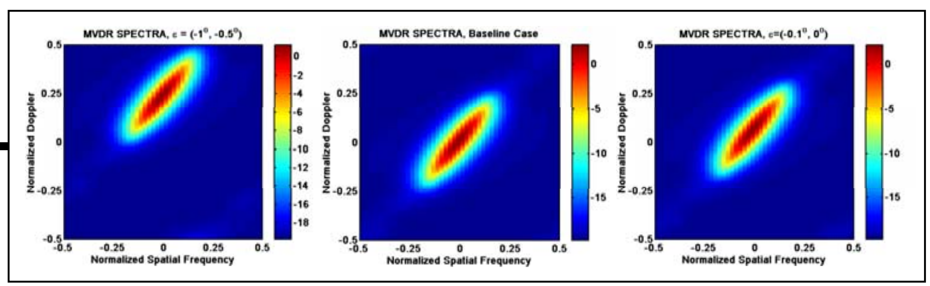
$\{\gamma_{yaw}, \phi_{roll}, \theta_{pitch}\}$ & $\{v_x, v_y, v_z\}$	Spectral: σ_v	Amplitude	Array Manifold Errors
⇩	⇩	⇩	⇩
Determines angle-Doppler null location	Determines null width	Determines null depth	Affects cancellation & matched filtering











Expect CNR dependence…

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Multi-Resolution Highlights

- Why multi-resolution?
  - Discretes are a “catastrophic” occurrence
    - Precise prediction and nulling limited by practical effects
  - Signal-to-clutter enhancement when needed
  - Give up ACR to maintain track on high priority target (“cradle to grave” track)
- Multi-resolution view provides further knowledge (e.g., cal, registration)
- Basic approaches…

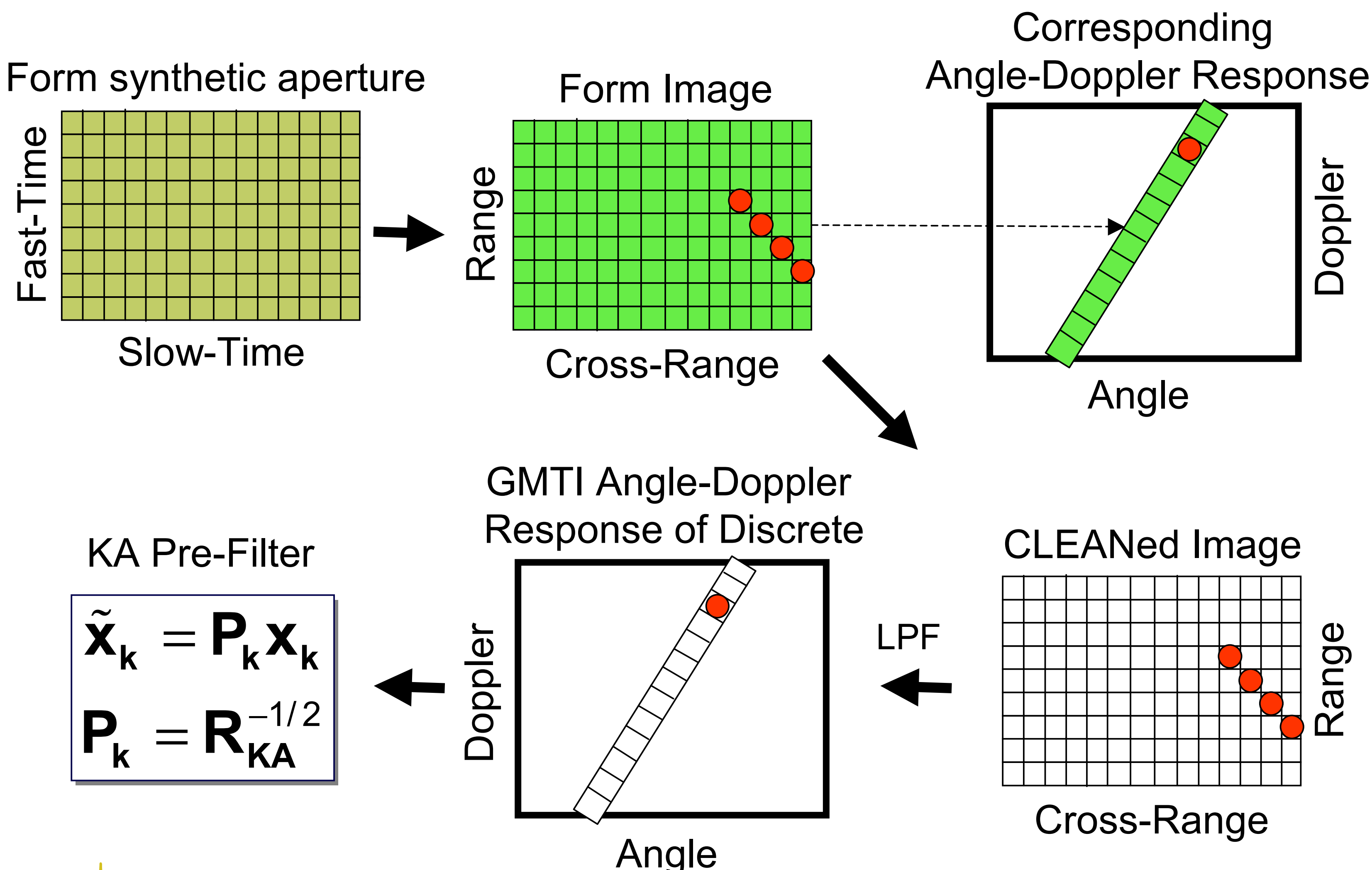
  (1) To avoid “guessing” at target phase history, construct pre-null filter and apply to sub-CPIs (subsequently described)

  (2) Operate on high resolution data
    - Blur detection, feature-aided, shadow detection, multi-channel SAR
      - Latter approach requires a steering vector “guess”
      - Increased cross-range resolution supports CID, ACR decreases

  (3) Evaluate “CLEANed” image
    - Automation challenge, affects ACR
- Challenges: ACR, target phase history, beam spoiling/beam coverage

See G.A. Showman & W.L. Melvin, “Multi-resolution processing to enhance knowledge-aided STAP,” this proceedings.

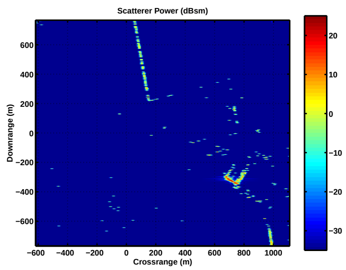
Discrete Pre-Nulling
Using Multi-Resolution Processing



$$\tilde{\mathbf{x}}_k = \mathbf{P}_k \mathbf{x}_k$$

$$\mathbf{P}_k = \mathbf{R}_{KA}^{-1/2}$$

Pre-filtering for Discretes Using APTI Data



100 MHz SAR Image

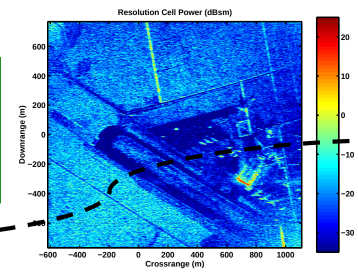
CLEAN

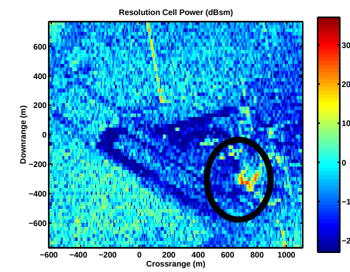
Discrete data

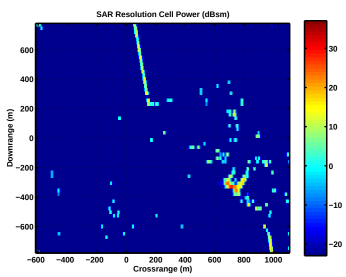
Noncoherent Decimation

Coherent Decimation

Green (right side) is emulation used to synthesize GMTI data from SAR imagery





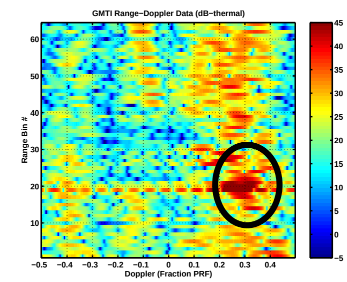


BW = 6 MHz

STAP Simulation

STAP Emulation

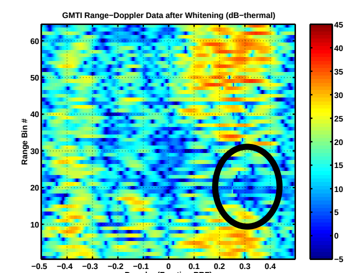
Angle Steer



Covariance Matrix (one per RB)

GMTI Data Cube

Range-Doppler Maps



Blue (left side) is the discrete pre-filtering chain

$R^{-1/2}$ or $(I-UU^H)$

Whiten

Angle Steer

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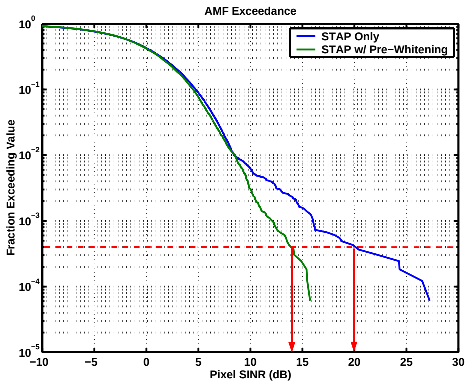
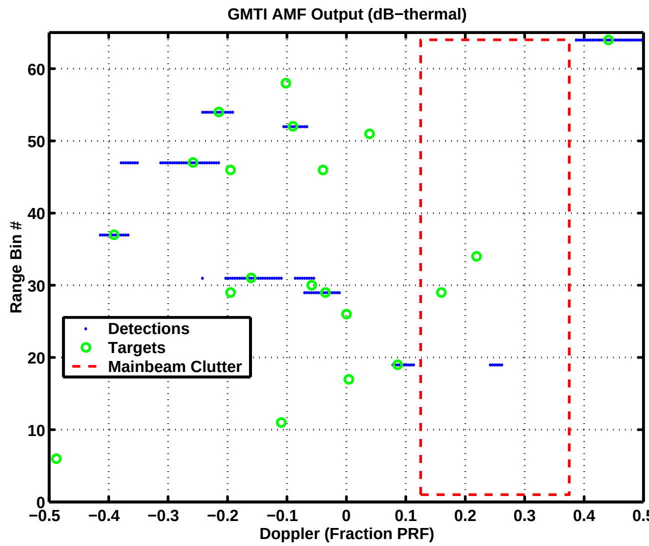
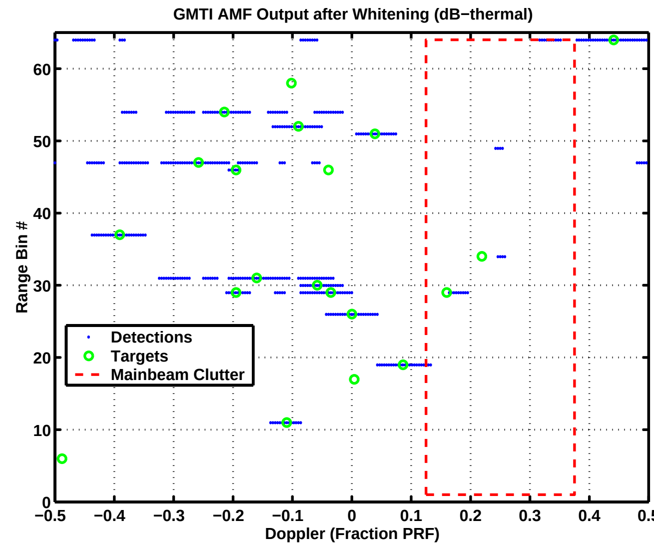
Detection Results



<u>Top</u>: Detection threshold set 5-6 dB higher w/o pre-filtering to equalize false alarm rate

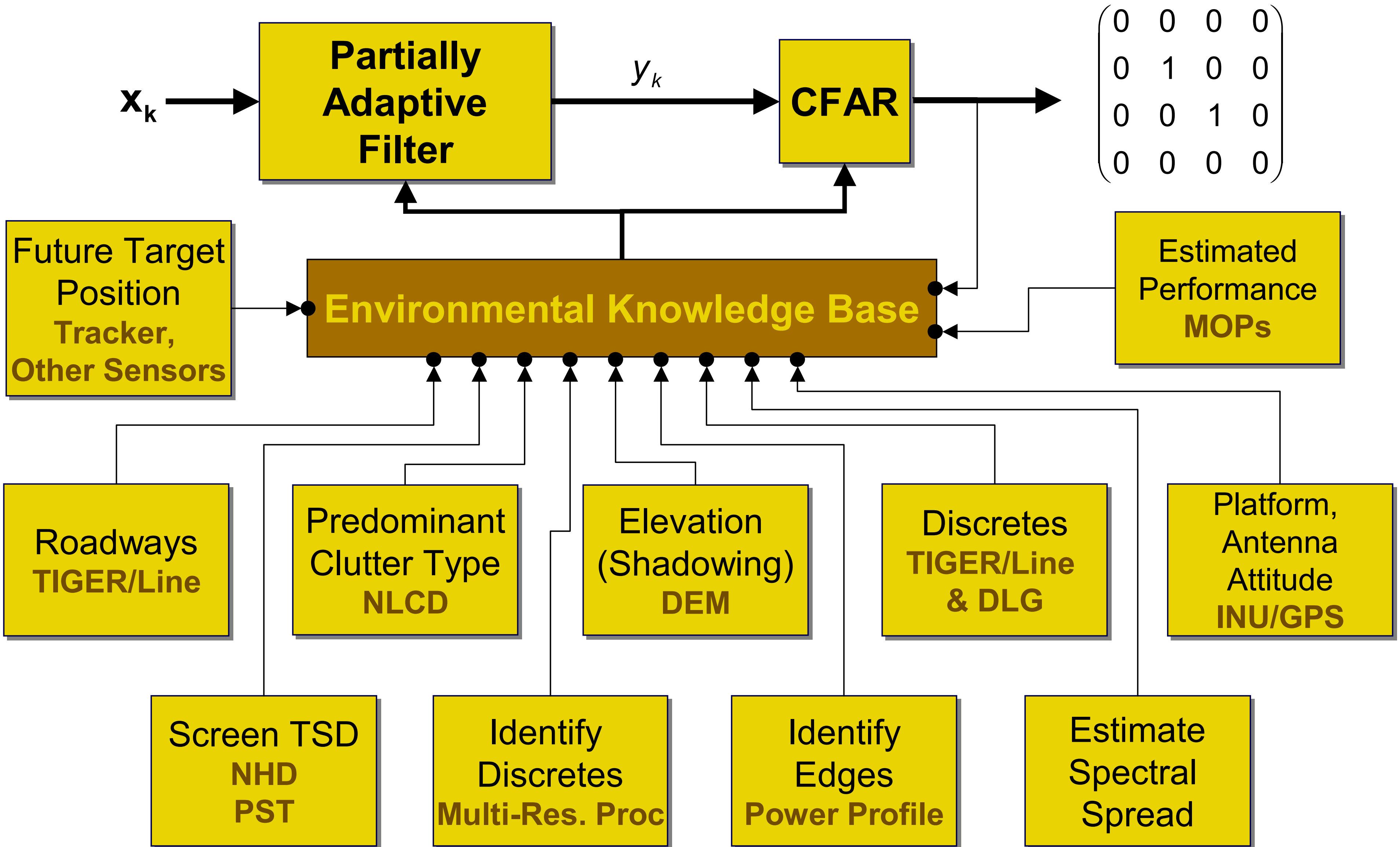




Range-Doppler detection maps without (left) and with (right) pre-filtering, same false alarm rate. Pre-filtering tolerates lower detection threshold, more targets are declared.

- Targets seeded into data
  - 20, Swerling 1, 10 dBsm, random range and Doppler
- Pre-filtering $\Rightarrow$ lower threshold & better target detection
  - One example: 15 / 20 versus 8 / 20 (detects/total targets)
  - Higher P_D for weaker and endo-clutter targets

A KA-STAP Processing Architecture



Summary

- GMTI is challenging
  - Discriminate slight differences between stationary clutter and target angle-Doppler responses
  - Heterogeneous/non-stationary signal environments
- STAP is a key element of WAS-GMTI
- A new signal processing paradigm, coupling traditional algorithms with additional knowledge, is being developed to improve target detection and reduce false alarm rate
- Several example shown herein suggest substantial performance improvement enhancement resulting from effective knowledge exploitation
- Key challenge: consistently identifying and exploiting knowledge sources leading to detection improvement while minimizing false alarm rate and maintaining area coverage