KASSPER Conference
April 2004

Supporting Algorithms for Knowledge-Aided STAP

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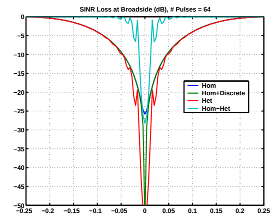
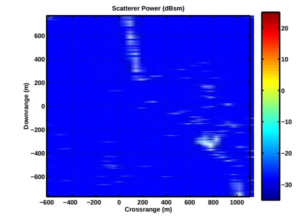
Outline

- Multi-resolution processing (MRP) update
- Discrete mitigation
- Calibration approaches supporting data pre-whitening
- Functions from site-specific predictions

Multi-Resolution Processing Summary

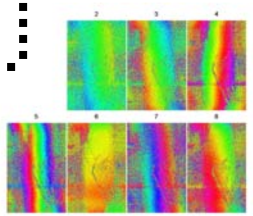
Exploit SAR-like mo-comp, focusing, and image formation techniques to make long-dwell STAP viable

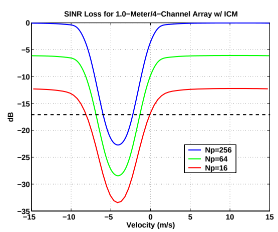




⇒ ⇒ Increasing Dwell Time ⇒ ⇒

Short-Dwell GMTI | **MoComp To Line** | **MoComp To Point** | **SAR Imaging (PFA)** → **Discrete Suppression** / **Array Calibration** → **STAP (EFA)**





- Benefits
  - Integration gain
  - Array calibration
  - Discrete removal
  - Arrest range walk of both clutter and movers
  - Training advantages
    - Many localized samples
    - TSD resistance

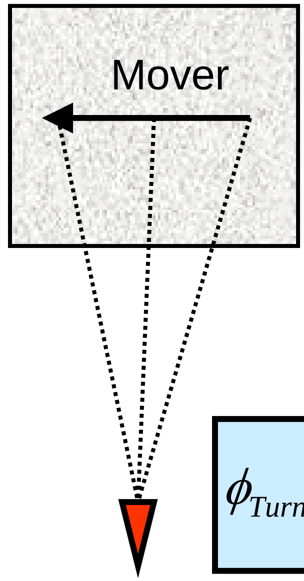
- Applications
  - Detect very slow movers
  - Operate in severe heterogeneity
    - Mountains, urban centers, etc.
  - Track movers through clutter notch
- KA Applications
  - Check short-dwell array calibration
  - Confirm land type & use
  - Register roads

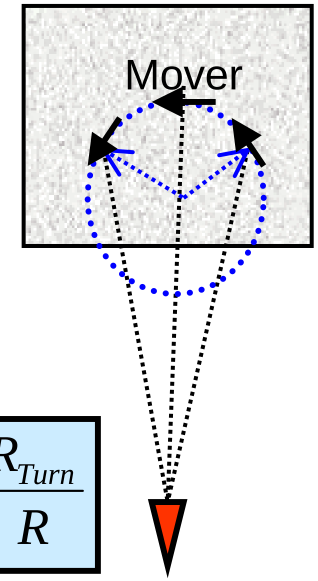
Effect of Mover Turning Radius

- PFA arrests range walk
- Target along-track motion generates a quadratic phase error (QPE)
  - Apply bank of QPE FIR filters to complex STAP detections
- Gently turning target also generates QPE
  - Can be as significant as linear motion QPE
  - 100 m/s radar, 1 m/s target, 100 km range, radius = 500 m

$$\phi_{Linear}(t) \cong -\frac{4\pi}{\lambda}\left(\frac{v_a v_t t^2}{R}\right)$$

$$\phi_{Turn}(t) \cong -\frac{4\pi}{\lambda}\left(\frac{v_t^2 t^2}{2R_{Turn}}\right)$$





$$\phi_{Turn} \cong \phi_{Linear} \Rightarrow \frac{v_t}{v_a} \cong 2\frac{R_{Turn}}{R}$$

- Target acceleration and higher order motion limit CPI
  - PDI over sub-CPIs or multiple-bins

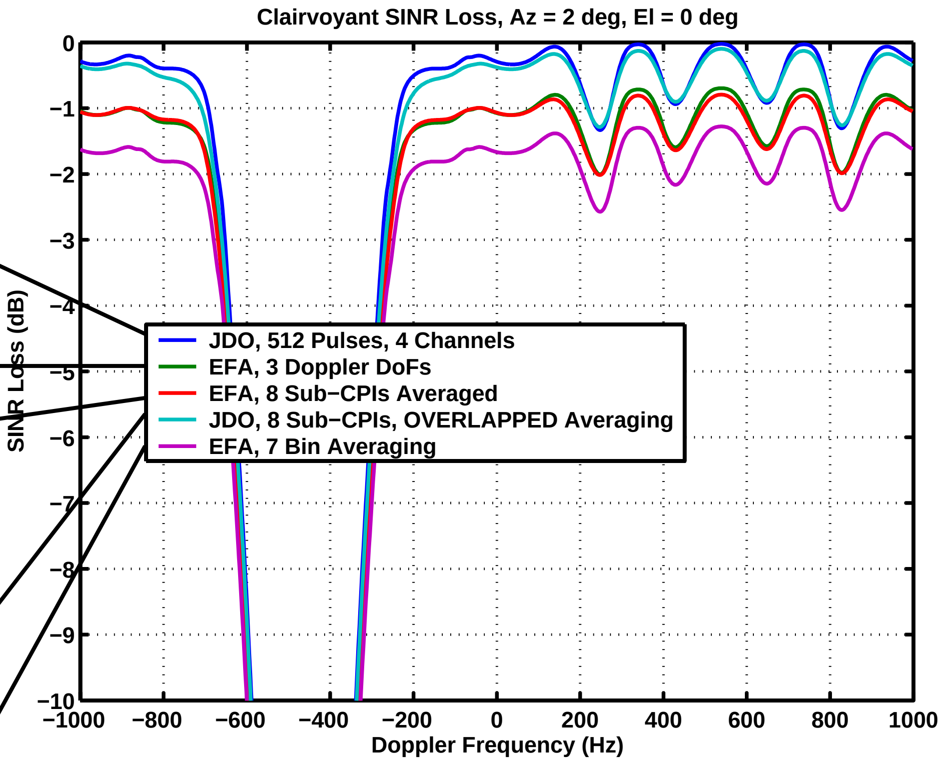
Multiple Sub-CPIs vs Multiple Doppler Bins

	Issue	Multiple Sub-CPIs	Multiple Doppler Bins
Coherent	Coherent Integration of Non-maneuvering Targets	Coherent output from each sub-CPI; FFT over sub-CPIs	Output contained within a single Doppler/cross-range bin
	Quadratic Phase Correction for Along-Track Target Motion	Quadratic phase weight across sub-CPIs	Low order quadratic phase filter
Non Coherent	Post Detection Integration (PDI)	Sum power over sub-CPIs	Sum power over cross-range bins
	Target with Multiple Scatterers	Target fading; Swerling 2 target statistics – PDI	Target scatterers sub-resolved in cross-range bins –PDI
	Maneuvering Target	Higher-order phase function over sub-CPIs – PDI	Target smeared in cross-range – PDI
Training	More Samples for Local Training	Each sub-CPI contributes a snapshot for each range bin; PFA ensure clutter stationarity,	If (1) dwell is long (local angle-Doppler coupling is approximately constant), or (2) raw data is resampled in slow-time to co-register channels, then performs like sub-CPI training

- Many operations can be performed either across multiple sub-CPIs or over multiple Doppler bins, with similar results
- Notional design uses multiple Doppler bins, to avoid the IFFT back to slow time

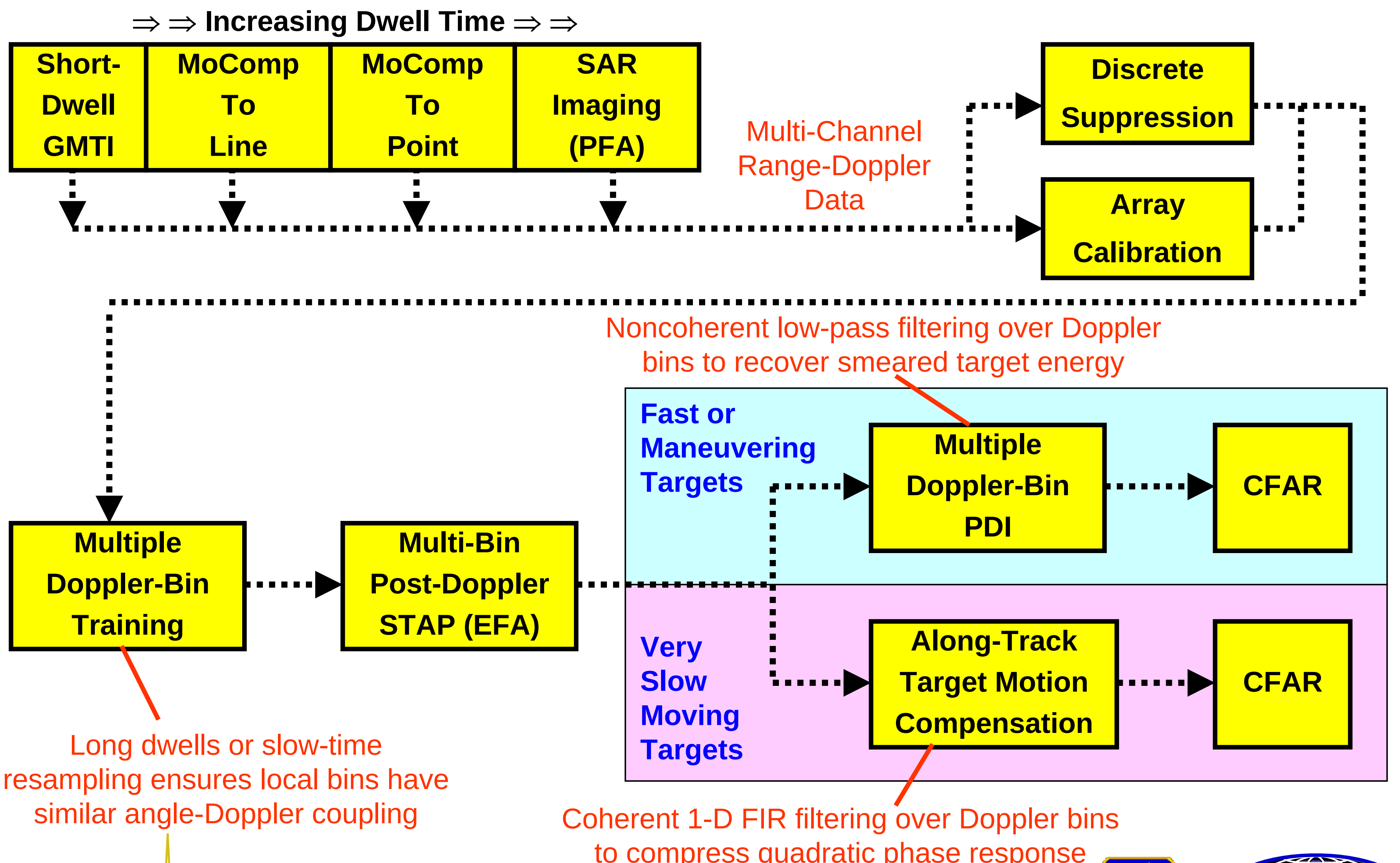
Training on Sub-CPIs versus Doppler Bins

- Notional airborne X-band radar
- JDO is full STAP
  - 4 x 512 DoFs
  - Ripples due to angle-aliased clutter (PRF > DPCA PRF)
- EFA uses all channels and 3 Doppler bins
- Sub-CPI processing
  - 64 pulses each
  - Output of each CPI coherently combined to recover SNR
  - <u>Overlapped</u> averaging of 64-pulses sub-CPIs provides enough samples for full space-time processing
- Bin averaging incurs slight additional loss due to drift in clutter angle versus Doppler



- Training over Doppler bins incurs additional 0.5 dB loss
- Sub-CPI averaging does not degrade EFA performance
- Overlapped averaging of sub-CPIs nears full JDO performance

MRP Summary


⇒ ⇒ Increasing Dwell Time ⇒ ⇒
Short-Dwell GMTI
MoComp To Line
MoComp To Point
SAR Imaging (PFA)
Multi-Channel Range-Doppler Data
Discrete Suppression
Array Calibration
Noncoherent low-pass filtering over Doppler bins to recover smeared target energy
Fast or Maneuvering Targets
Multiple Doppler-Bin PDI
CFAR
Multiple Doppler-Bin Training
Multi-Bin Post-Doppler STAP (EFA)
Very Slow Moving Targets
Along-Track Target Motion Compensation
CFAR
Long dwells or slow-time resampling ensures local bins have similar angle-Doppler coupling
Coherent 1-D FIR filtering over Doppler bins to compress quadratic phase response

Outline

- Multi-resolution processing (MRP) update
  - Target acceleration limits CPI length
  - Two-path architecture is the consequence
    - Coherent integration for very slow, stable movers
    - Doppler bin PDI for fast, maneuvering targets
  - Overlapped sub-CPI averaging an interesting alternative
- Discrete mitigation
- Calibration approaches supporting data pre-whitening
- Functions from site-specific predictions

Processing Solutions

1. Include CUT in training (SP)

   Demonstrated on APTI data

2. PVT (ER)

   Demonstrated on Tuxedo data

Discretes are a change in the covariance

3. Null short-dwell data (KA)

   3a. Locations derived from SAR imagery

   Demonstrated on APTI data

   3b. Locations derived from map data

   Difficult to do with confidence

4. CLEAN long-dwell imagery (KA)

   MRP architecture, FOPEN results

5. CLEAN short-dwell AMF (ER)

   See following presentation……

Discretes are a shift in the mean

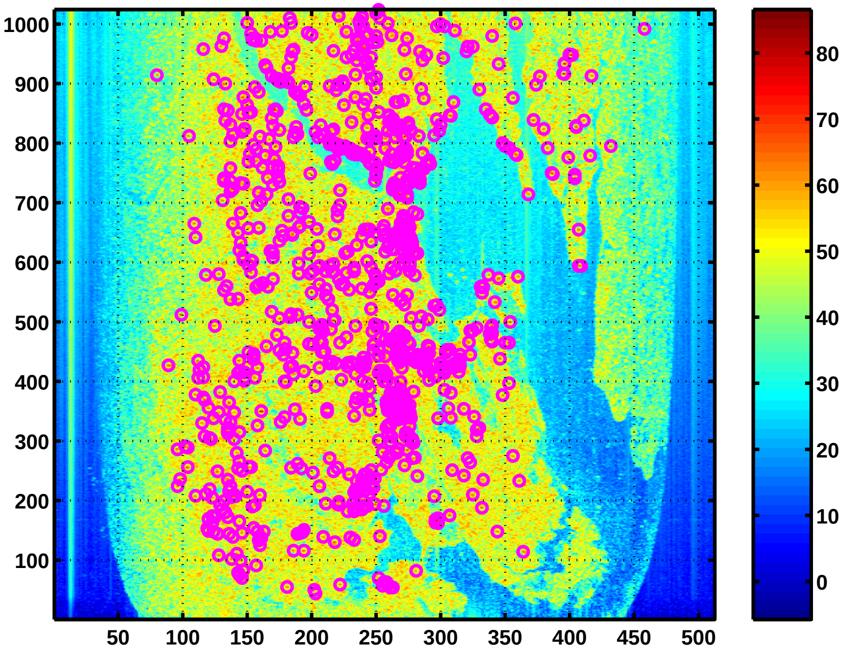
SP = Signal Processing

KA = Knowledge-Aided

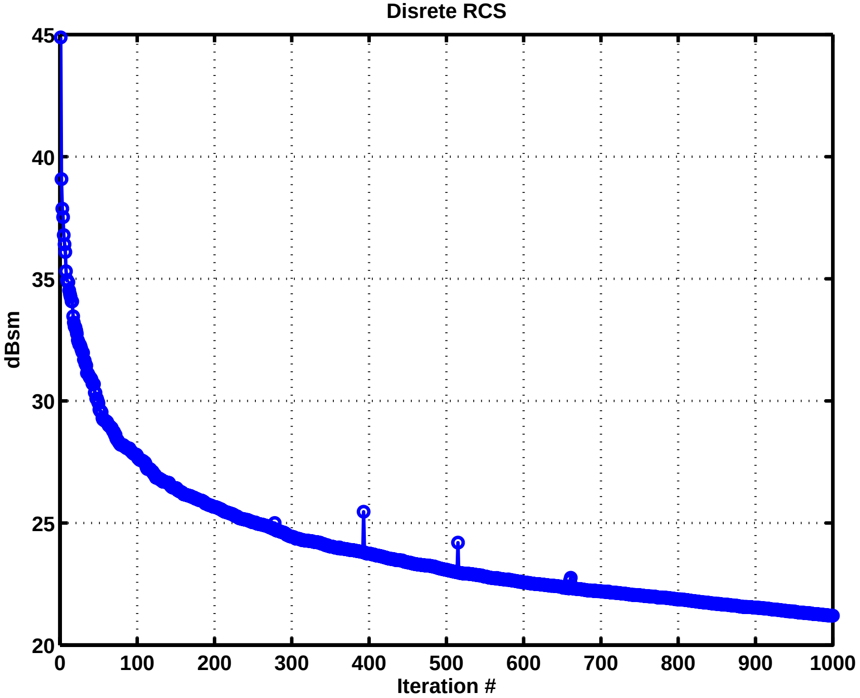
ER = Expert Reasoning

CLEAN in Range-Doppler

Discrete Locations



Discrete RCS vs. CLEAN Iteration



- Remove discretes from data prior to STAP
- False alarms reduced, but computationally intensive
- Why not remove only those discretes that “matter”???

AMF CLEANing

- Discretes are manifested as detections in two ways:
  - As very strong returns on the clutter ridge
  - As false alarms due to sidelobes in range-angle-Doppler
- Iterative procedure
  - 1. Form angle-Doppler detection map (e.g., AMF) for each range bin
  - 2. Find strongest detection
  - 3. Remove its PSF from detection map
    - The PSF is spatially-variant in the AMF domain
    - We must remove PSF from the data, and regenerate the AMF
- After iterating we have
  - A detection map of residual noise (discard)
  - A collection of point-target returns
    - Some of these are discretes on the clutter ridge
    - Some of these are movers off the clutter ridge
    - False alarms due to discrete sidelobes are avoided

CLEANing Detections

Find detection, e.g. $AMF = \dfrac{\left|\mathbf{v}^H \mathbf{R}^{-1} \mathbf{x}_k\right|^2}{\mathbf{v}^H \mathbf{R}^{-1} \mathbf{v}}$, with maximum power

$$\mathbf{v}_{kMLE} = \arg \max_{\mathbf{v}} \frac{\left|\mathbf{v}^H \mathbf{R}^{-1} \mathbf{x}_k\right|^2}{\mathbf{v}^H \mathbf{R}^{-1} \mathbf{v}}$$

$$\hat{\mathbf{s}}_{kMax} = \hat{\alpha}_{kMLE} \mathbf{v}_{kMax} = \left(\frac{\mathbf{v}_{kMax}^H \mathbf{R}^{-1} \mathbf{x}_k}{\mathbf{v}_{kMax}^H \mathbf{R}^{-1} \mathbf{v}_{kMax}} \right) \mathbf{v}_{kMax}$$

$$\mathbf{x}_{k+1} = \mathbf{x}_k - \hat{\mathbf{s}}_{kMax}$$

Contrasting Two CLEAN Approaches

	Finding the Peak	Determining Signal Complex Gain
Detection Domain	$\mathbf{v}_{kMLE} = \arg\max_{\mathbf{v}} \frac{\left\lvert \mathbf{v}^H \mathbf{R}^{-1} \mathbf{x}_k \right\rvert^2}{\mathbf{v}^H \mathbf{R}^{-1} \mathbf{v}}$	$\hat{\alpha}_{kMLE} = \frac{\mathbf{v}_{kMLE}^H \mathbf{R}^{-1} \mathbf{x}_k}{\mathbf{v}_{kMLE}^H \mathbf{R}^{-1} \mathbf{v}_{kMLE}}$
Angle-Doppler Domain	$\mathbf{v}_{kMLE} = \arg\max_{\mathbf{v}} \frac{\left\lvert \mathbf{v}^H \mathbf{x}_k \right\rvert^2}{\mathbf{v}^H \mathbf{v}}$	$\hat{\alpha}_{kMLE} = \frac{\mathbf{v}_{kMLE}^H \mathbf{x}_k}{\mathbf{v}_{kMLE}^H \mathbf{v}_{kMLE}}$

- Advantages of CLEANing in the detection domain
  - Works at low to moderate resolutions
  - Superior parameter estimates (angle-Doppler-amplitude-phase)
  - Requires far fewer CLEAN iterations
- Disadvantages
  - Detection map must be regenerated after each CLEAN iteration
  - Unless covariance estimate also modified, over-nulling can still occur

Robust Mover-Discrete Tests

1. Determine if $\mathbf{v}_{\max}$ is on or off the clutter ridge
   - Exploits knowledge of the clutter ridge angle-Doppler support

2. INR
   - Measures loss on target due to interference cancellation

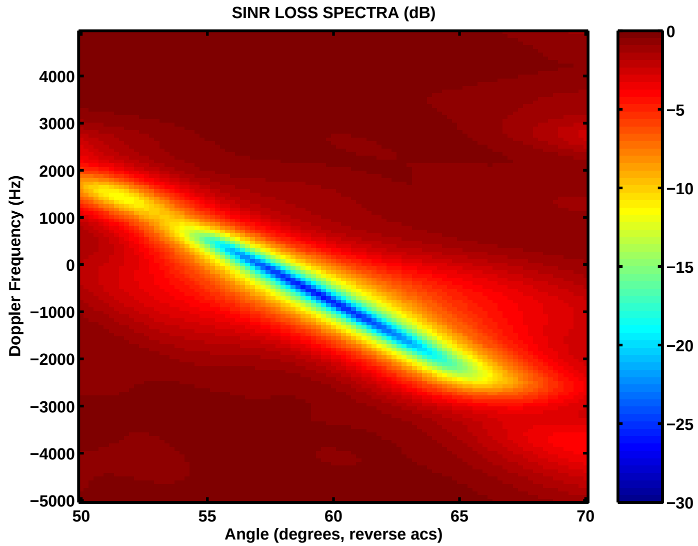
$$INR = \frac{\mathbf{v}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{v}}{\mathbf{v}^{\mathbf{H}}\mathbf{R}^{-1}\mathbf{v}} = \frac{MN/\sigma_n^2}{\mathbf{v}^{\mathbf{H}}\mathbf{R}^{-1}\mathbf{v}}$$

3. SNR
   - Unit response against thermal noise

$$SNR = \left|\hat{\alpha}_{MLE}\right|^2 \mathbf{v}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{v}$$

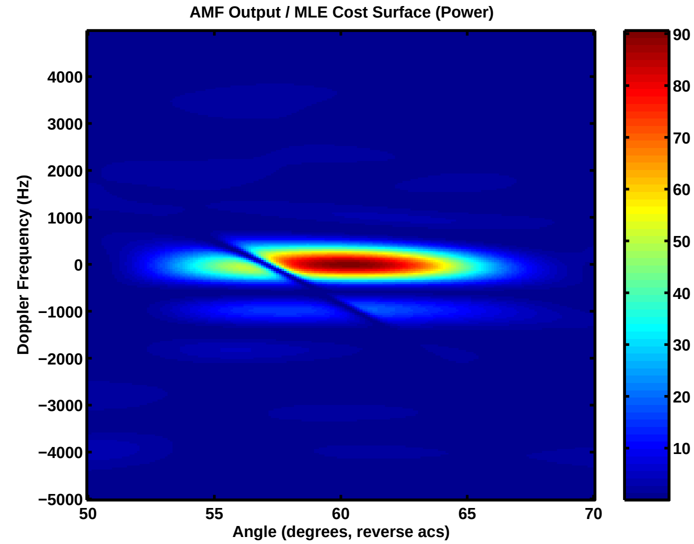
$$= MN \frac{\left|\hat{\alpha}_{MLE}\right|^2}{\sigma_n^2}$$

Airborne Fire-Control GMTI Example



SINR loss versus azimuth angle and Doppler (dB)

AMF/MLE output for a single data snapshot (power)



- Radar characteristics
  - X-band
  - 8-channel APTI-type circular array
  - MPRF operation
  - Scanned off array normal by 60°
- Interference
  - Clutter, thermal noise
  - CNR 25-30 dB
- AMF/MLE output
  - Clutter suppressed
  - Single target at (60°, 0 Hz) clearly visible
- Measured SINR = 19.5 dB
  - Consistent with true SNR = 27 dB and JDO loss = 7 dB

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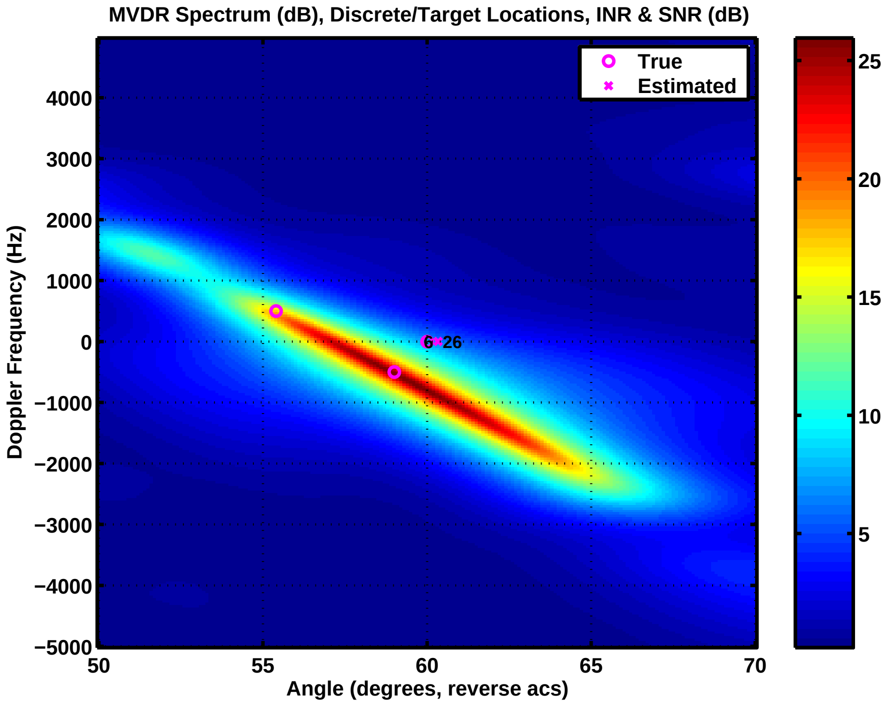
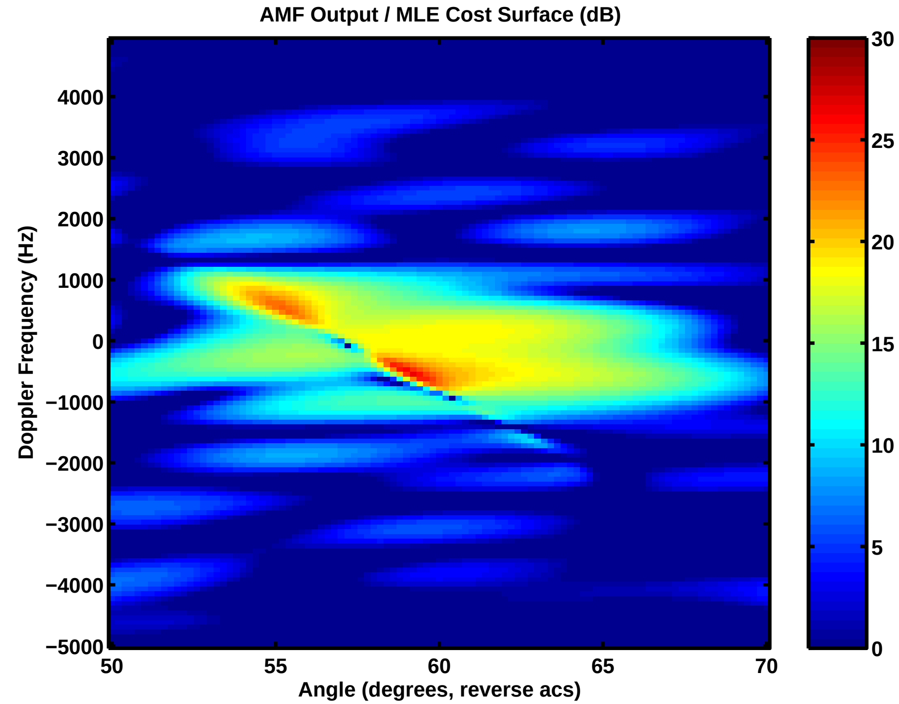
Adding Discretes to Target-Only





- MVDR image of clutter
- Target-only MLE location (angle and Doppler) and metric estimates (INR = 6 dB, SNR = 26 dB) close to actual values

- AMF/MLE with two discretes
  - Appear in MVDR image as o
- Discretes and their sidelobes are very strong in the detection map

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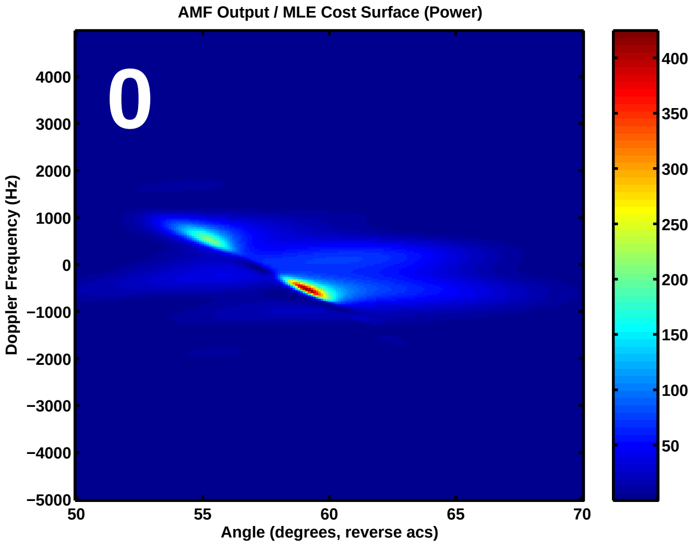
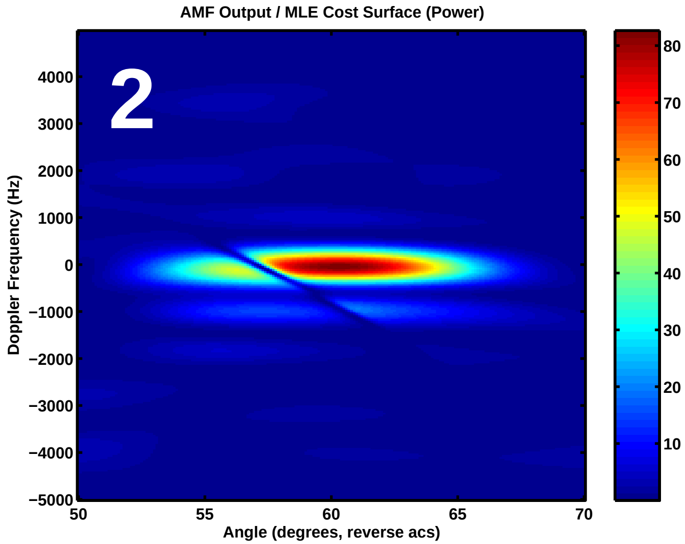
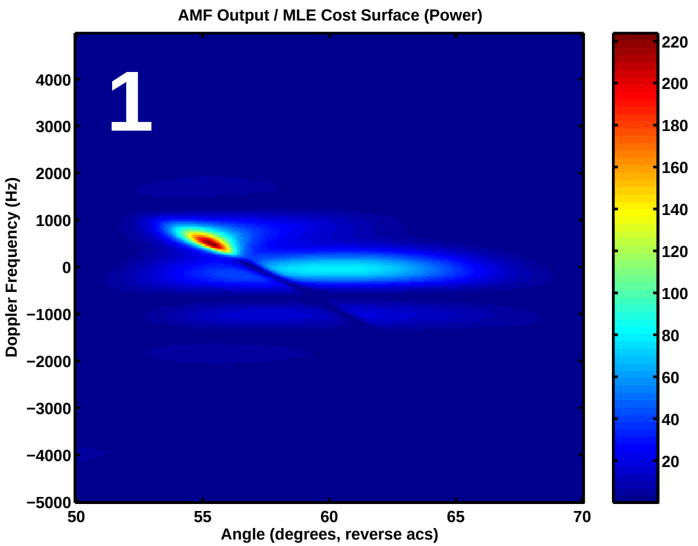
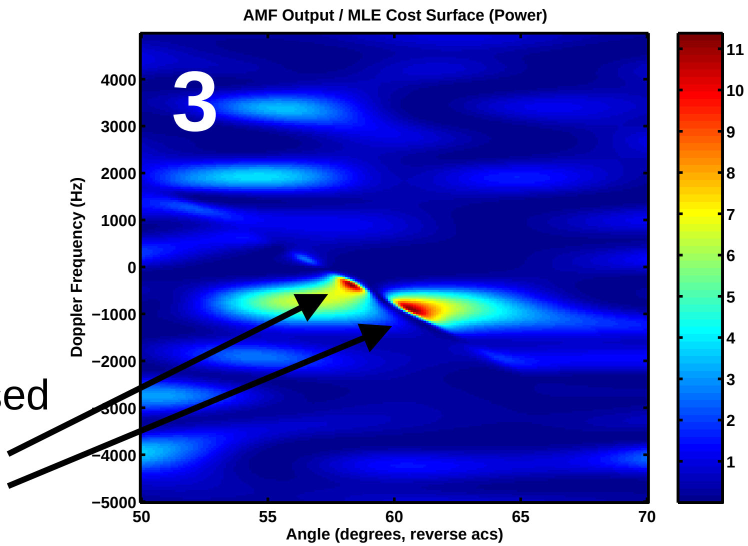
CLEAN Iterations on Discretes





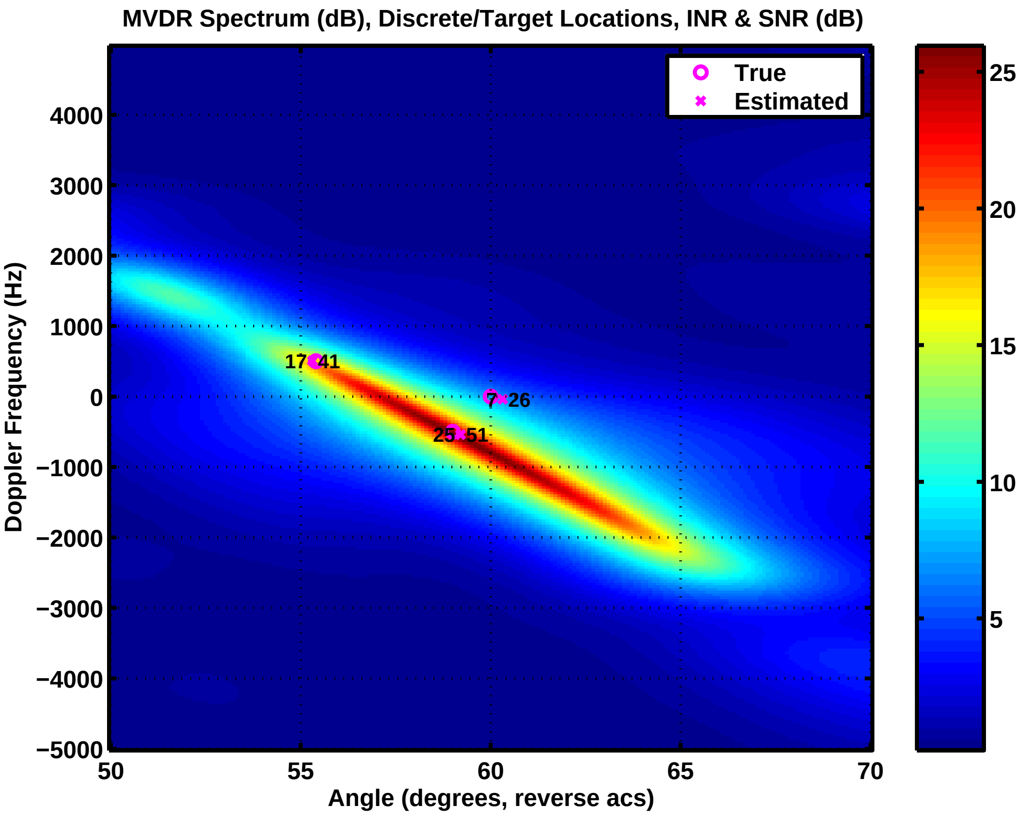


Discretes increased off-ridge residual power by ~ 2 dB



AMF CLEAN Results

- Both discretes were properly located and removed
  - INR & SNR estimates are accurate
  - High INR and SNR levels suggest returns are discretes
- Target was detected and properly located



Outline

- Multi-resolution processing (MRP) update
- Discrete mitigation
  - “CLEAN” them from the data using detection information
  - Fewer CLEAN iterations required
  - Requires (at least partial) regeneration of detection map
- Calibration approaches supporting data pre-whitening
- Functions from site-specific predictions

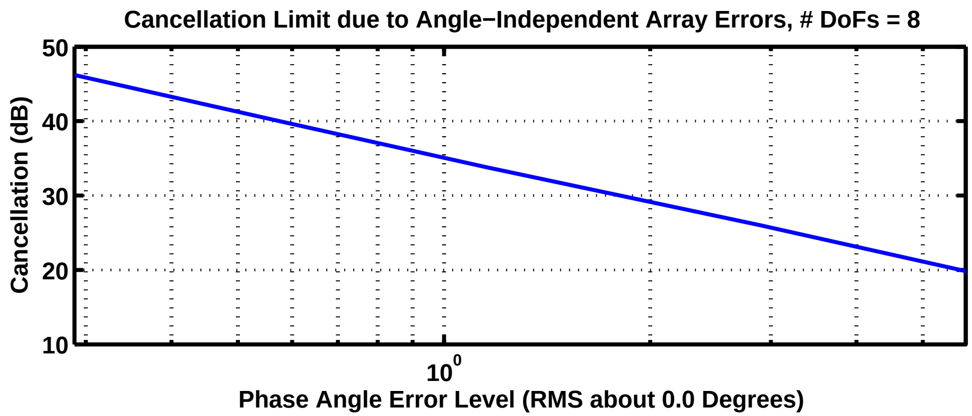
Array Error Problems; Calibration Solutions

Problem	Solution
1. Target mismatch in STAP – STAP fully compensates for array errors on interference – Losses incurred due to mismatched steering vector	1. Cal-on-clutter – Either measurements corrected or steering vectors modified – NOTE: For moderate error levels mismatch losses are small
2. Deterministic processing errors – STAP too hard (heterogeneity) – Instead, do DPCA + “time slip” – Array & geometry errors limit deterministic clutter cancellation	2. Cal-on-clutter – Correction of angle-dependent “errors” tantamount to aligning channel records in time – Like reduced dimension STAP!
3. KA-STAP implementations – Measured and predicted signals differ by array errors – <u>Statistics</u>: colored-loading (CL), pre-whitening (PW), etc. – <u>Data</u>: SCHISM	3. Cal-on-clutter – <u>Statistics</u>: correct measurements or “corrupt” predictions – <u>Data</u>: correct measurements – Our emphasis in this study

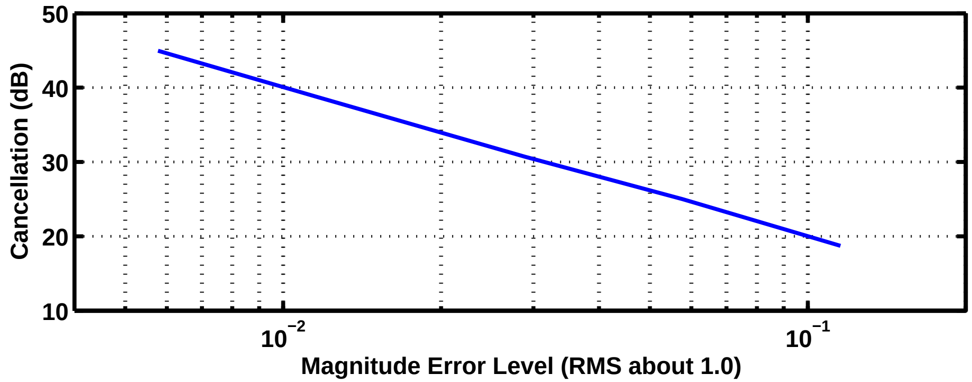
Array Calibration for KA-STAP

- Two error categories
  1. Angle-independent errors
     - Complex channel gains
     - No effect on clutter rank
  2. Angle-dependent errors
     - Subarray phase center locations, etc.
     - Increase clutter rank
- This study concentrates on angle-<u>independent</u> errors
  – Short dwell constraint imposed: limited DoFs, few Doppler bins over clutter, finite data overlap between channels, etc.
  – In our experience, resolving angle-independent errors gets you most of the way there
  – For KA-STAP, even small errors can limit cancellation…..

Angle-Independent Errors and Cancellation



Phase Error (Degrees)	Cancellation (dB)
10	15
2.0	29
1.0	35
0.1	55

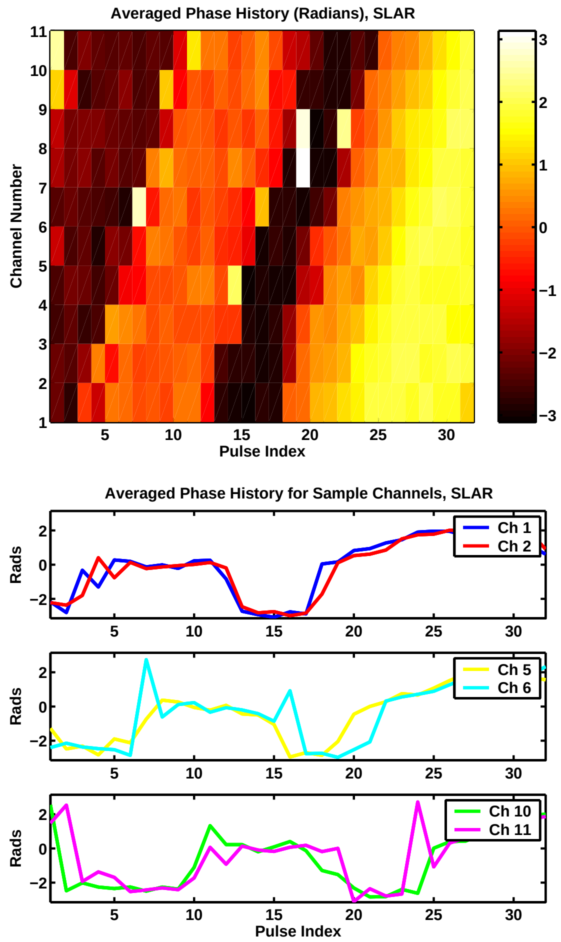


Magnitude Error	Cancellation (dB)
0.2	14
0.1	20
0.05	26
0.025	32

- 30 dB requirement:
  - 2° phase error or less
  - 0.025 magnitude error or less

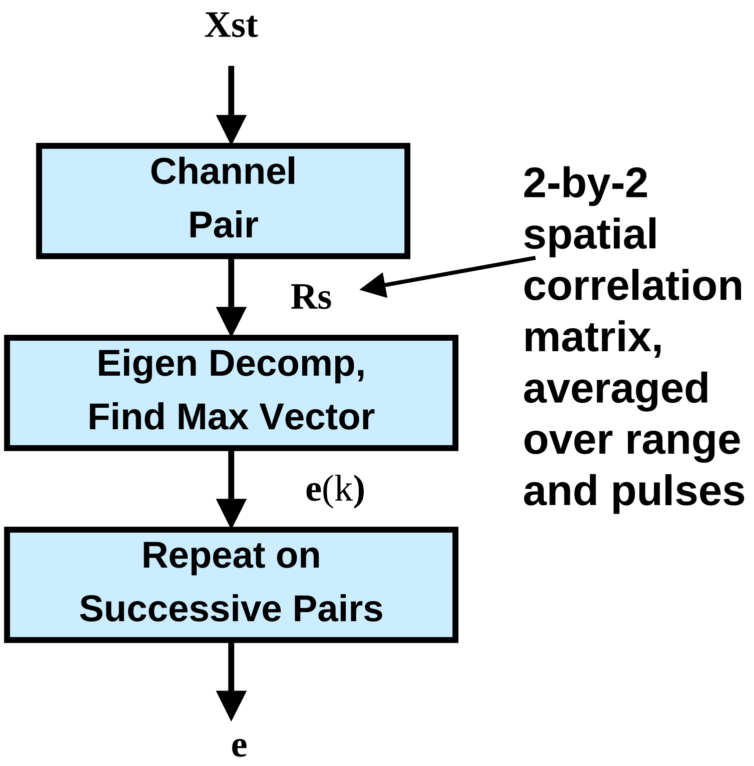
We evaluated a number of array estimation techniques, including two developed specifically for short-dwell data sets…

Channel-Pair Calibration



Phase history for short CPI (32 pulses)

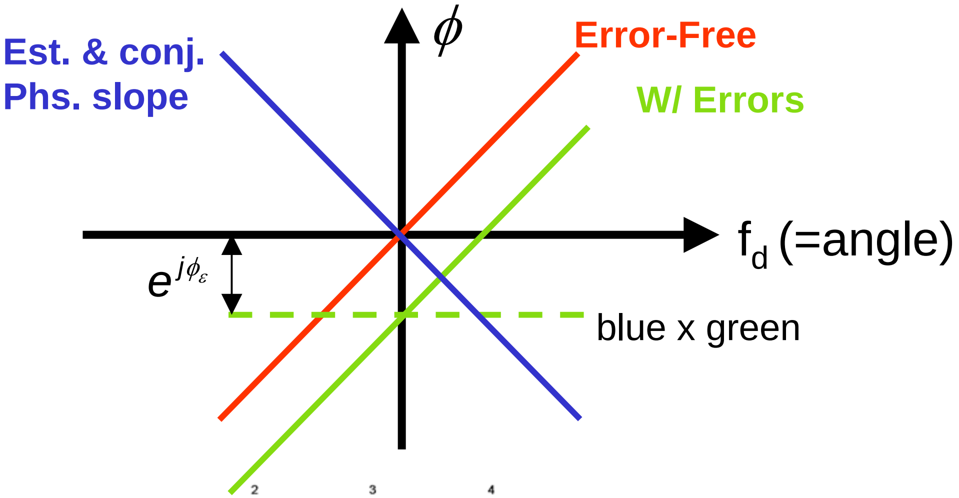
Phase history for various adjacent channel pairs

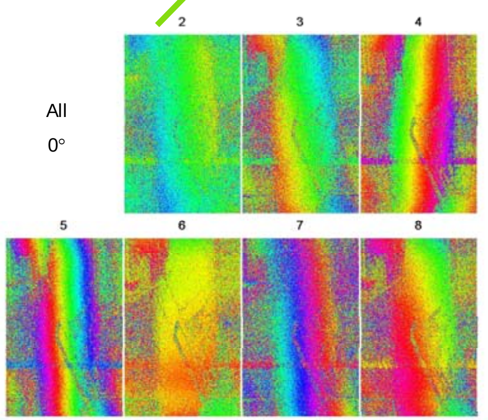


- Adjacent channel pairs show most overlap in phase history
- Ideally, any phase difference due to channel mismatch only

Channel-Pair Range-Doppler Technique

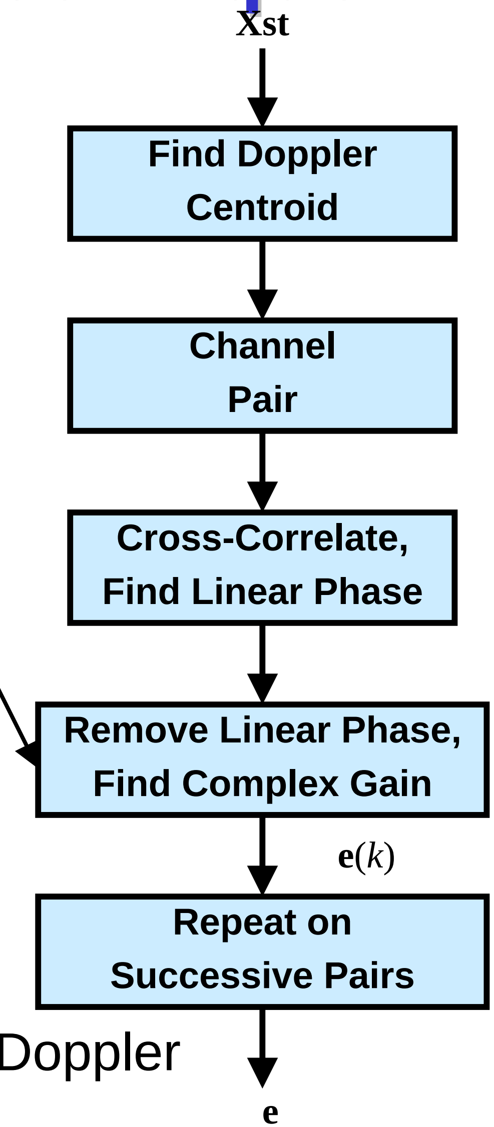
Consider two channel pairs:





APTI Data: Range-Doppler phase maps w.r.t. channel #1

Much like the baseline channel-pair technique



- Exploit presumed linear phase among channels over Doppler
- Deviation from zero intercept is due to error

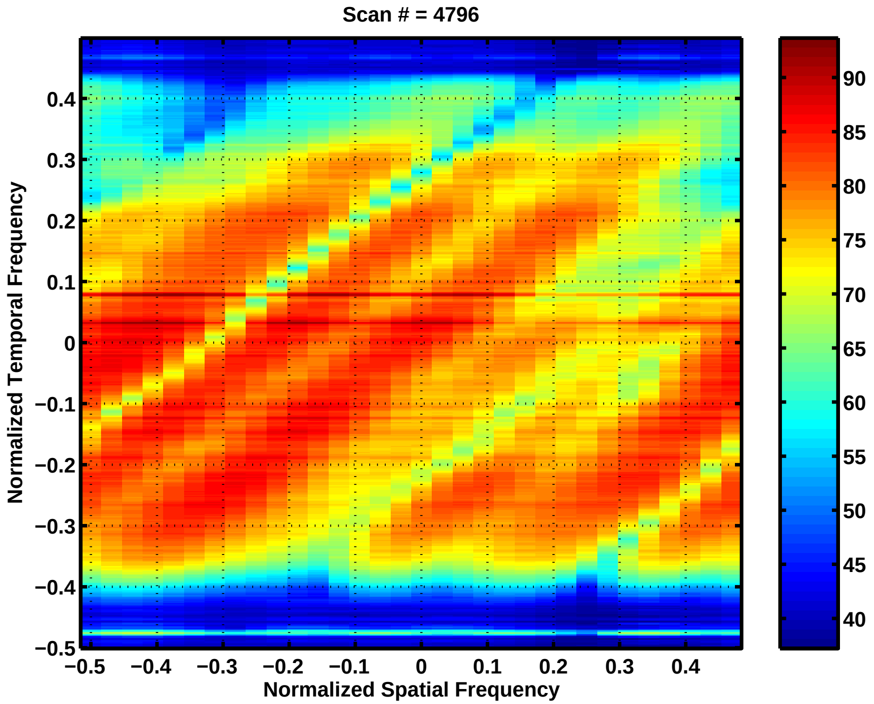
Parametric Results (RMS Errors)

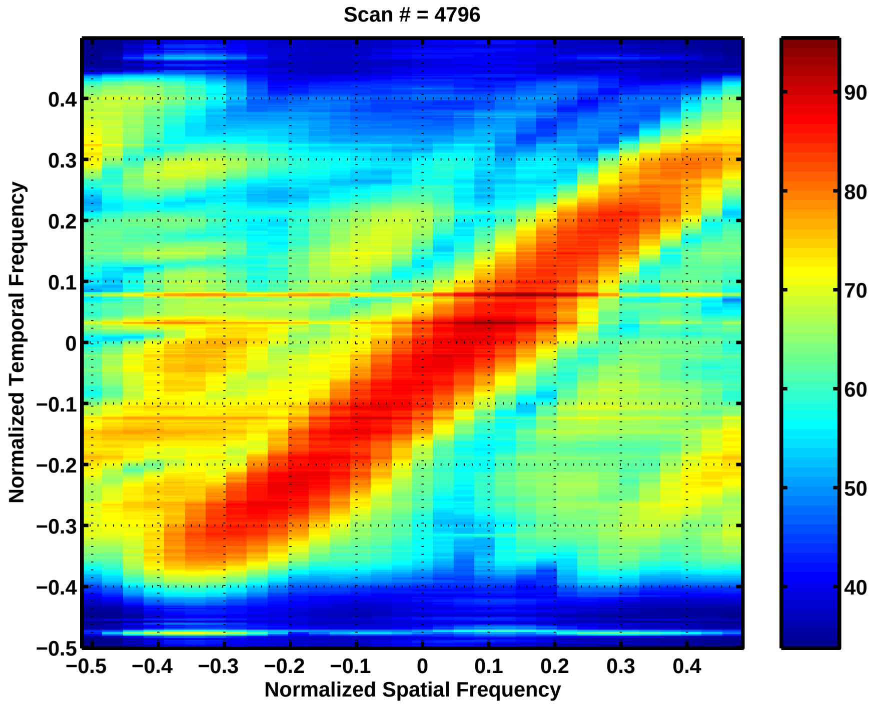
Set-Up	Channel Pair	Range-Doppler
16 pulses, 128 bins	1.48°, 27x10^{-3}	1.92°, 26x10^{-3}
16 pulses, 512 bins	0.65°, 23x10^{-3}	1.33°, 22x10^{-3}
32 pulses, 128 bins	1.07°, 25x10^{-3}	1.23°, 19x10^{-3}
32 pulses, 512 bins	0.47°, 22x10^{-3}	0.79°, 15x10^{-3}

• Non-DPCA and ICM	• +2° scan and +2° crab

- Assumptions
  - Airborne (not space-based) X-band clutter ridge slope
  - Short-dwell GMTI (as few as 16 pulses)
  - ULA, subarrays are identical
  - Homogeneous clutter; moderate to high CNR
  - Moving target power is negligible
  - Initial RMS errors uniform over 10° and 0.1 (0°±20° & 1.0±0.2)
- Both techniques meet the 30 dB cancellation requirement with 16 pulses and 128 range bins

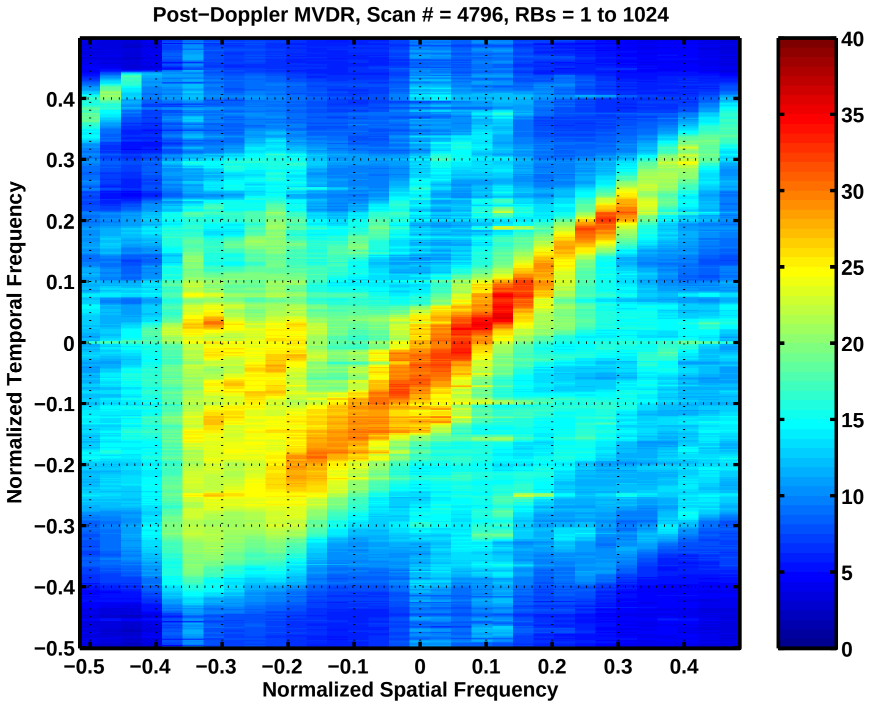
FOPEN Angle-Doppler PSDs

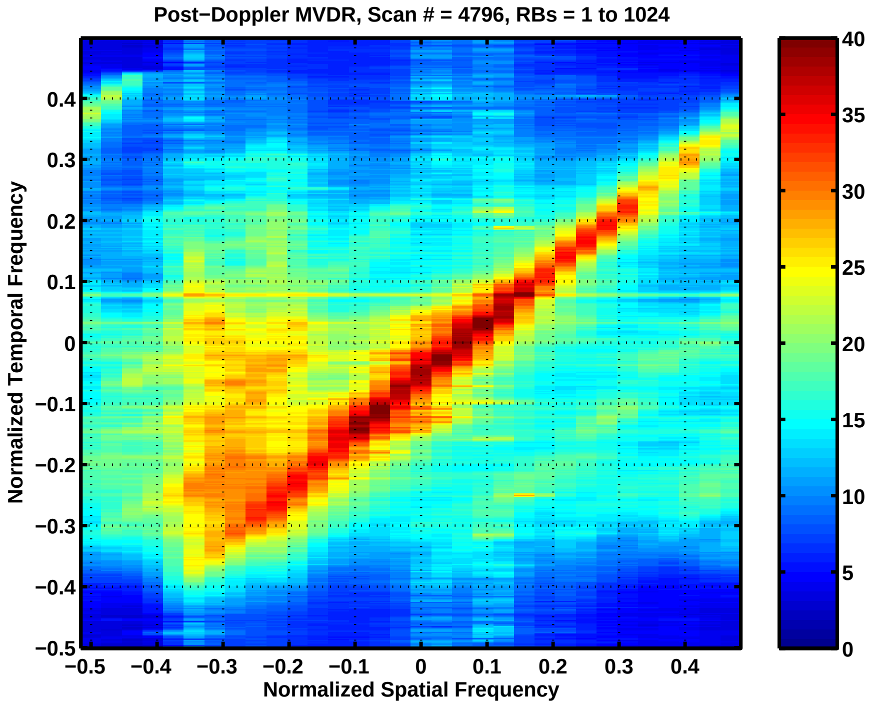




- Raw data; 12-channel, 480-pulse
  - Dramatic variation in amplitude and phase between channels
  - No discernible clutter ridge
- Both channel pair techniques yielded a clutter ridge
  - Range-Doppler processing (shown) a little better

Frequency Equalization Results





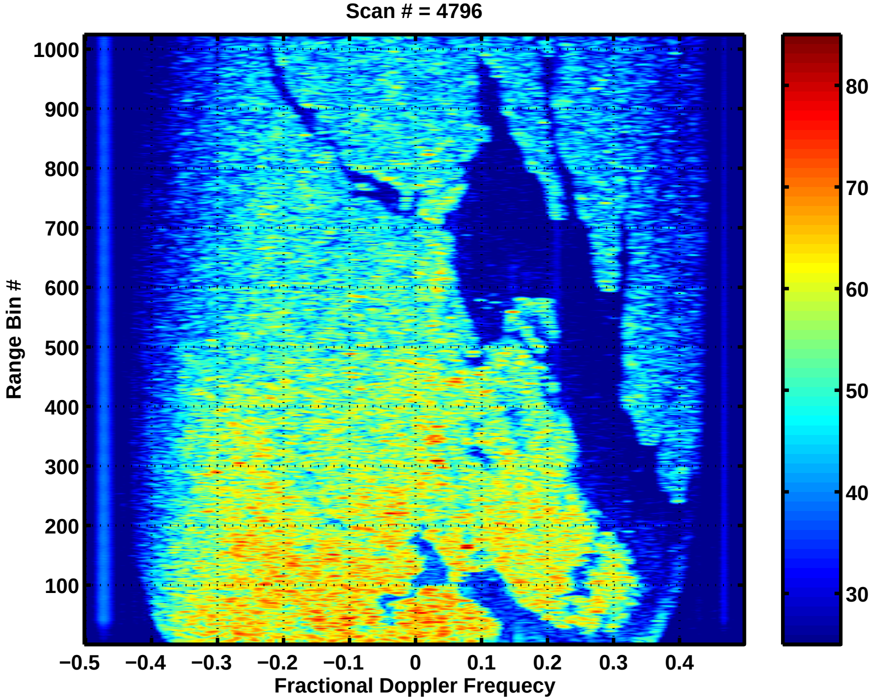
- MVDR spectrum
  - After range-Doppler channel-pair calibration
- After frequency equalization across channels
  - Mostly small time delay differences between channels (fractions of a range bin)

Outline

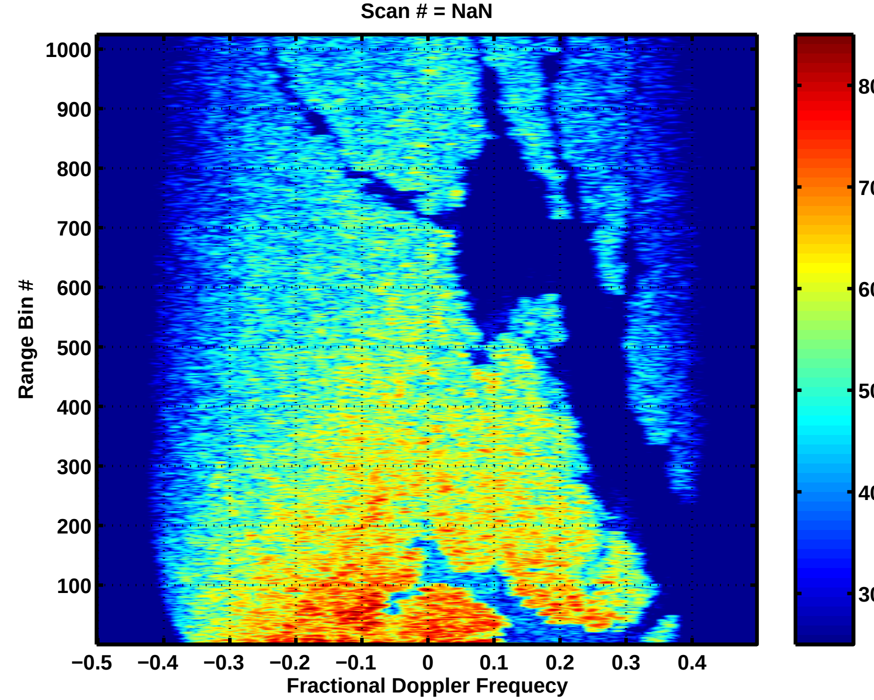
- Multi-resolution processing (MRP) update
- Discrete mitigation
- Calibration approaches supporting data pre-whitening
  - Developed methods appropriate for short CPIs
    - Exploit data redundancies in adjacent channels
  - Simulation results met 30-dB cancellation requirement
  - Applied to FOPEN data set
- Functions from site-specific predictions

FOPEN-Prediction Comparison

FOPEN Data, 128 Pulses



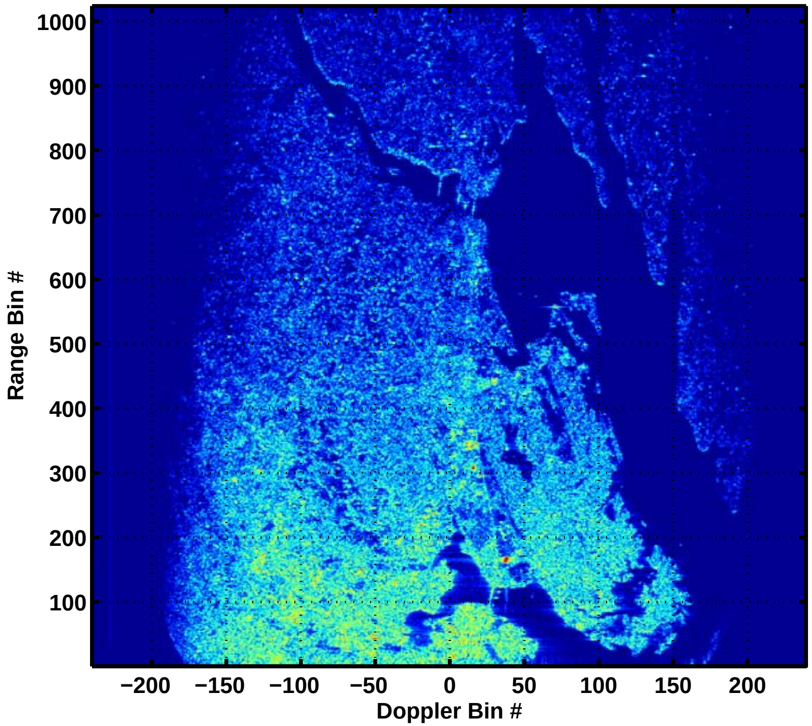
Prediction, 128 Pulses



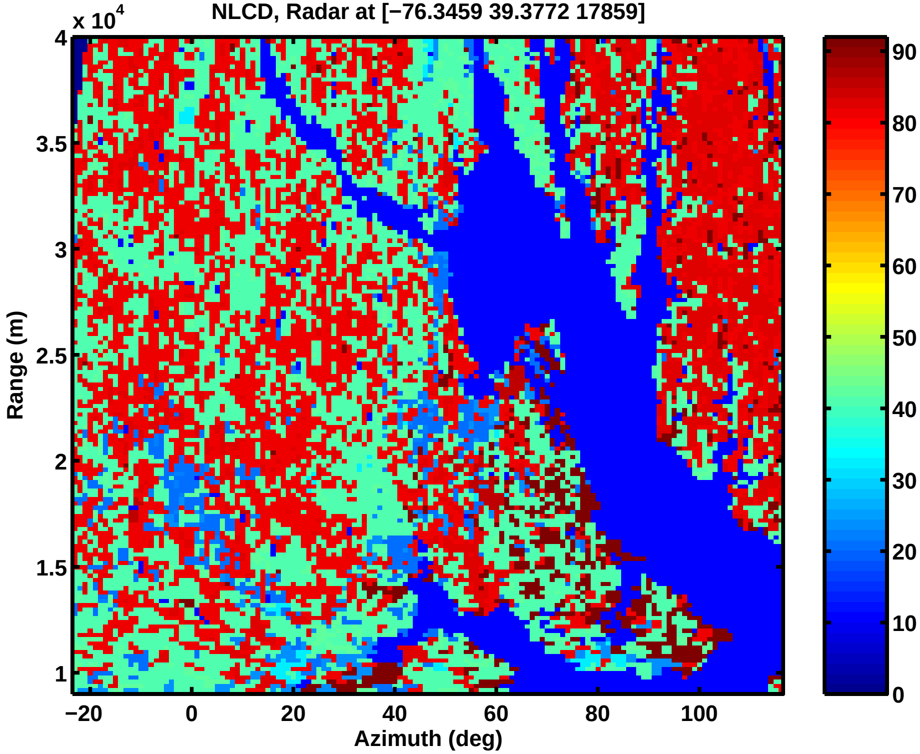
- Differences
  - Near-range saturation of radar front end
  - RFI
  - Doppler offset corresponding to 2.24° velocity vector difference

Range-Doppler Map Comparison

FOPEN Data



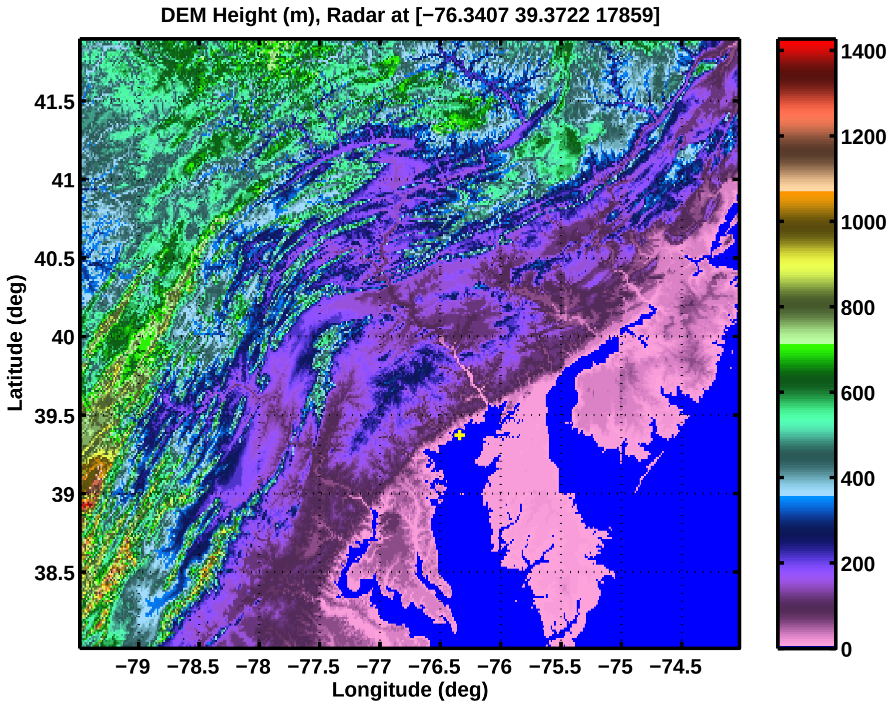
NLCD (Land Type/Use)



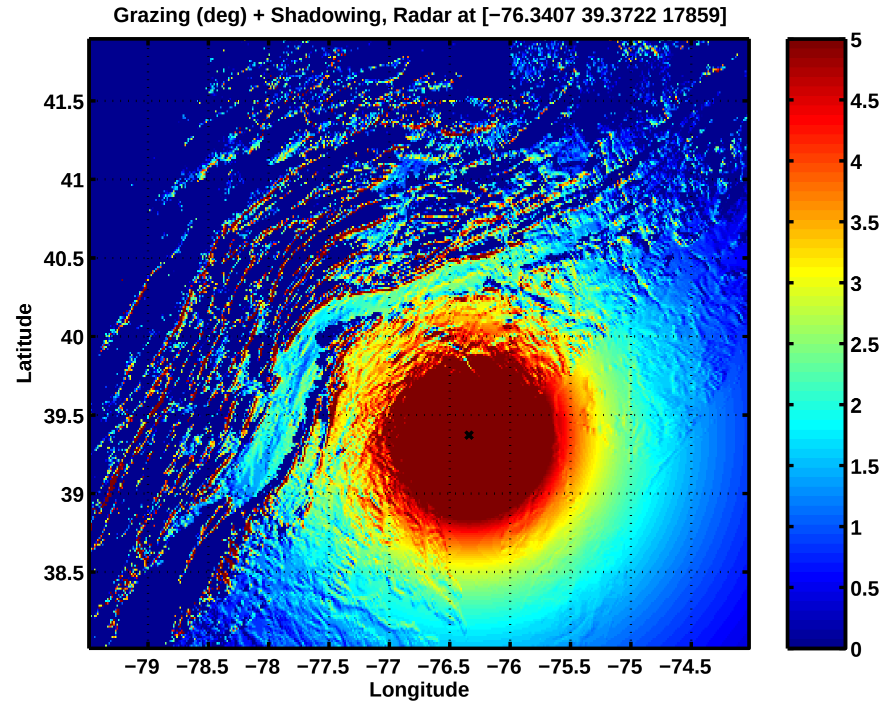
- Range-Doppler image is for full 480-pulse CPI
- NLCD data is sufficient to designate large “no-return” areas
- (Note that the angle-Doppler function is non-linear at large angles)

Shadowing Prediction

DEM (Terrain Height) Data



Predicted Grazing + Shadowing



- Digital Elevation Model (DEM)
  - Provides shadowing information (and grazing angle)
- Flight test data needed to validate shadowing predictions
  - <u>KASSPER ‘03</u>: Lockheed-Martin showed good shadowing match with Utah Tuxedo data

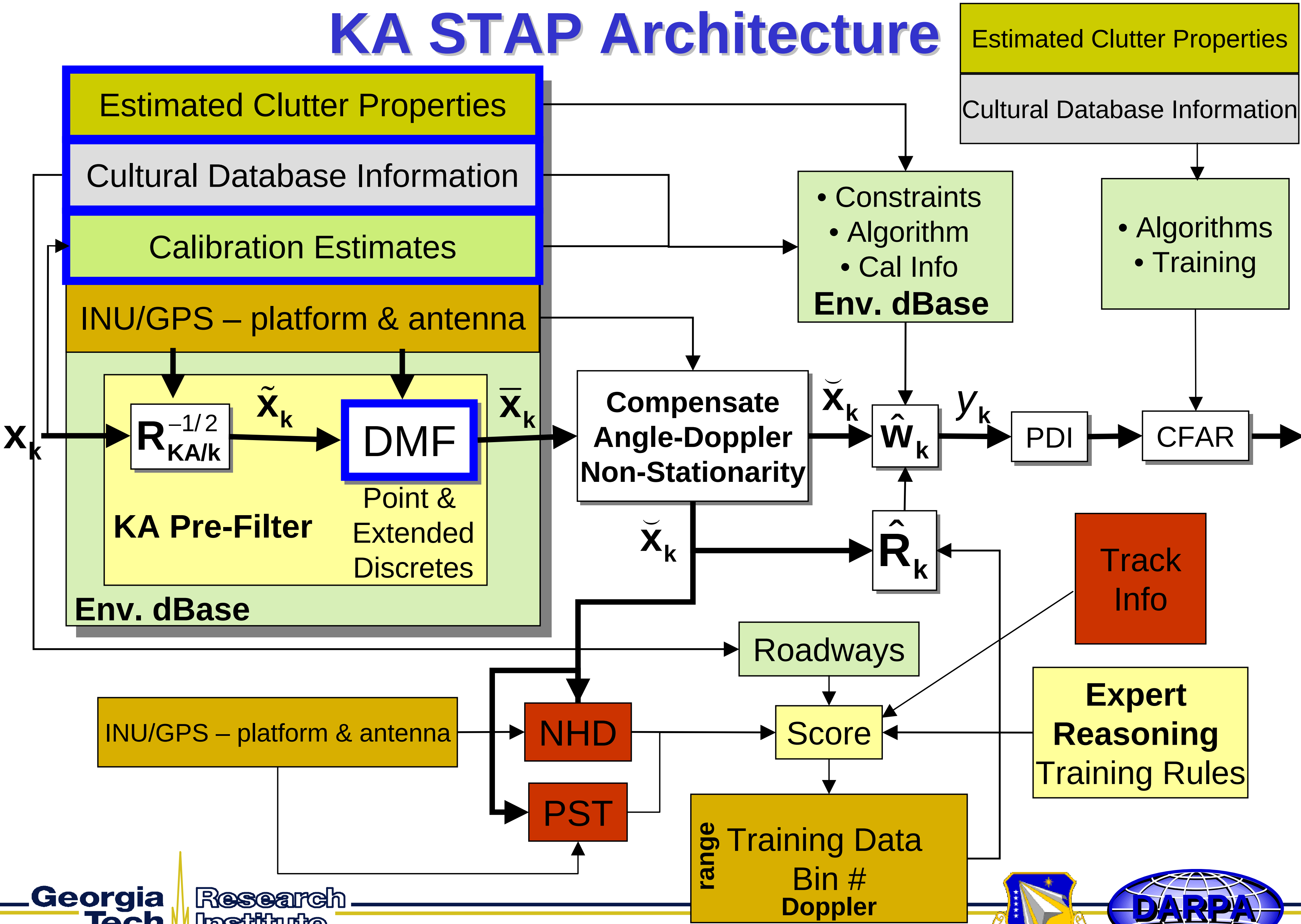
Outline

- Multi-resolution processing (MRP) update
- Discrete mitigation
- Calibration approaches supporting data pre-whitening
- Functions from site-specific predictions
  - Masks for STAP and CFAR training
    - Low/No-return areas
    - Shadowed areas mask
  - TBD
    - High-return mask (urban areas)
    - Road scoring

Special thanks to Marshall Greenspan and crew at Northrop Gruman Electronic Systems for providing FOPEN flight test data and granting us permission to publish results

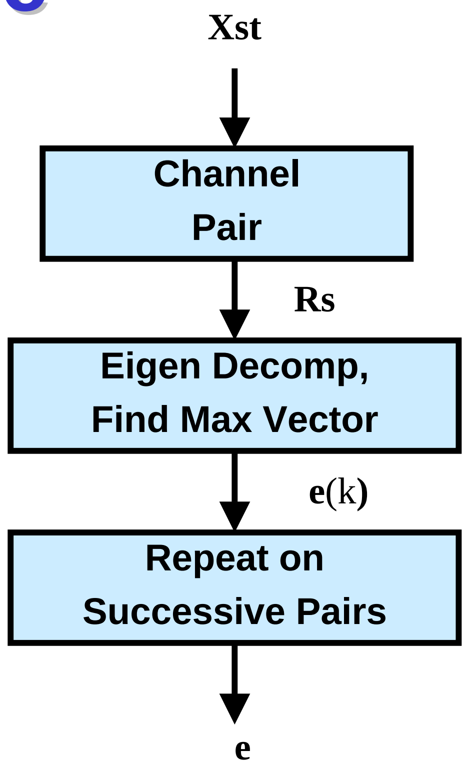
Back-Up and Spare Material

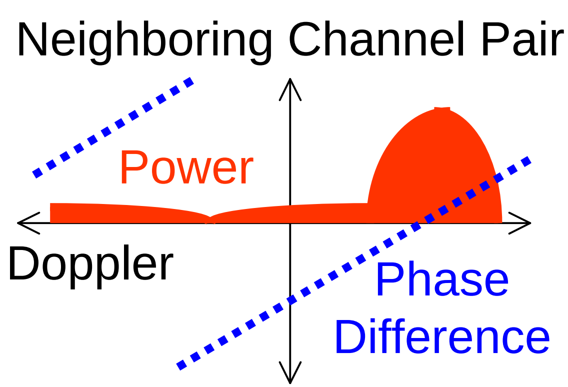
KA STAP Architecture



Channel Pair Technique

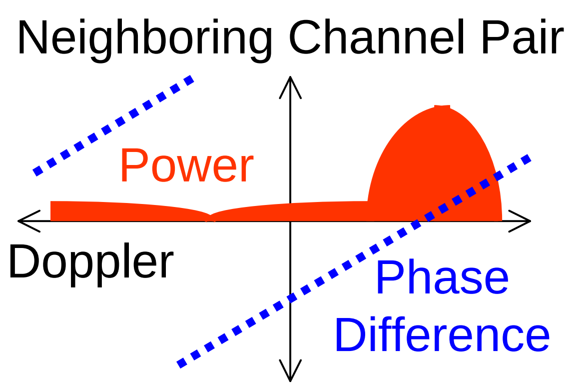
- Development
  - Evaluate each adjacent channel pair
    - 1-2, 2-3, …
  - Form spatial correlation matrix
    - 2-by-2
    - Over all data (pulses, ranges)
  - Imbalance = correlation ratios, or entries in maximum eigenvector
- Technique limitations
  - Plus and minus phase contributions on mainbeam skirts cancel <u>in the limit</u>, not so with finite samples
  - Poor performance if clutter fills Doppler space (i.e., rapidly decorrelates)

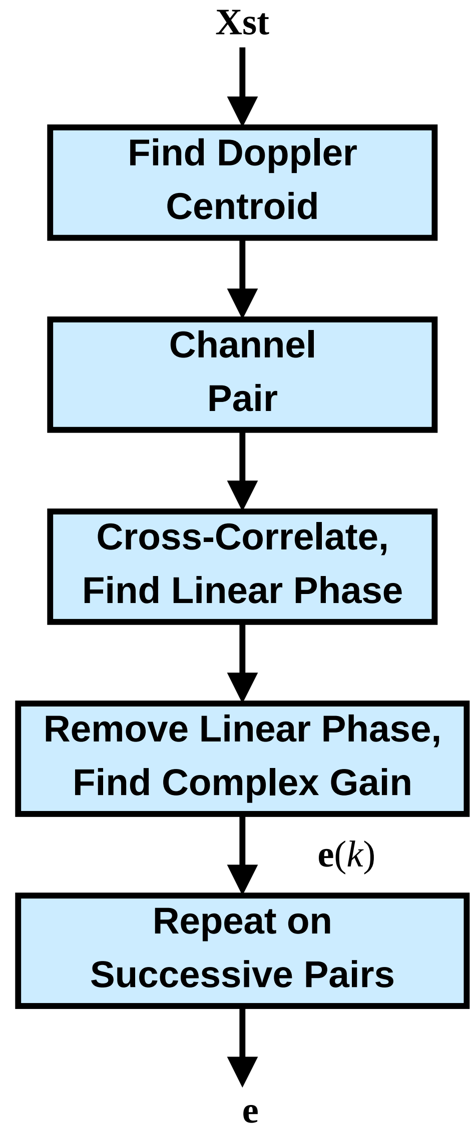




Range-Doppler Processing

- Why is the Doppler centroid required?
  - Linear phase must be removed with phase center at the center of the mainbeam
  - Otherwise, phase bias is introduced
- If Doppler centroid known, this method is powerful, with very low RMS error
  - Once linear phase is removed, all clutter energy is available to estimate channel gain
  - Also, error goes down with increasing clutter power
  - However, in general the Doppler centroid calculation is required, and introduces error

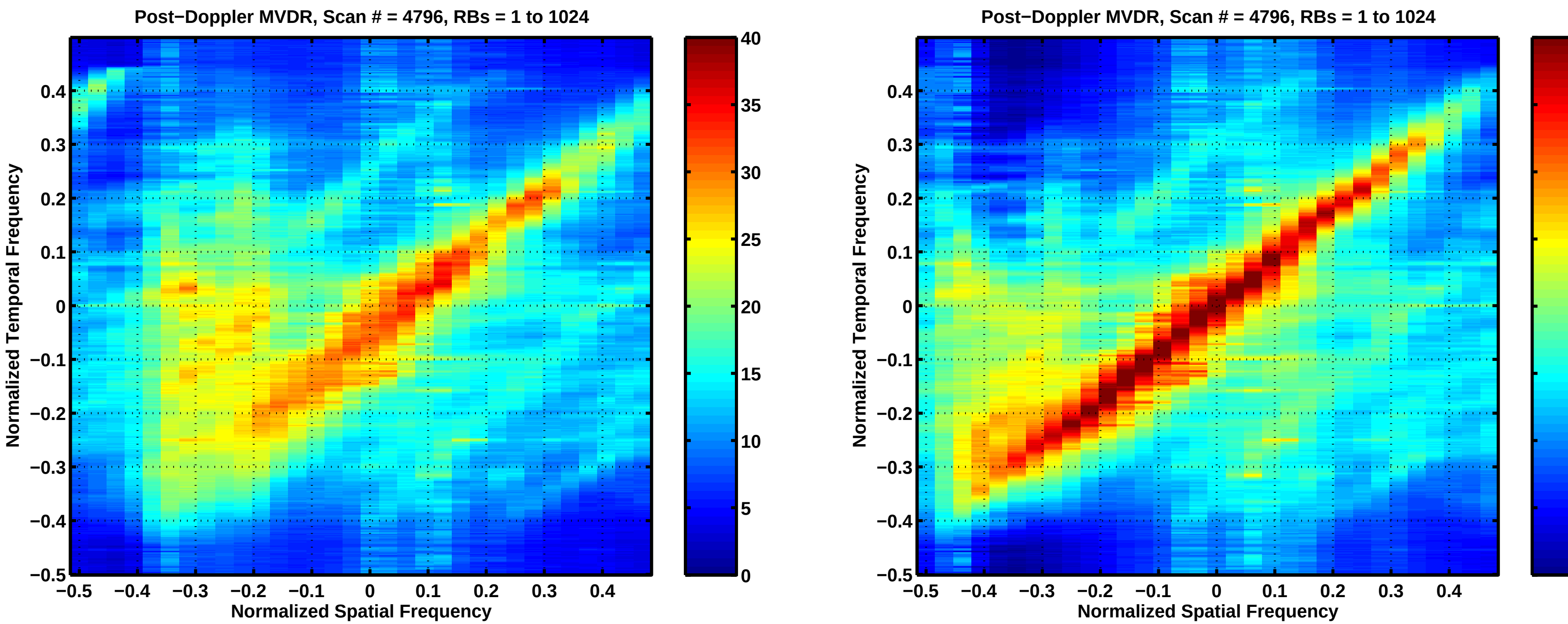




Yegulalps' Calibration Technique

- Multi-channel calibration (MCC)
  - Based on multi-channel Wiener filter theory
- Procedure
  - Generate Doppler-domain data
  - Examine spatial response in each range-Doppler cell
  - Clutter (expected) to fall along a ridge
  - Ideal spatial response $\mathbf{s}$, measured response $\mathbf{m}$
    - $\mathbf{s}$ is linear phase (DFT vector)
    - $\mathbf{m}$ is modified measurement (first channel set to 0-phase)
  - Model: $\mathbf{m} = \mathbf{D}\mathbf{s}$
- Examine all range-Doppler cells and estimate $\mathbf{D}$
  - $\mathbf{M} = \mathbf{D}\mathbf{S}$
  - Estimated $\mathbf{D} = \mathbf{M}\mathrm{pinv}(\mathbf{S}) = \mathbf{M}\mathbf{S}^{H}(\mathbf{S}\mathbf{S}^{H})^{-1}$

Yegulalp's Calibration Results



- Left is baseline range-Doppler calibration, right is MCC
- Reasonable MCC results required careful application of weighting on reference vectors (as a function of angle) to lower the gain at large angles