Terrain Knowledge Assisted STAP

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Agenda

- Problem Addressed
- Conventional STAP
- Environmental Based Clutter Modeling
- Environmental Based STAP
  - Fully Adaptive KASSPER
  - Partially Adaptive KASSPER
- Conclusions
- Current Status and Results
- New Issues to be Addressed

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Problem Addressed

- Real-world radar clutter may be nonstationary.
- Actual data may not be available or too few samples.
- Pre-available resource (maps, images) can be used.
- Terrain images can be used for clutter generation and reconstruction of the weight vector.
- This may improve terrain assisted performance modeling techniques.
- Useful in a limited sample support scene.
- Four different methods are addressed.

Conventional STAP Detection

Spatio-Temporal Steering Vector:

$$\mathbf{a} = \mathbf{a}(\theta, \omega_d) = \mathbf{b}_M(\omega_d) \otimes \mathbf{a}_N(\theta)$$

$$\mathbf{a}_N(\theta) = \begin{bmatrix} 1 \\ e^{-j\pi \sin\theta} \\ \vdots \\ e^{-j\pi(N-1)\sin\theta} \end{bmatrix}, \qquad \mathbf{b}_M(\omega_d) = \begin{bmatrix} 1 \\ e^{-j\pi\omega_d} \\ \vdots \\ e^{-j2\pi(M-1)\omega_d} \end{bmatrix}$$

Find weight vector $\mathbf{w}$ so that

$$Z = \left| \mathbf{w}^* \mathbf{x}_r \right| \underset{No}{\overset{Yes}{\gtrless}} \eta$$

can be used for threshold detection optimally.

$\mathbf{x}_r$: data vector of size *MN*
M: Number of pulses
N: Number of sensors

Conventional STAP Detection

Maximize output signal to interference plus noise ratio (SINR).

- **Optimum weight vector:** $\mathbf{R} \Rightarrow \mathbf{w}$
- $\mathbf{R}$ **is** $MN \times MN$ **and usually unknown.**
- **In practice, unknown** $\mathbf{R}$ **needs to be estimated from the available sample snapshots.**
- **Optimum estimation of** $\mathbf{R}$ **from** K **independent sample snapshots**

$$\hat{\mathbf{R}} = \frac{1}{K}\sum_{k}^{K} \mathbf{x}_k \mathbf{x}_k^*.$$

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Generation of Realistic Clutter Data

Resource:

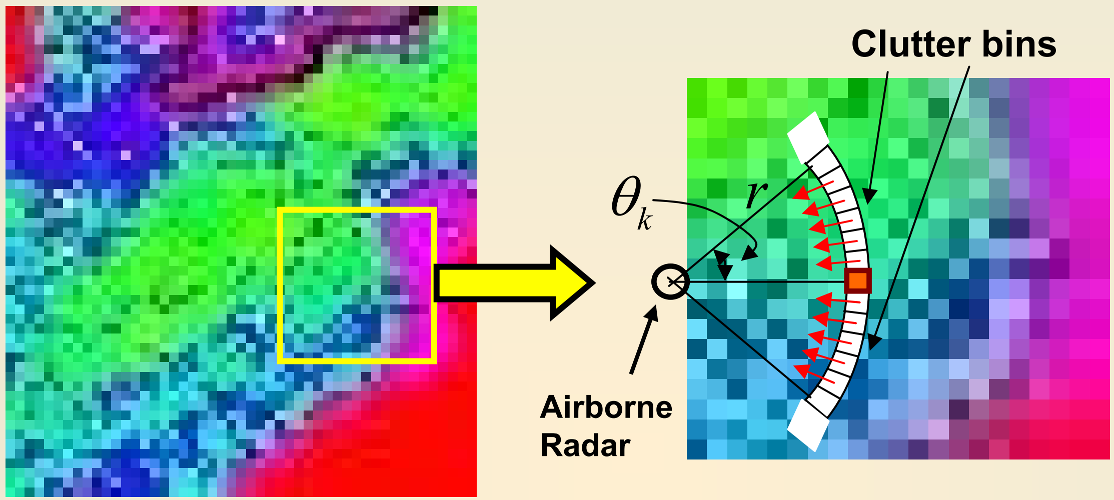
- Image intensity, geodetic data (NASA/NIMA data)
- Terrain spectral characteristics

Solution:

- Images give magnitude of the clutter discrete
- Global terrain can be partitioned into different regions…
- Reconstruct clutter phases using convex projection methods and terrain type from image

NASA's Multidisciplinary Data (MODIS)

ftp://modis.gsfc.nasa.gov/pub/Data_Sets/outgoing/Data_Sets/CD/land/JPG/TREE_COVER/MOD44B_TreeCover_2001.jpg



When an image is given, suggest a way to determine clutter discrete.
For different regions, phase information needs to be reconstructed.

Clutter discriminant random variables →

$$\alpha_k^{(r)} = \sqrt{p_{r,k}}\; e^{j\phi_{r,k}}$$

phases unknown

Magnitudes known,

Random Phase

Phase reconstruction (Image partitioning)

Terrain Knowledge Based STAP

The clutter from *r*-th range bin at the airborne platform

$$\mathbf{x}_r = \sum_k \alpha_k^{(r)} \mathbf{a}(\theta_k, \omega_{d_k})$$

$\alpha_k^{(r)}$: Clutter Discrete

$\mathbf{a}(\theta_k, \omega_{d_k})$: Steering Vector for *k*-th clutter bin

- Quality of the clutter discrete depends on the environment (geodetic data)
- Type of terrain information is critical (eg. Forest, Ocean, Desert, etc.) for clutter generation
- Realistic clutter data is required for performance analysis of STAP algorithms
- How to generate a realistic clutter discrete?

Terrain Knowledge Based STAP

Use Terrain Image Map to Compute STAP Weight Vector $\mathbf{w}$

- **How to accommodate terrain map intensity images (eg. NASA MODIS public domain data) in computing STAP weight vector $\mathbf{w}$ a-priori?**

Terrain Knowledge Based STAP

- $\mathbf{w}$ using only Terrain Map (Fully Adaptive KASSPER)
  - **Method A**
  - **Method B**
- $\mathbf{w}$ using Terrain Map and actual measured data (Partially Adaptive KASSPER)
  - **Method C**
  - **Method D**

Terrain Knowledge Based STAP

I. Fully Adaptive KASSPER

Method A :

Computes the clutter covariance matrix using the images

Method B :

Generates data from images and then estimates the clutter covariance matrix

II. Partially Adaptive KASSPER

Method C (Weight Vector Update):

Combines the ideal weight vector from Method A together with the estimated weight vector from measured data.

Method D (Covariance Matrix Update) :

Combines the ideal clutter covariance matrix from Method A together with the estimated clutter covariance matrix from measured data.

Terrain Knowledge Based STAP

- **Fully Adaptive KASSPER: (Uses Only Terrain Map)**

Method A: Covariance matrix from images:

Compute the ideal clutter covariance matrix from image intensity and aircraft-earth geometry

$$\mathbf{R}_{\mathrm{A}} = \sum_k p_k \, \mathbf{a}_k \, \mathbf{a}_k^*$$

Image Intensity

Steering vector

Use this covariance matrix to compute the weight vector

$$\mathbf{R}_{\mathrm{A}} \Rightarrow \mathbf{w}_{\mathrm{A}}$$

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Terrain Knowledge Based STAP

- **Fully Adaptive KASSPER: (Uses Only Terrain Map)**

Method B: Generate data from images and estimate clutter covariance matrix

Generate the data using image intensity and aircraft-earth geometry

$$\mathbf{x} = \sum_k \sqrt{p_k}\, e^{j\phi_k}\, \mathbf{a}_k\, \mathbf{a}_k^*$$

Random phase is used under the assumption of uncorrelated clutter

Image intensity

Steering vector

Estimate clutter covariance matrix from data:

$$\hat{\mathbf{R}}_{\mathrm{B}} = \frac{1}{K}\sum_k^K \mathbf{x}_k \mathbf{x}_k^*.$$

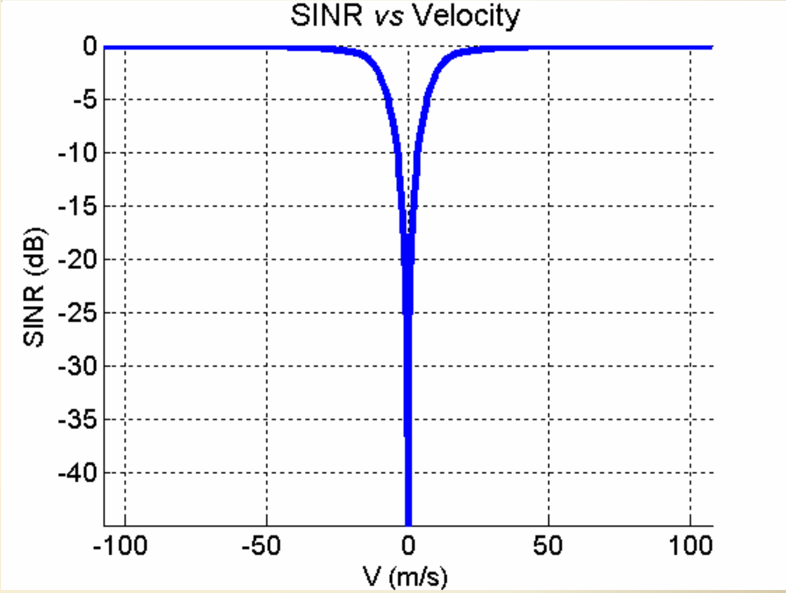
Use this covariance matrix to compute the weight vector

$$\hat{\mathbf{R}}_{\mathrm{B}} \Rightarrow \hat{\mathbf{w}}_{\mathrm{B}}$$

Illustration Parameters

$$SINR_{Ideal} = \mathbf{a}(\theta_{\mathbf{t}}, \omega_d)^* \mathbf{R}^{-1} \mathbf{a}(\theta_{\mathbf{t}}, \omega_d)$$

$$SINR = \frac{|\hat{\mathbf{w}}^* \mathbf{a}(\theta_{\mathbf{t}}, \omega_d)|^2}{\hat{\mathbf{w}}^* \mathbf{R}^{-1} \hat{\mathbf{w}}}$$



Doppler: $\omega_d = \dfrac{2V\,T_r}{\lambda/2}$

Sample Matrix Inversion with Diagonal Loading (SMIDL)

Covariance Matrix Tapering (CMT)

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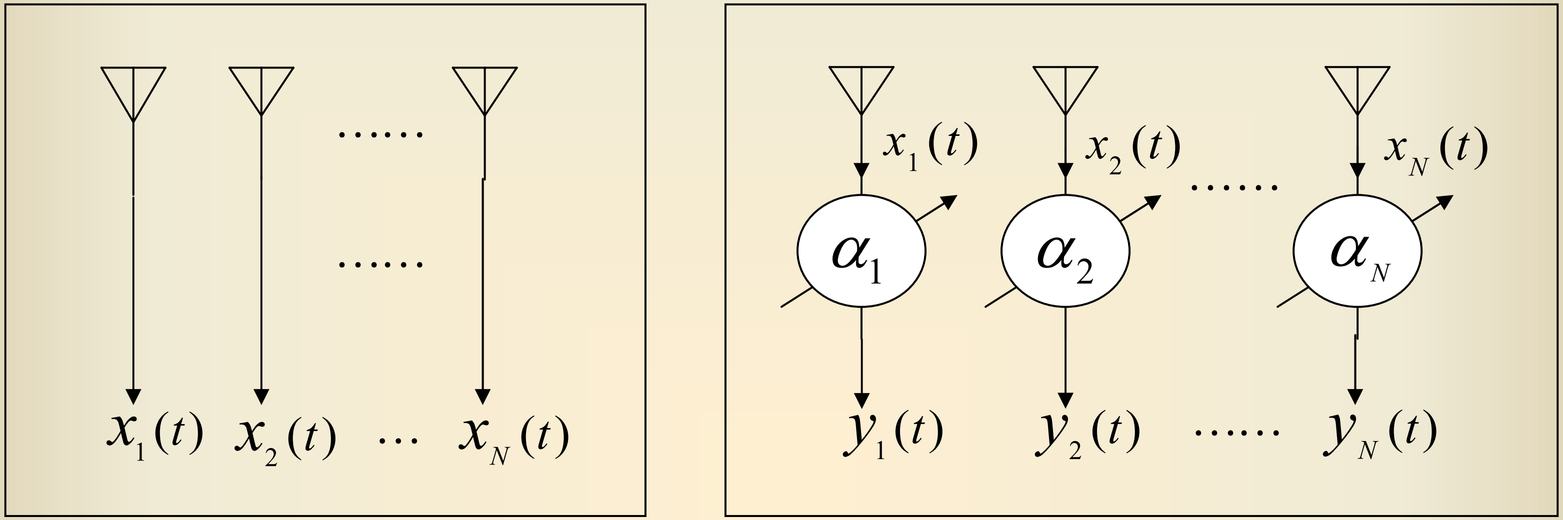
Covariance Matrix Tapering



(a) Traditional Array **(b) Tapered Array**

Tapering an array: $\hat{\mathbf{R}}_T = \hat{\mathbf{R}} \odot T$

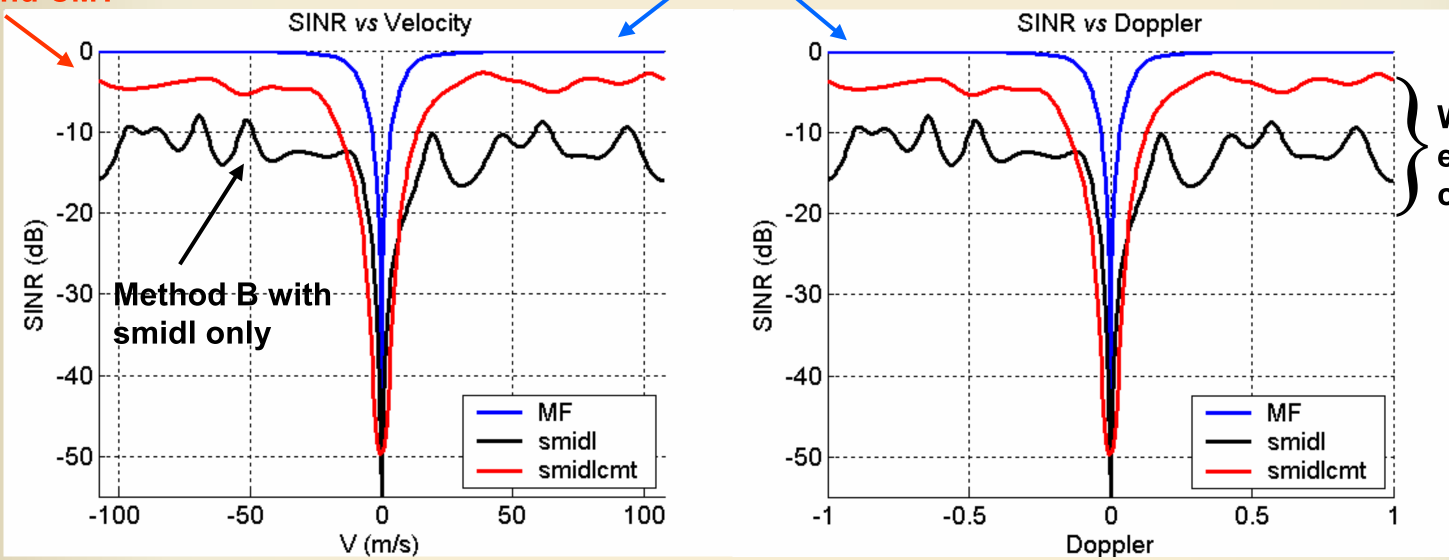
where T is a tapering matrix and $\hat{\mathbf{R}}$ is the original estimate

Clutter Suppression using CMT

Number of sensors = 14, Number of pulses = 16, Radar operating frequency = 435 MHz, Inter-element spacing = half wavelength, CNR = 40 dB, Number of samples = 30

Method A: Weight vector from ideal clutter covariance matrix

Method B with smidl and CMT



Weight vector from estimated clutter covariance matrix

Clutter suppression with (---) and without (---) CMT

The figures above are generated from synthesized clutter data using NASA image intensity for the New York tri-state area along with reconstructed phases for a specific airborne configuration. CMT boosting on estimated covariance matrix gives better clutter suppression the smidl alone.

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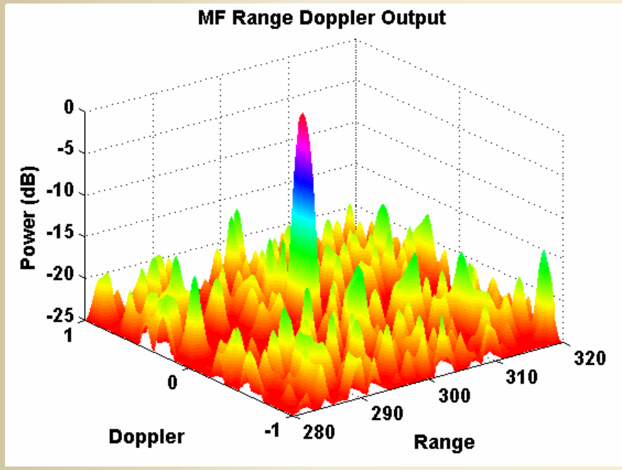
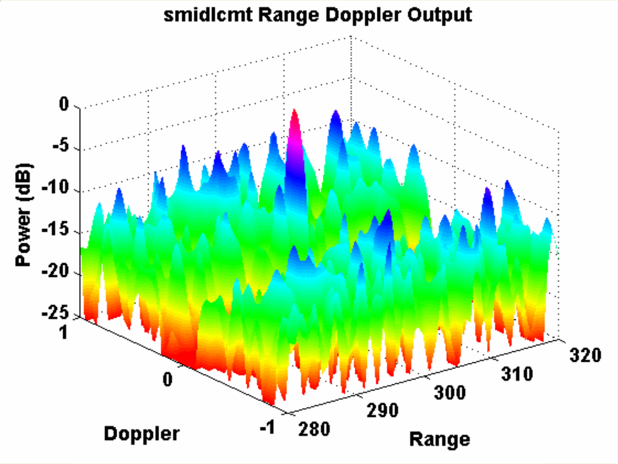
Target Detection Performance

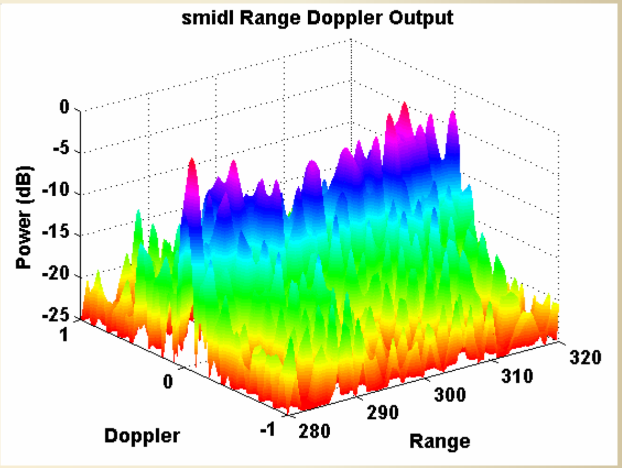
Target Location =300th range bin, Target azimuth = 0°, SNR = 0 dB, Target Doppler = 0.2, Number of samples used for estimated Cov. Matrix = 30



Method A



Method B with smidl and CMT



Method B with smidl

The figures above are generated from synthesized clutter data with target injected at a single range bin. In practice, one data will be collected and will be interrogated with the synthetic weight vector to detect target. Method A using ideal clutter covariance matrix gives the best performance. CMT boosting on estimated covariance matrix gives improved target detection.

Terrain Knowledge Based STAP

Partially Adaptive KASSPER:

Use a-priori information together with actual measurements

- Image gives the prior terrain information, actual data depends on other factors such as when the data is collected, weather, etc…
- Actual data from measurement is related to the prior terrain information with some variations.
- To account for these variations, the data can be generated using the image plus an additional component.

The actual measurement is simulated as follows:

Magnitude and phase depend on images, the prior information.

$$\mathbf{x} = \beta \sum_{k(l,m)} \sqrt{p_{k(l,m)}}\, e^{j\phi_{k(l,m)}}\, \mathbf{a}_k \mathbf{a}_k^* + (1-\beta) \sum_i \sqrt{Q_i}\, e^{j\psi_i}\, \mathbf{a}_i \mathbf{a}_i^*, \quad 0 \le \beta \le 1$$

Weight Factor

Unknown magnitude and phase depend on the actual measurement.

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Partial KASSPER – Obtain Weight Vector from Priori Information and Actual Measurement

- Terrain image gives the ideal clutter covariance matrix $\mathbf{R}_{\mathrm{A}}$ using

$$\mathbf{R}_{\mathrm{A}} = \sum_{k} p_k \, \mathbf{a}_k \, \mathbf{a}_k^*$$

This provides the ideal weight vector to be : $\mathbf{R}_{\mathrm{A}} \Rightarrow \mathbf{w}_{\mathrm{A}}$

- Actual data measurement gives the estimated clutter covariance matrix $\hat{\mathbf{R}}$ using

$$\hat{\mathbf{R}} = \frac{1}{K} \sum_{k} \mathbf{x}\,\mathbf{x}^*$$

This gives the estimated weight vector: $\hat{\mathbf{R}} \Rightarrow \hat{\mathbf{w}}$

How to make use of both priori information and actual measurement?

Partial KASSPER

- **Method C (Weight Vector Update) :**

Combine the ideal weight vector $\mathbf{w}_\mathrm{A}$ from Method A together with the estimated weight vector $\hat{\mathbf{w}}$ from data.

$$\mathbf{w}_\mathrm{C} = \gamma\, \mathbf{w}_\mathrm{A} + (1-\gamma)\,\hat{\mathbf{w}}, \quad 0 \le \gamma \le 1$$

Weight factor γ determines the dependency of the prior information.

When γ increases, the weight vector $\mathbf{w}_\mathrm{C}$ dependency on the prior information increases.

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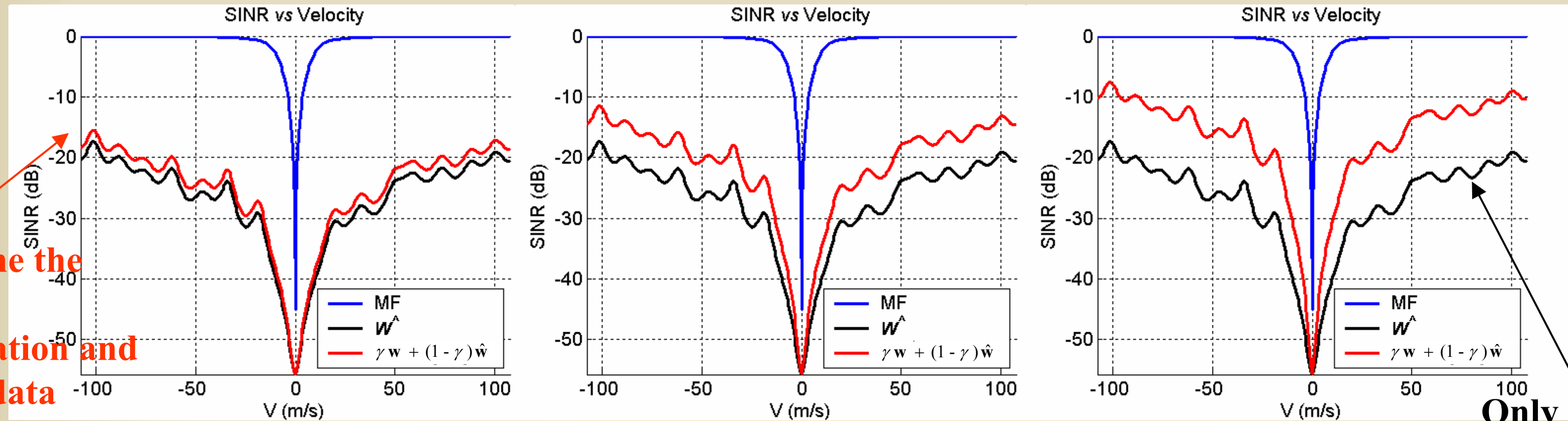
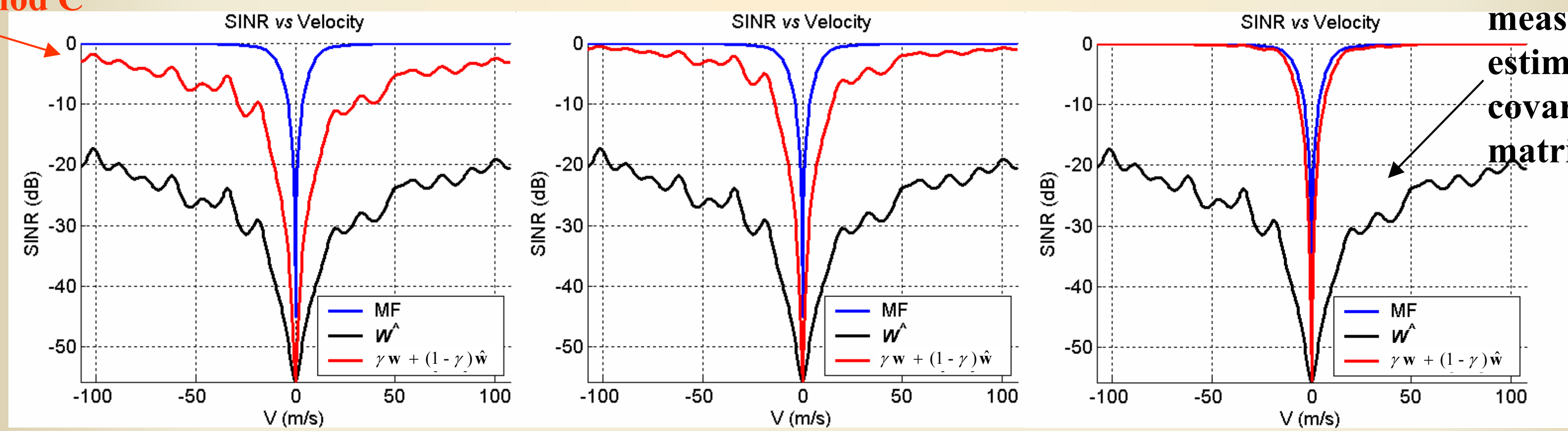
Method C -- Clutter Suppression Performance

Combine the prior information and actual data measurement as in Method C



(a) $\gamma = 0.2$ (b) $\gamma = 0.5$ (c) $\gamma = 0.7$

Only use the actual data measurement to estimate clutter covariance matrix



(d) $\gamma = 0.9$ (e) $\gamma = 0.95$ (f) $\gamma = 0.99$

Combining the prior information gives better performance. Large percentage ($\gamma = 0.95$) of the prior information is required for acceptable improvement on clutter suppression performance.

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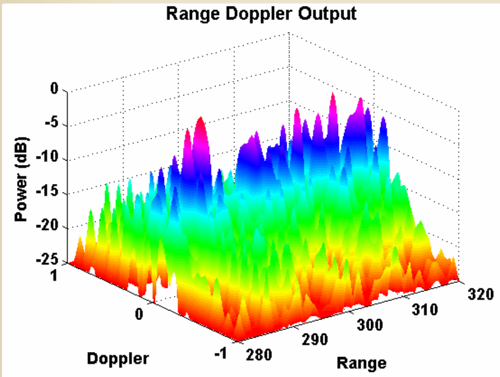
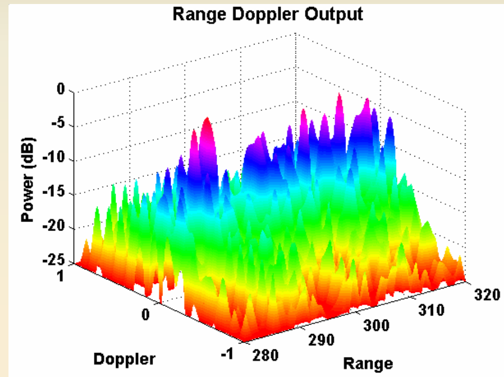
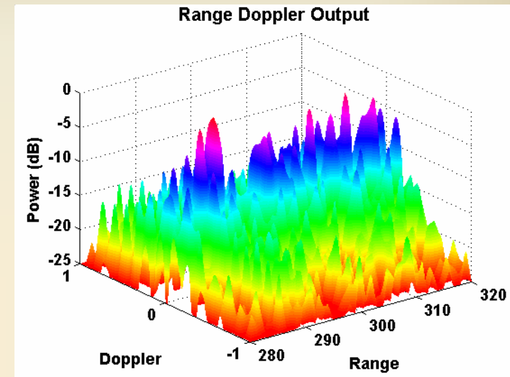
Method C – Target Detection Performance



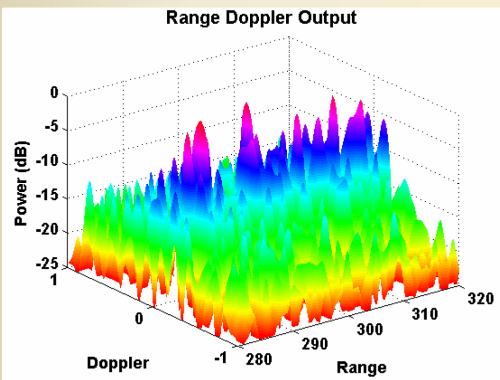
(a) $\gamma = 0.2$



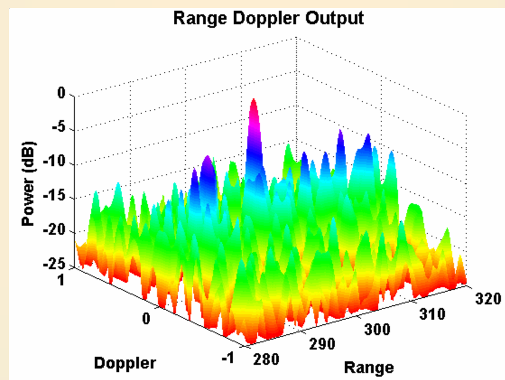
(b) $\gamma = 0.5$



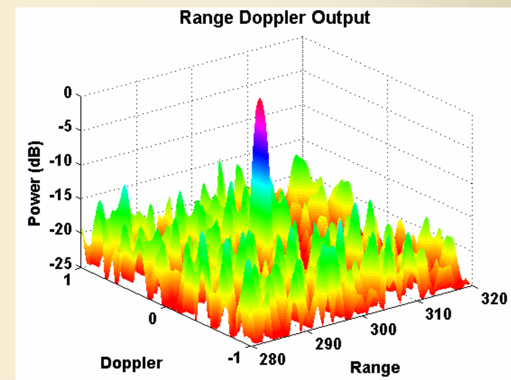
(c) $\gamma = 0.7$



(d) $\gamma = 0.9$



(e) $\gamma = 0.95$



(f) $\gamma = 0.99$

Target Location =300th range bin, Target azimuth = 0^{o}, SNR = 0 dB, Target Doppler = 0.2, Number of Samples used: 26

Large percentage of prior information is needed to detect target.

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Partial KASSPER

- **Method D (Covariance Matrix Update):**

Combine the ideal clutter covariance matrix $\mathbf{R}_{\mathrm{A}}$ from Method A together with the estimated clutter covariance matrix $\hat{\mathbf{R}}$ from data.

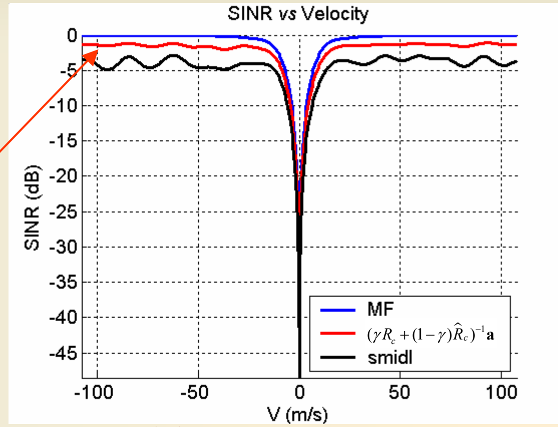
$$\mathbf{R}_{\mathrm{D}} = \gamma \mathbf{R}_{\mathrm{A}} + (1-\gamma)\hat{\mathbf{R}}, \quad 0 \le \gamma \le 1$$

$$\mathbf{R}_{\mathrm{D}} \Rightarrow \mathbf{w}_{\mathrm{D}}$$

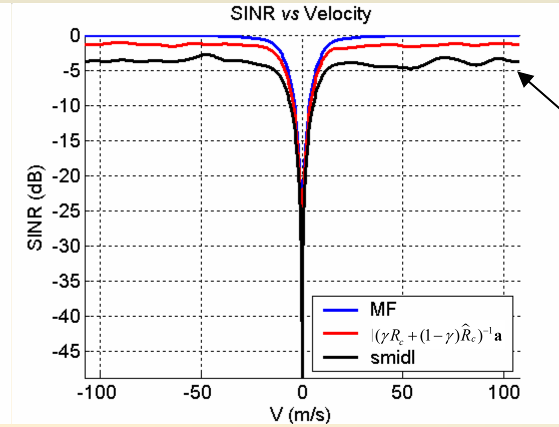
Weighting factor γ sets the dependency of the prior information. When γ increases, the weight vector $\mathbf{w}_{\mathrm{D}}$ dependency on the prior information also increases.

Partial KASSPER Method D -- Clutter Suppression Performance

Combine the prior information and actual data measurement as in Method D

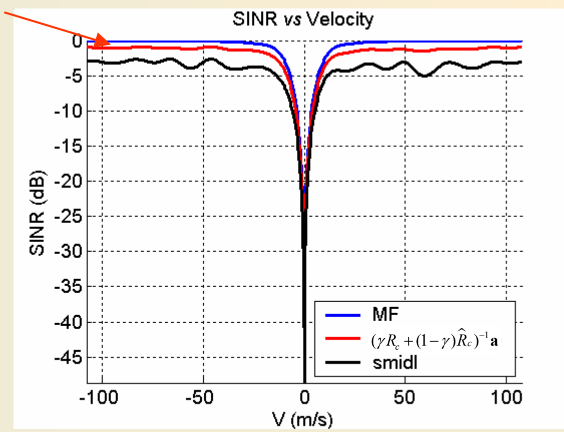


(a) $\gamma = 0.01$

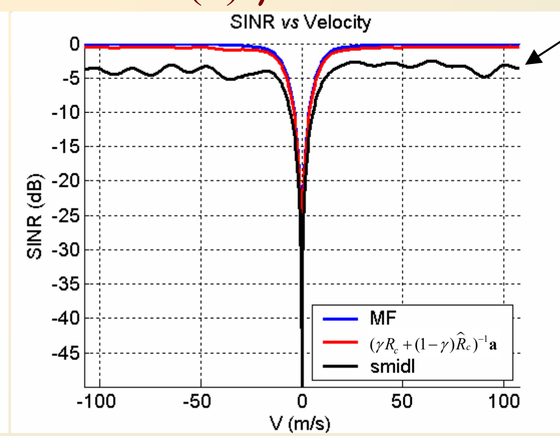


(b) $\gamma = 0.1$

Only use the actual data measurement to estimate clutter covariance matrix



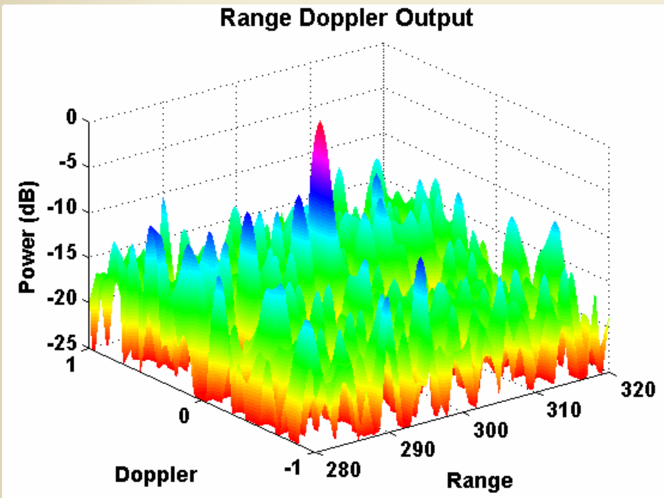
(c) $\gamma = 0.5$



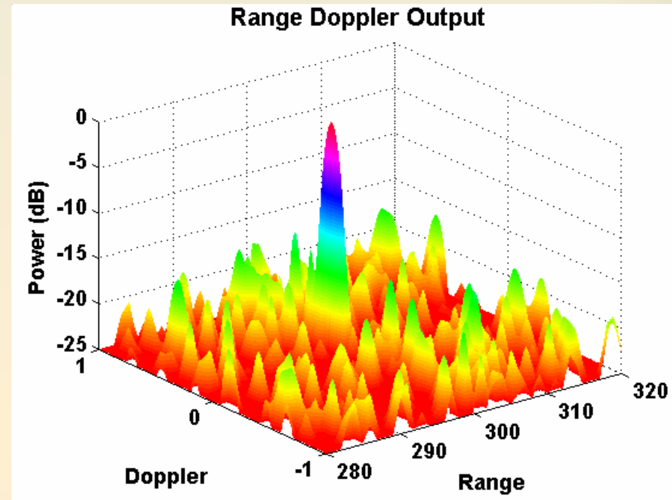
(d) $\gamma = 0.95$

Combining the prior information gives better performance. Only a small percentage ($\gamma = 0.01$) of the prior information is required for improved clutter suppression.

Partial KASSPER Method D – Target Detection Performance



(a) smidl using the actual measurement with 40 data samples



(b) Method D $(\gamma = 0.1)$

Target Location =300th range bin, Target azimuth = 0°, SNR = 0 dB, Target Doppler = 0.2

Combining prior information gives better target detection performance

Conclusions

- For uncorrelated data fully adaptive KASSPER can be used.
- For correlated data partial KASSPER should be used.
  - Method A cannot be used
  - Phase reconstruction is required for clutter generation
- Performance improvement is noticeable when a-priori terrain information is utilized.
- Target detection performance is also dependent on the quality of the image.

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Current Status and Results

- Generated terrain specific clutter data using terrain scene from NASA MODIS data for New York Tri-State Region
- Preliminary performance analysis of STAP techniques are investigated.
- Quantified *SINR* performance analysis on the generated terrain specific data.
- Four different methods for clutter suppression are analyzed.

Terrain Knowledge STAP – New Issues to be addressed

- Generate appropriate clutter data using terrain scenes from different data scenes.
- Quantify performance analysis of Covariance Matrix Tapering effects on the generated data.
- Investigate different methods to reconstruct clutter discrete from terrain information.
- For correlated data, how to reconstruct unknown phase for clutter discrete.
- Utilizing the clutter data generated using the geodetic information, conduct performance analysis to determine the limitations of GMTI applications.