SAR-Based Covariance Estimation for STAP

Nathan A. Goodman
The University of Arizona, Dept. of ECE

KASSPER Workshop
April 6, 2004

Outline

- Overview of our proposed method.
- The sample covariance matrix from the SAR-based perspective.
- Our proposed SAR-based architecture.
- Results with various practical issues.
- Future work and conclusions.

Summary of Proposed Method

- Heterogeneous clutter causes performance loss in adaptive space-time filtering because training data is statistically different from the range under test.
- There are many techniques for handling heterogeneous clutter, including reduced-rank and structured-covariance methods for reducing the required secondary data support.
- SAR provides a range-Doppler spectral estimate of ground reflections – where each spectral component corresponds to reflections from a specific location on the Earth.
- Since SAR inherently produces an estimate of clutter, use the SAR imagery along with knowledge sources to average in the SAR image domain. Knowledge sources provide the boundaries within which it makes sense to average.

Clutter Covariance Model

$$R_c(\tau,\chi) = E\left[d_c(t,r_x)\,d_c^*(t+\tau,r_x+\chi)\right]$$

$$= \int_X E\left[\sigma_c(x)\right] h(t,r_x,x)\,h^*(t+\tau,r_x+\chi,x)\,dx$$

$$\rightarrow \mathbf{R}_c = \sum_{k=1}^{N_c} \sigma_k \mathbf{v}_k \mathbf{v}_k^H$$

- $E\left[\sigma_c(x)\right]$ is the *average* RCS profile in along-track.
  - A Power Spectral Density, PSD.
- $\mathbf{R}_c$ represents clutter statistics in the data domain.
- $E\left[\sigma_c(x)\right]$ represents statistics in the spectral domain.
- Given steering vectors, $\mathbf{v}_k$'s, data and spectral domain representations are equivalent.

Sample Covariance Matrix (SCM)

- SCM is adaptively estimated.
- Clutter component is:

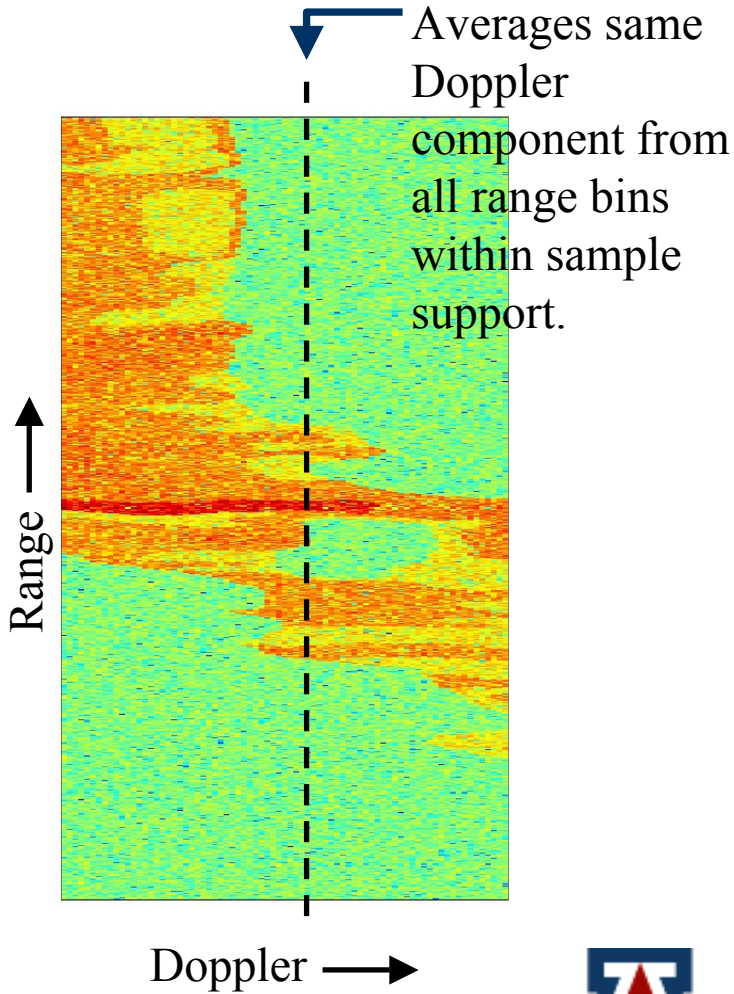
$$E\left[\mathbf{d}_c\mathbf{d}_c^H\right] \approx \hat{\mathbf{R}}_c = \frac{1}{N_s}\sum_{i=1}^{N_s}\mathbf{d}_{c,i}\mathbf{d}_{c,i}^H$$

$$\vdots$$

$$= \sum_{k=1}^{N_c}\left\{\frac{1}{N_s}\sum_{i=1}^{N_s}\gamma_{k,i}\gamma_{k,i}^*\right\}\mathbf{v}_k\mathbf{v}_k^H$$

$$= \sum_{k=1}^{N_c}\hat{\sigma}_k\mathbf{v}_k\mathbf{v}_k^H$$

$\gamma_{k,i}$ → reflectance of k^{th} clutter patch in i^{th} secondary data bin.



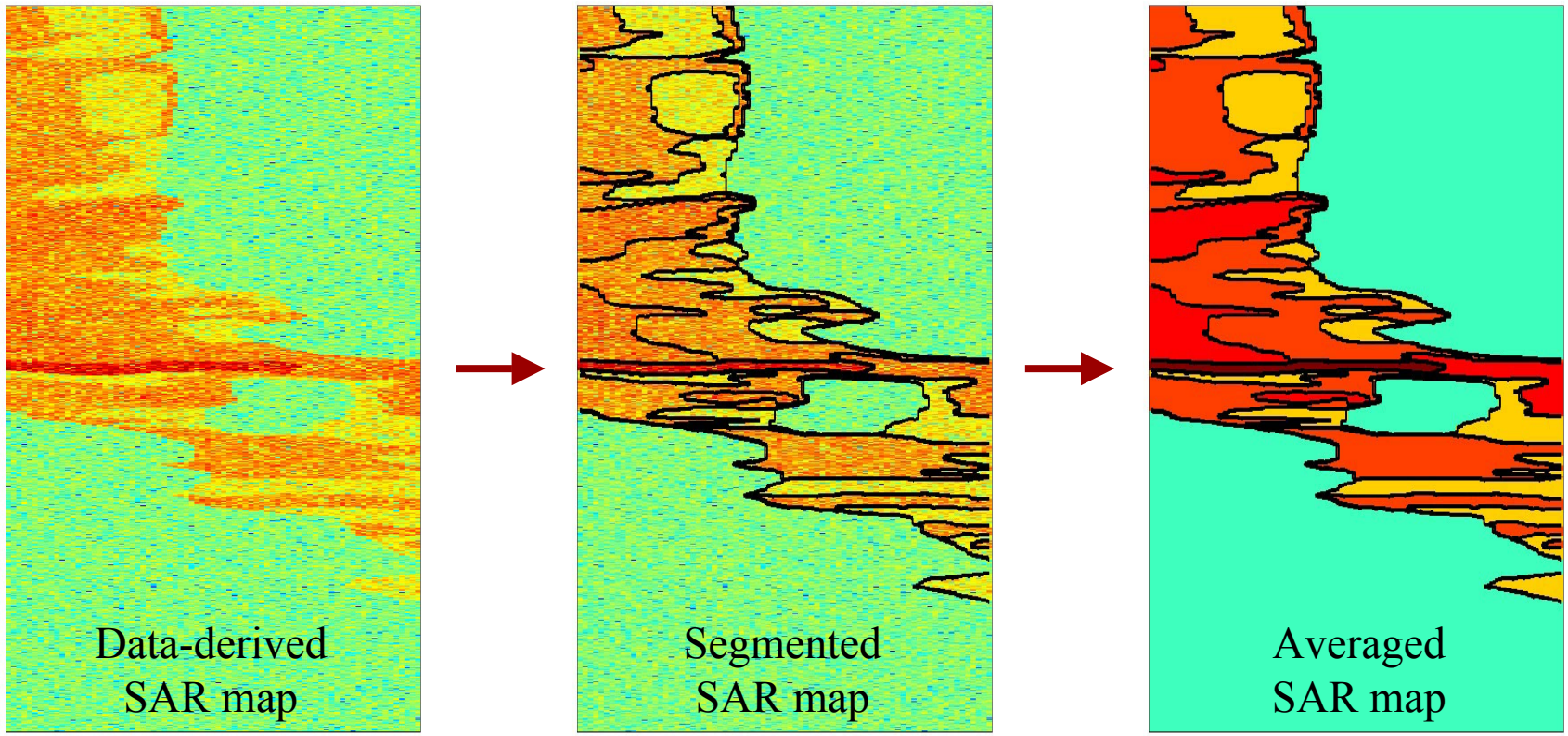
SAR is an Estimate of Clutter

- SAR, by definition, produces an estimate of clutter power as a function of range and Doppler frequency.

  SAR $\rightarrow$ $\hat{\sigma}_c(x, r)$ ($x \rightarrow f_d$ for given r)

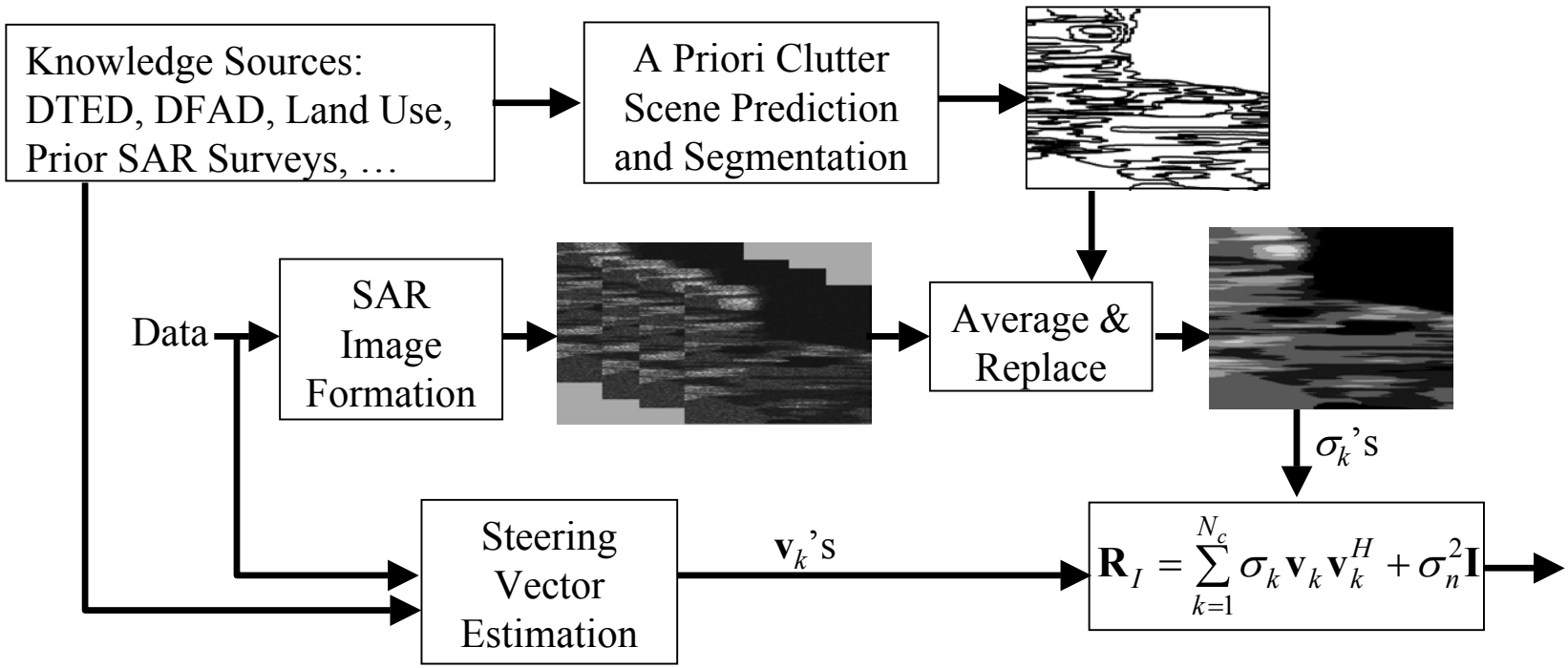
- So why not use $\hat{\sigma}_c(x, r_0)$ as our clutter estimate?
  - We can't use directly because of speckle. That is, $\hat{\sigma}_c(x, r_0)$ by itself is not a good estimate of $E[\sigma_c(x)]$.
  - We wouldn't know if fluctuations were due to speckle or due to slow-moving targets leaking into the SAR images.
  - We must average.
- But we don't want to average the same spectral frequencies, we want to average based on similar scattering statistics.

KA Segmentation and Averaging



- Knowledge-aided segmentation into homogeneous scattering regions.
- Rather than average the same angle-Doppler components, average within the boundaries of a region.
- “Average by numbers”.
- Space-time steering vectors are needed to transform to data domain.

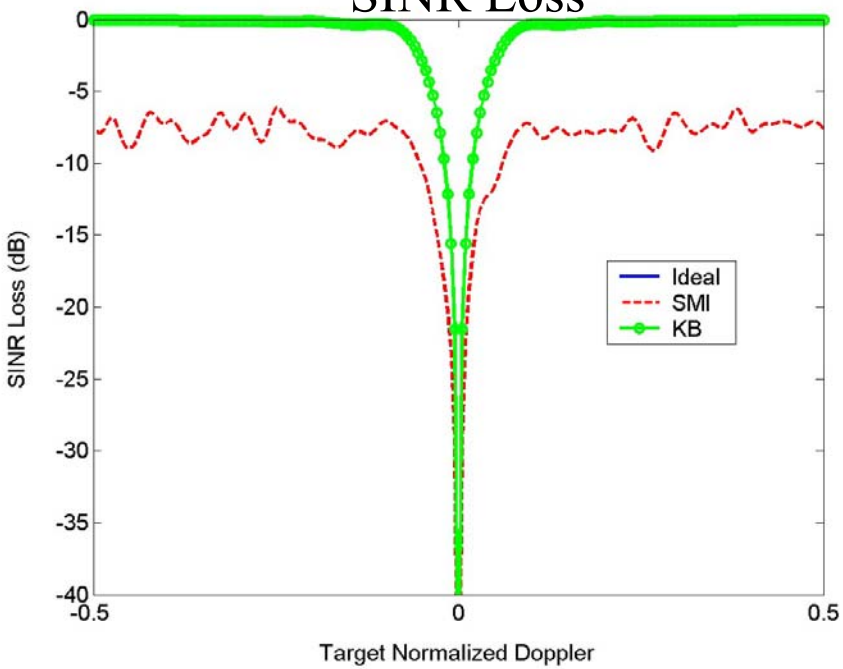
Proposed Architecture



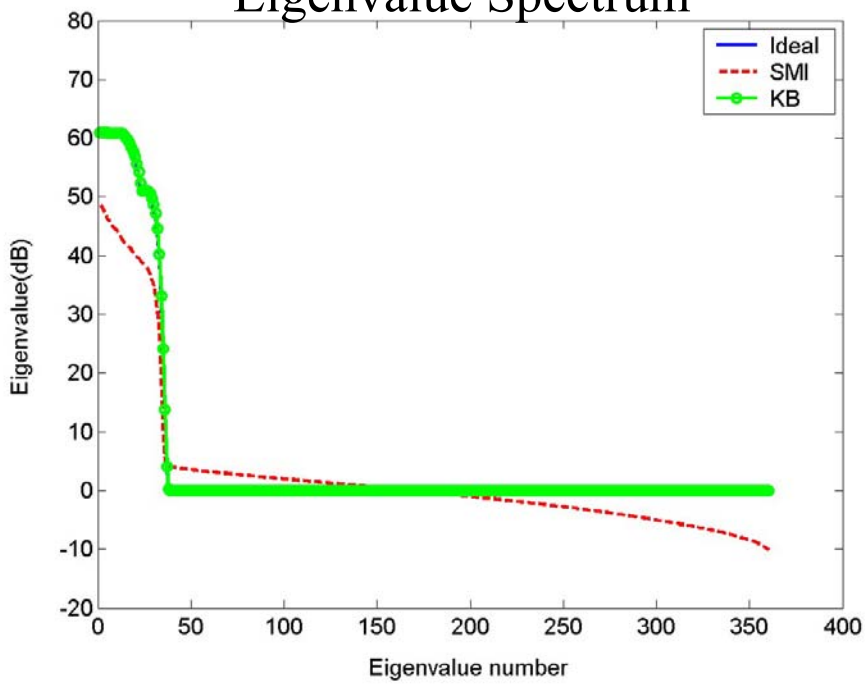
- Use knowledge sources to compute a priori segmentations, then fit the segmentations to real-time SAR maps.
- Use knowledge and real-time data to estimate steering vectors.

Example – Perfect Knowledge

SINR Loss



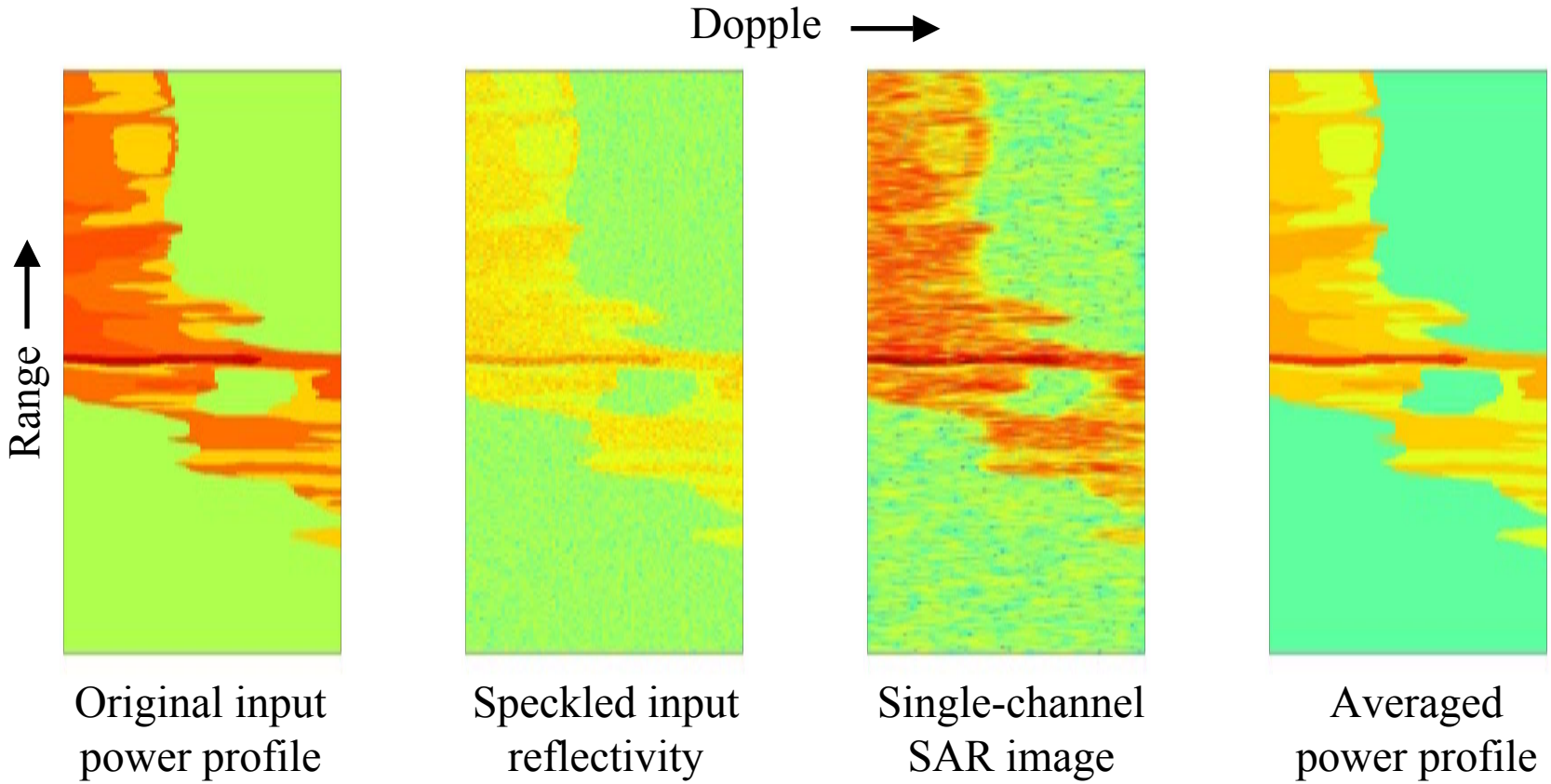
Eigenvalue Spectrum



- Ideal segmentation and averaging.
- No crab or ICM.
- Perfect ownship knowledge.
- Known noise floor.
- CNR ≈ 47 dB. (RUT)

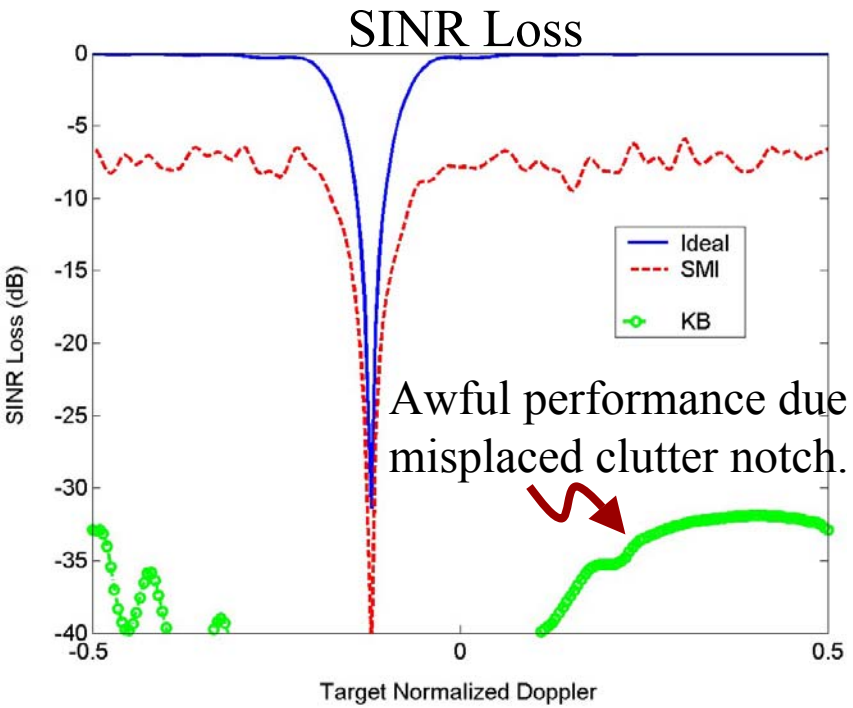
- Partial improvement due to ideal noise floor.
- Also improvement due to improved clutter estimation.
  - Seen in the eigenspectrum.

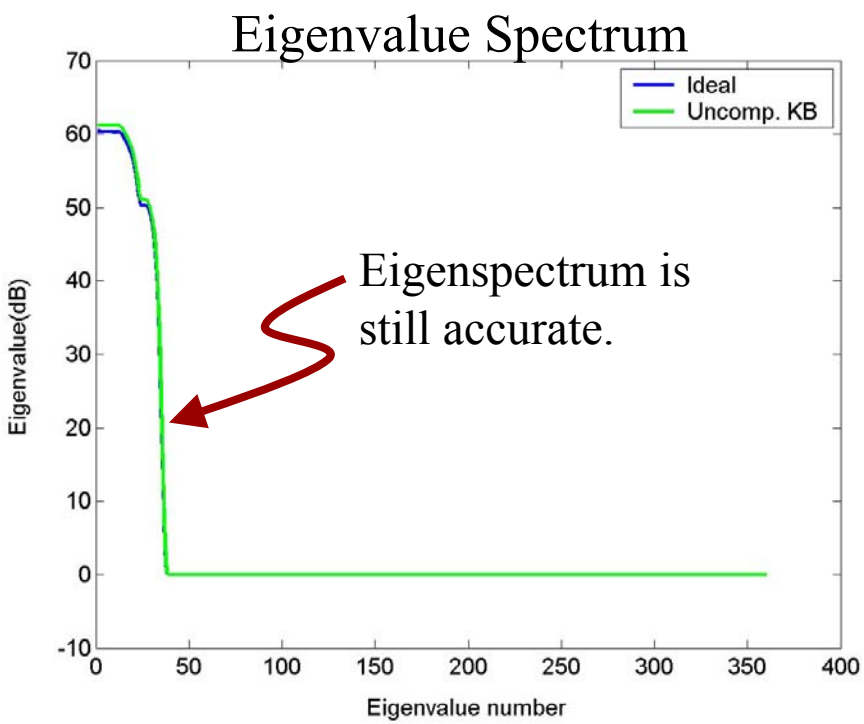
Single-Channel Averaging Results



- Final averaged profile is slightly biased due to Doppler sidelobes in the image formation process.
- Good performance, but what happens if finite-precision knowledge causes steering vector error?

Performance with Platform Crab

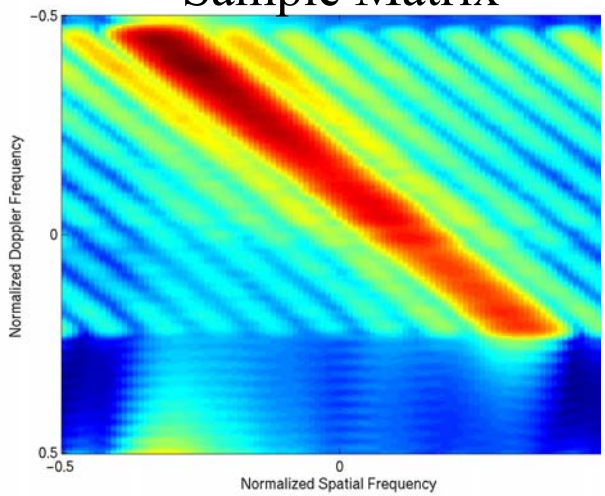




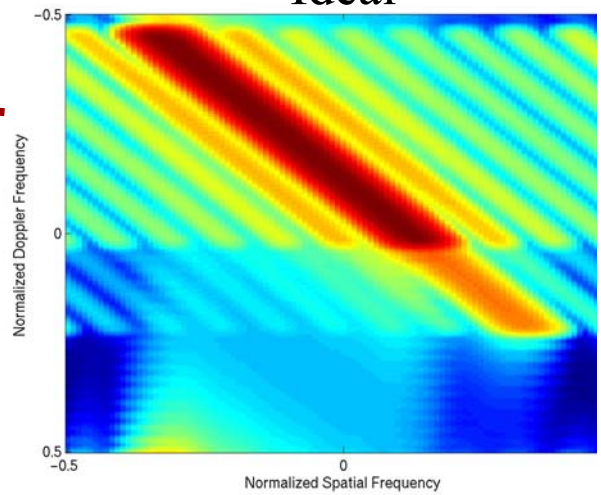
- Results shown for 3.5° actual crab angle. KB computed for 0° crab.
- Performance very sensitive to imperfect crab knowledge due to narrow clutter notch and narrow clutter ridge.
- Eigenspectrum relatively unchanged – error is in the steering vectors.
- Sensitivity will decrease when ICM is present.

Angle-Doppler Clutter Spectra

Sample Matrix

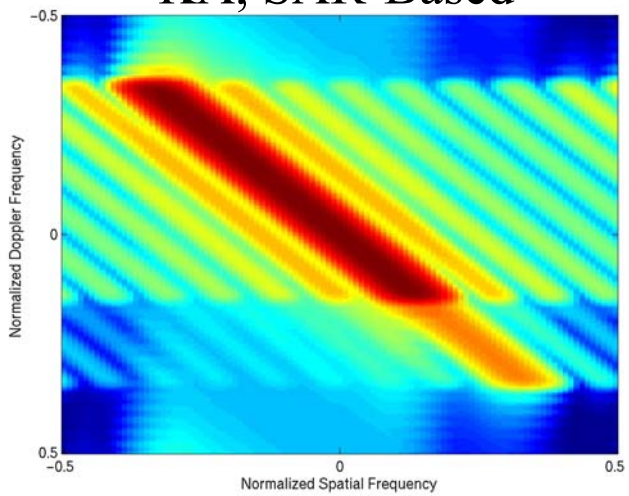


Ideal



Correct location of clutter ridge, but incorrect power distribution

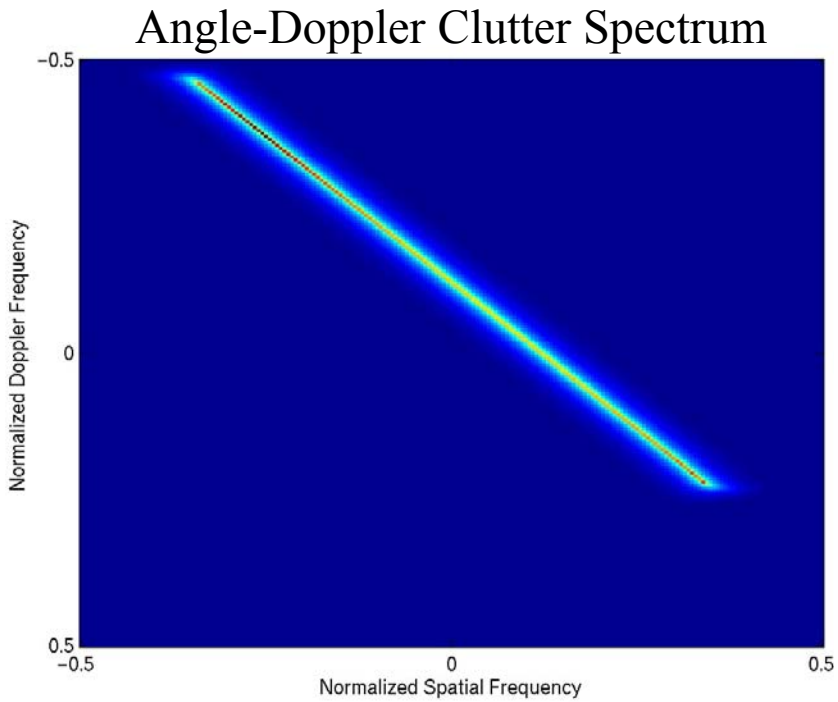
KA, SAR-Based

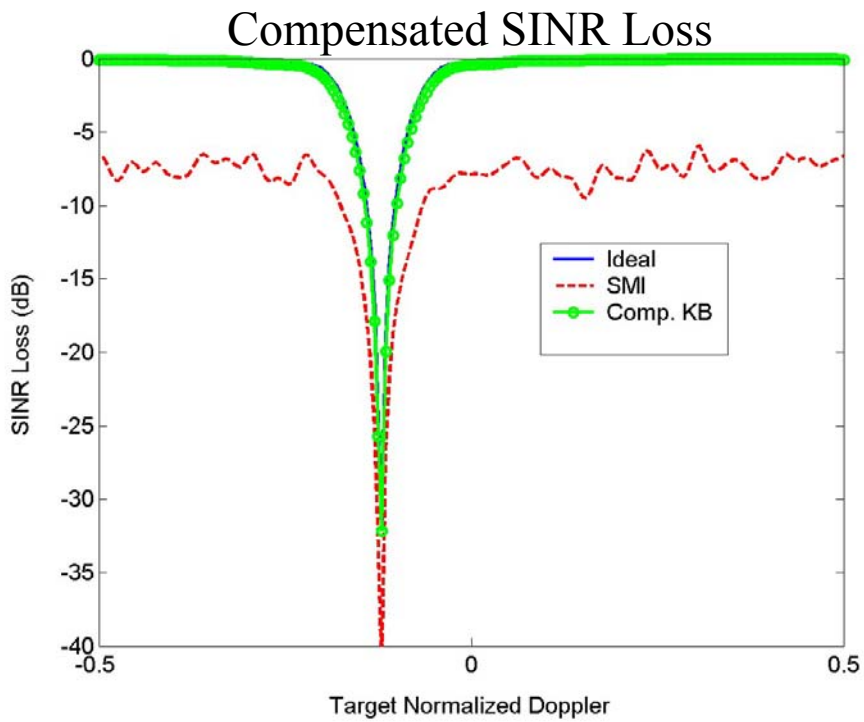


Correct distribution, but clutter ridge is shifted from ideal

- With uncompensated or inaccurate crab angle, clutter ridge is shifted
  ⇒ clutter notch misses its mark.

Data-Derived Crab Estimate

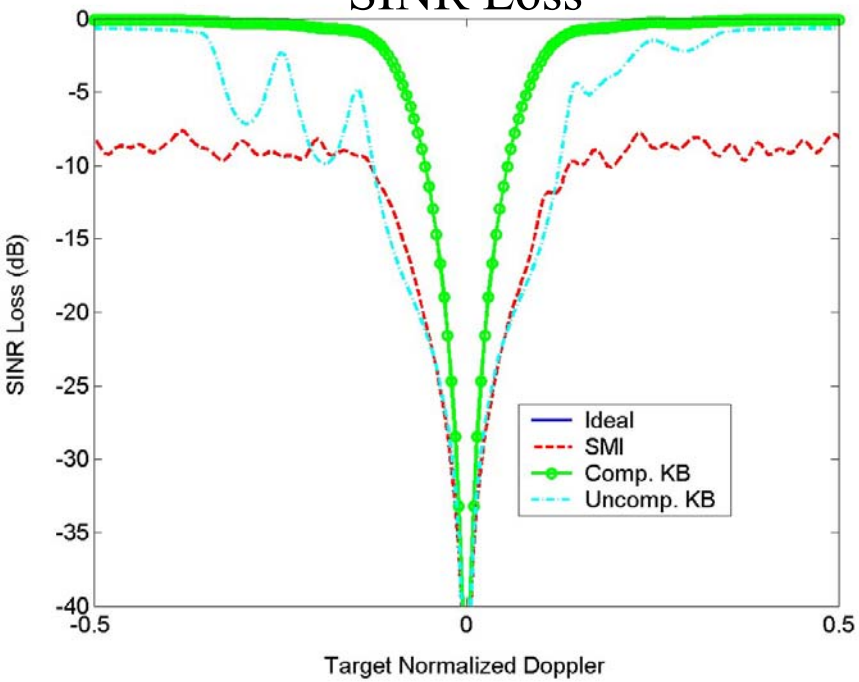




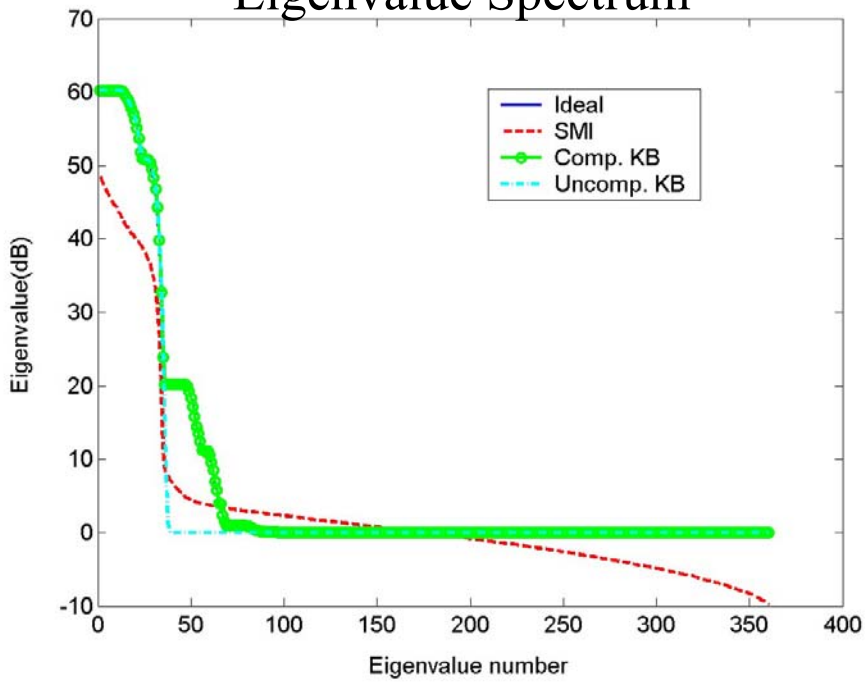
- Used clutter rank estimate to divide sample covariance matrix into *clutter+noise* and *noise only* subspaces.
- Find superresolution estimate of clutter ridge in angle-Doppler.
- Calculate crab angle. Very accurate estimates for high CNR.

Performance with ICM

SINR Loss

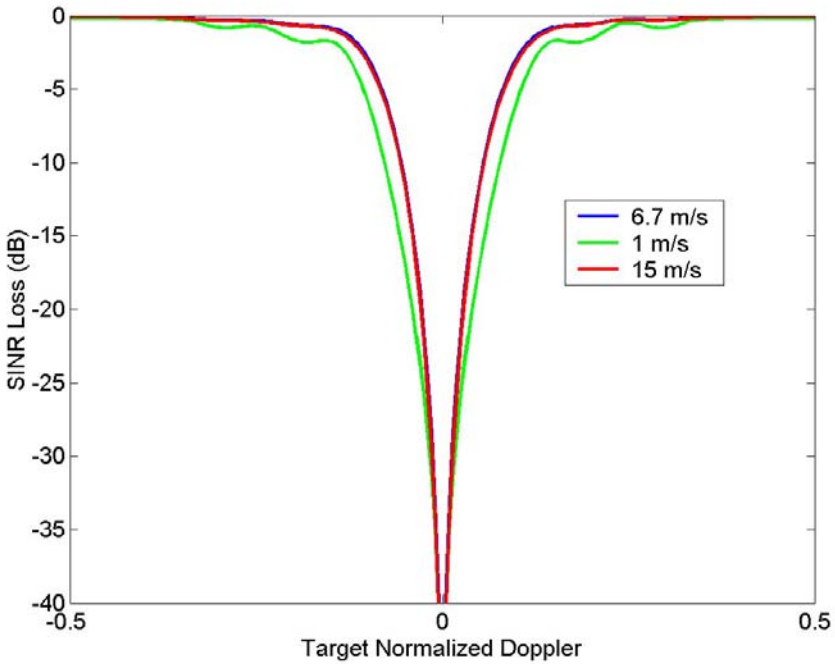


Eigenvalue Spectrum



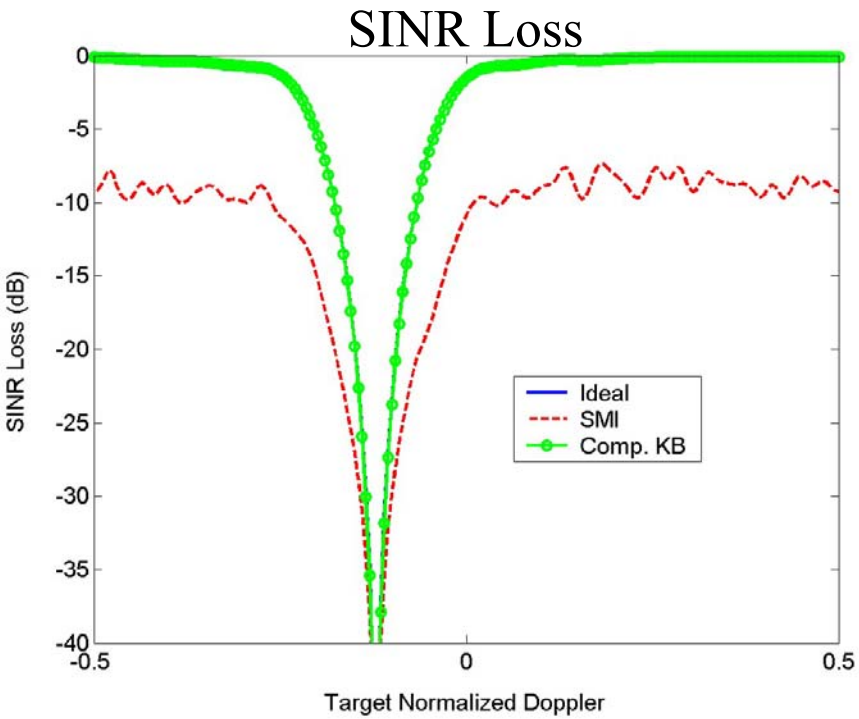
- Results shown for ICM, exponential model, wind speed = 15 mph (6.7 m/s).
- ICM increases the width of the clutter ridge through temporal clutter modulation.
- Can be accounted for in our SAR-based approach through use of a covariance matrix taper.

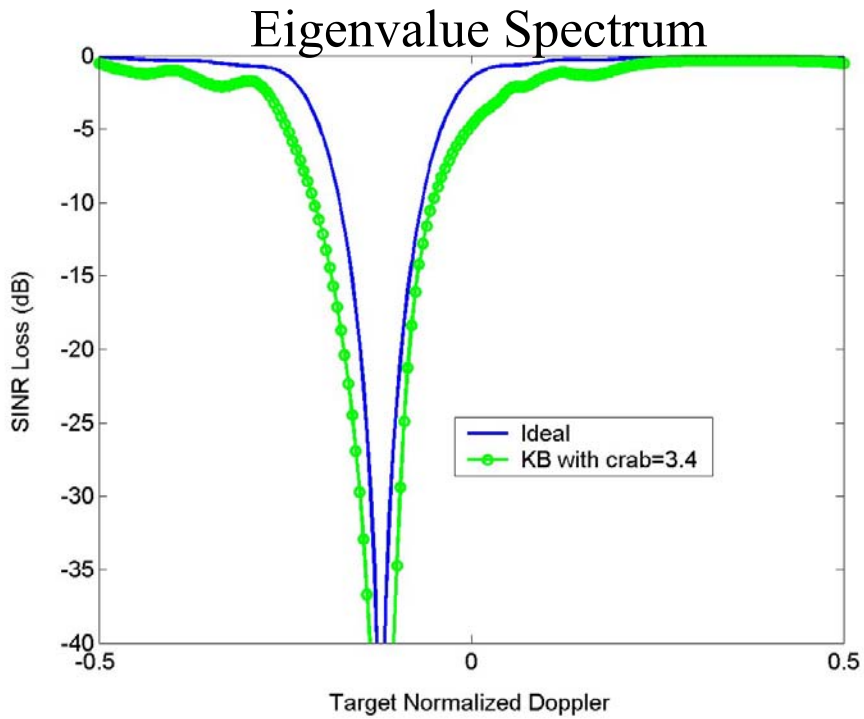
Sensitivity to ICM



- Not very sensitive to imperfect knowledge.

ICM and Platform Crab





- Crab angle computed from data ⇒ used in calculating steering vectors.
- CMT applied to account for ICM.
- Reduced sensitivity to crab mismatch, but still requires an accurate crab estimate.

Future Work

- More model fidelity.
  - Compensate for illumination pattern in SAR averaging.
- Issues with SAR image formation.
  - Automated scaling.
  - Multi-channel images (to remove moving targets from image?).
  - Optimum temporal windows – limit sidelobe leakage across region boundaries.
- More practical factors/issues.
- Mathematical framework.
  - Gerlach and Picciolo? – incorporate our method as an a priori covariance estimate?
- Jammers.
- Combine with reduced-dimension and other techniques.
  - Extraction of clutter discretes and targets in the training data.

Conclusions

- We feel that the proposed spectral-averaging/SAR-based approach naturally provides a mechanism for including a priori knowledge through site-specific clutter prediction.
- Future work should show compatibility with reduced-dimension techniques and other knowledge-aided approaches.
- Could potentially see a significant performance improvement, but…
- Some practical issues need to be addressed. How much improvement is feasible in the presence of many real-world limitations?

- Questions?