June 2024

ISART™ 2024: In Pursuit of Consensus on Clutter

An Overview of Radar Clutter

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Preface

To: Melvin, Bill <william.melvin@gtri.gatech.edu>
Cc: Glenn, Jeremy <jglenn@ntia.gov>; Dietlein, Charles <cdietlein@ntia.gov>; Kozma, William <WKozma@ntia.gov>
Subject: RE: [ISART 2024] Technical Talk on Radar Clutter

Bill:

In the propagation world, "clutter" is everything that sits on top of the bare earth, e.g., buildings, vegetation. Clutter propagation loss has been a source of policy-level debate. Without trustworthy (validated) clutter propagation models in the interference link budget, conservative rules have been adopted (e.g., CBRS) with large margins. This results in low probability of interference but underutilization of the spectrum resource. More recently, the pendulum has swung back the other way and high clutter propagation loss is being assumed as a measure to reduce conservative margins. There is increased probability of interference in this scenario and subsequent reduced utilization of the CBRS band.

Goals for the radar clutter technical presentation at ISART:

1. Acknowledge difference in definition/terminology between radar clutter v clutter propagation
2. Illustrate high spectrum utilization gained by good technology and engineering practices (mitigation of radar clutter/interference by leveraging DOF), in contrast to low spectrum utilization due to lack of good engineering practices

Thanks,
Mike

- Goals:
  - Discuss radar clutter, clutter modeling, and impact on radar detection
  - Discuss radar clutter mitigation leveraging multidimensional degrees of freedom (DoFs)
- We have ½ hour, plus 15 minutes for Q&A…
  - I'll use aerospace radar to motivate our discussion
    - Surface radar systems are a special case where platform velocity and height go to ~zero

Topics

- Introduction
- Radar clutter
- Detection processing and metrics
- Space-time adaptive processing
- Summary

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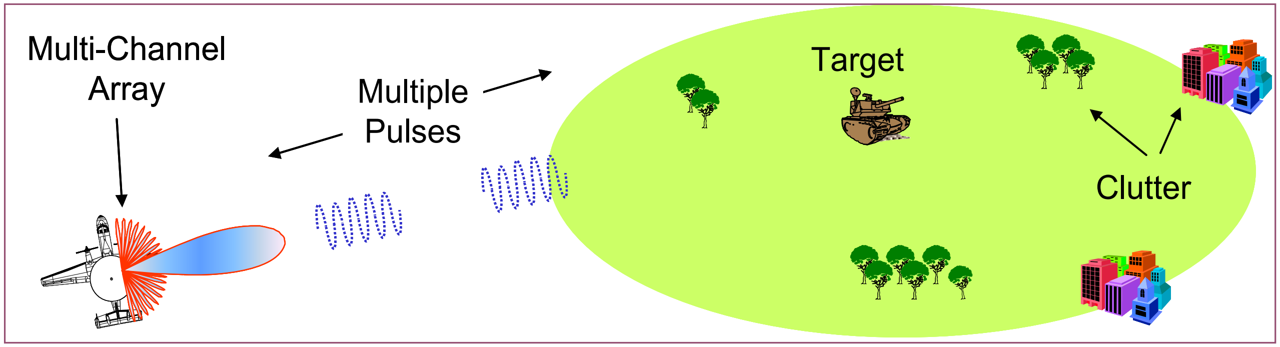
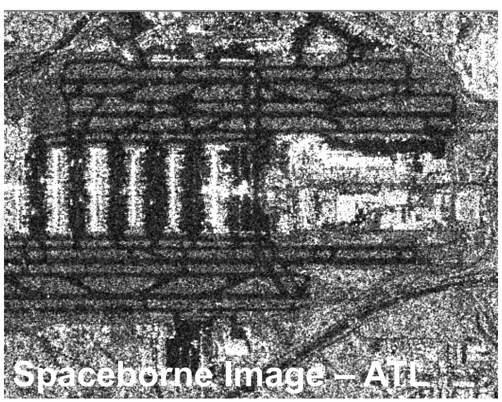
Some Basic Radar Comments

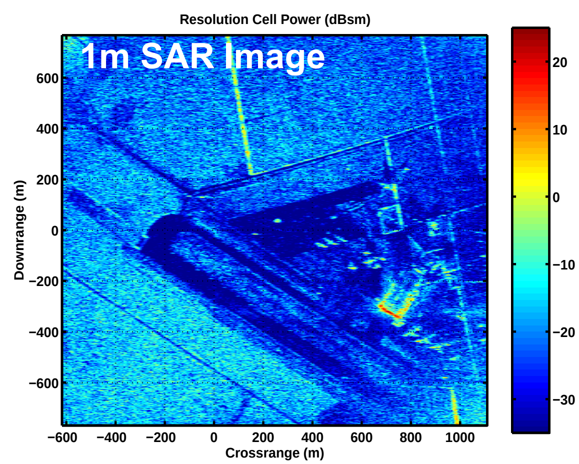
- Radar systems strive to achieve noise-limited detection performance → maximize signal-to-noise ratio (SNR)
- Radar systems employ complex designs to mitigate radio frequency interference (RFI) and clutter → maximize signal-to-interference-plus-noise ratio (SINR)
  - Exploiting radar degrees of freedom (DoFs) is a central
    - Spatial frequency, polarization, fast-time, multi-pass
    - Waveform attributes
    - Resource management
  - SNR >= SINR
- "One person's clutter is another's target"
  - For this discussion, we'll stick with Doppler-spread ground clutter impeding target detection

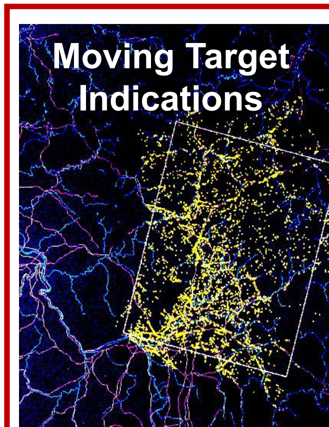
Coherent Radar Signal Processing



Combine thousands of voltages collected using a pulsed, multichannel sensor to detect (1) moving targets, (2) image fixed targets, or (3) determine changes in a scene from a prior pass → sophisticated algorithms generate radar product







Our present focus

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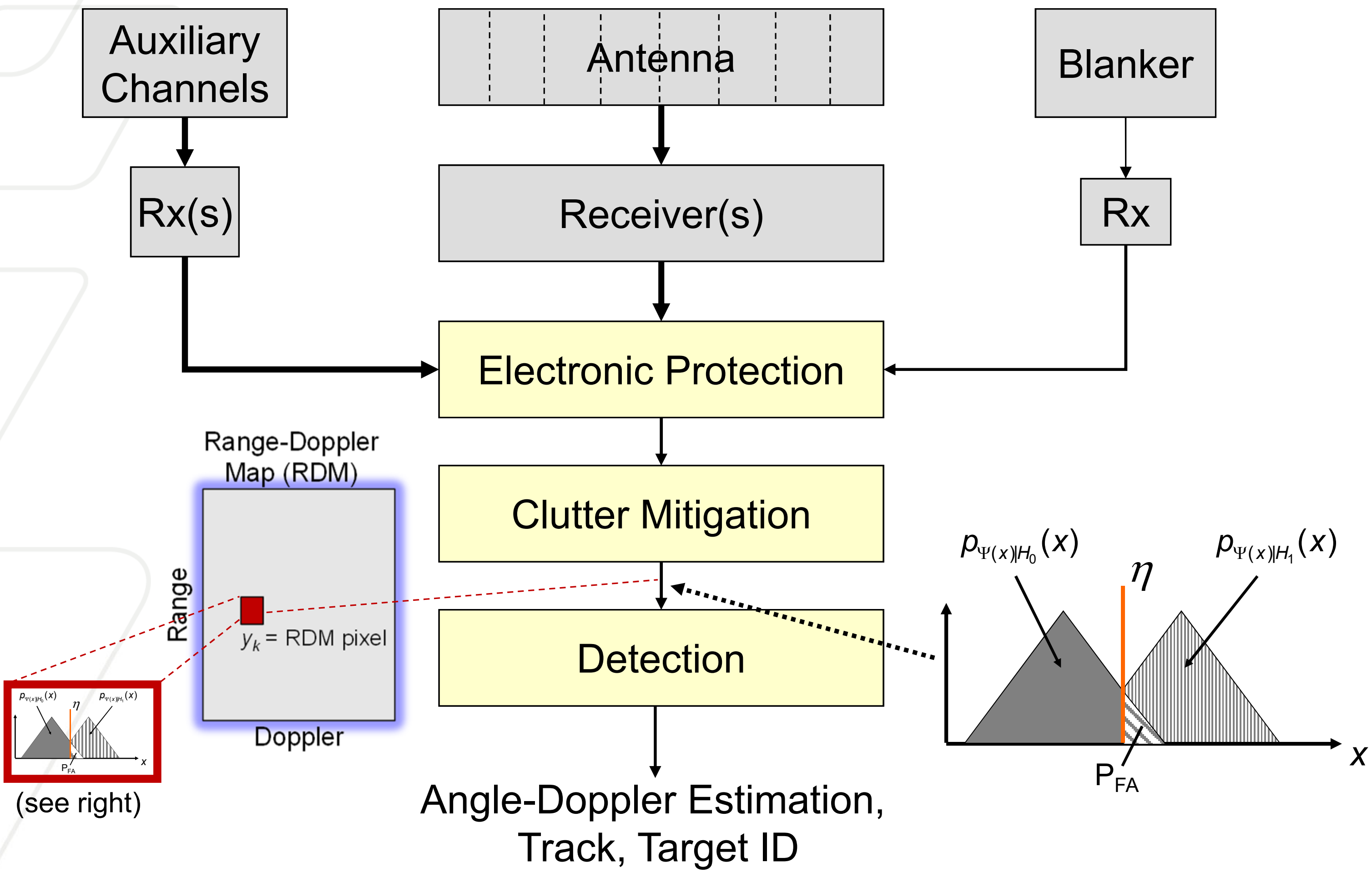
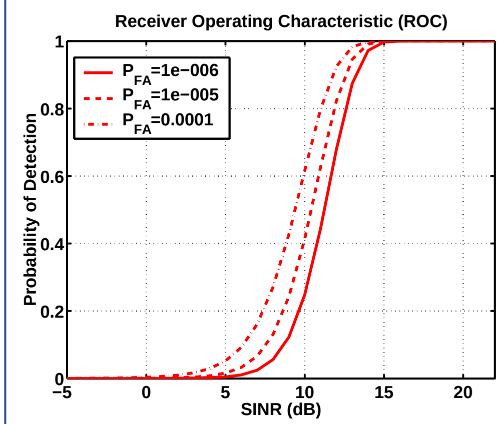
Multidimensional Radar Signal Processing [1-2]

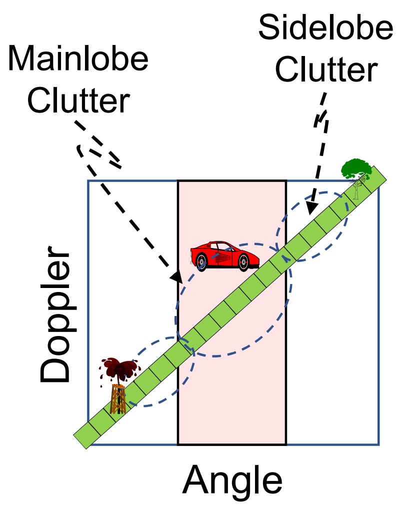


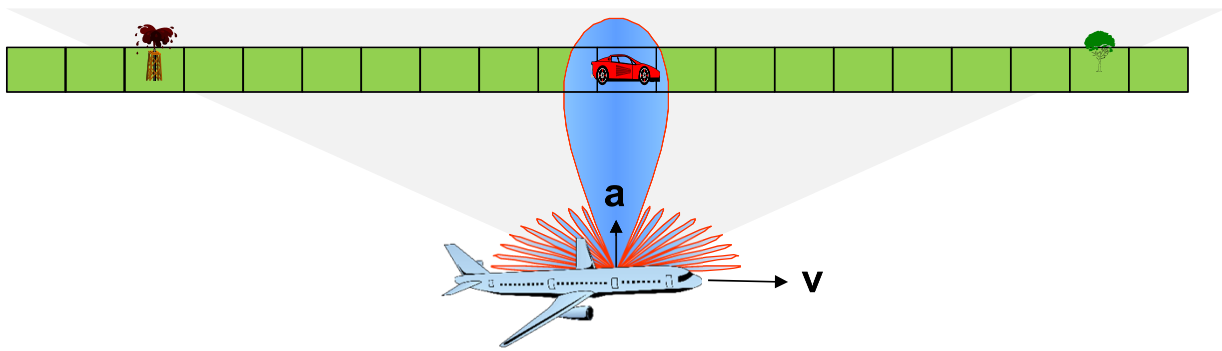
Goal: maximize detection performance by maximizing output SINR



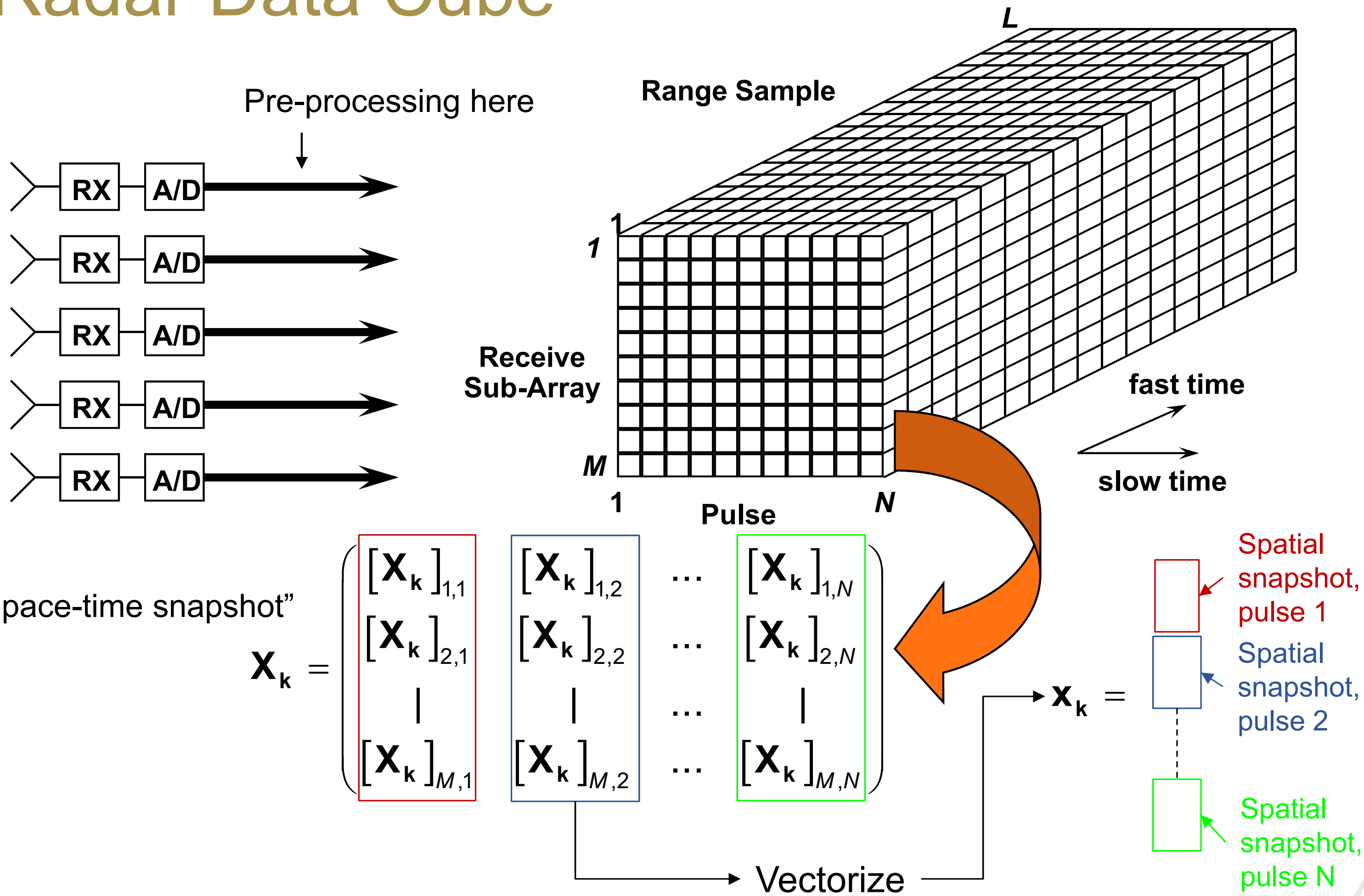
Clutter-Limited Detection [2-10]

- Doppler-spread mainlobe clutter masks slow moving targets, sidelobe clutter degrades detection of targets at higher range rates
- Stationary clutter response is coupled in angle and Doppler
  - Specifying angle uniquely specifies Doppler and vice versa
- Detection statistic objective: discriminate the target's angle-Doppler response from that of the stationary clutter background





The Radar Data Cube



$$\mathbf{X}_k = \begin{pmatrix} [\mathbf{X}_k]_{1,1} & [\mathbf{X}_k]_{1,2} & \cdots & [\mathbf{X}_k]_{1,N} \\ [\mathbf{X}_k]_{2,1} & [\mathbf{X}_k]_{2,2} & \cdots & [\mathbf{X}_k]_{2,N} \\ | & | & \cdots & | \\ [\mathbf{X}_k]_{M,1} & [\mathbf{X}_k]_{M,2} & \cdots & [\mathbf{X}_k]_{M,N} \end{pmatrix}$$

$$\mathbf{x}_k =$$

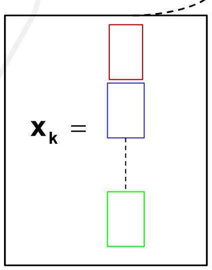
Space-Time Signal Vector

Response of pulse-Doppler array to a unity amplitude signal with a specific direction of arrival and Doppler frequency

Temporal steering vector — Spatial steering vector

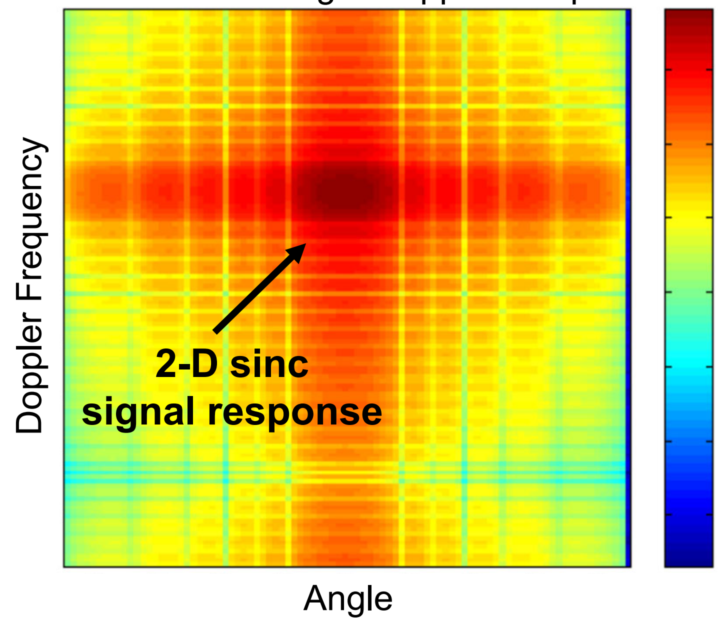
$$\mathbf{s}_{\mathbf{s\text{-}t}}(\gamma_s,\tilde{f}_d) = \mathbf{s}_{\mathbf{t}}(\tilde{f}_d) \otimes \mathbf{s}_{\mathbf{s}}(\gamma_s)$$

$$\mathbf{s}_{\mathbf{s\text{-}t}}(\gamma_s,\tilde{f}_d) = \begin{bmatrix} 1 \cdot \mathbf{s}_{\mathbf{s}}(\gamma_s) \\ e^{j\tilde{f}_d} \cdot \mathbf{s}_{\mathbf{s}}(\gamma_s) \\ \vdots \\ e^{j(N-1)\tilde{f}_d} \cdot \mathbf{s}_{\mathbf{s}}(\gamma_s) \end{bmatrix}$$



Kronecker product replicates data formatting

Point Scatterer Angle-Doppler Response



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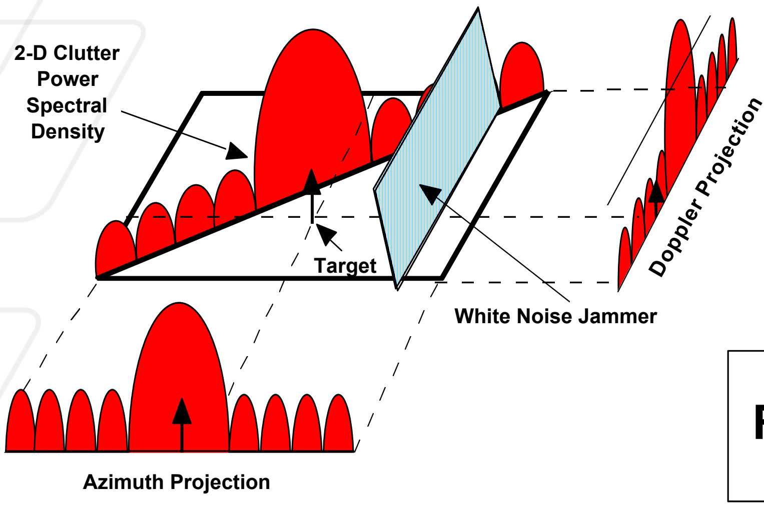
Basic Ground Clutter Model [6-9]



Voltage due to m[th] patch, n[th] range ambiguity

$$\mathbf{c_k} = \sum_{m=1}^{N_c} \sum_{n=1}^{N_a} \alpha_{m,n} \mathbf{s_{s\text{-}t}}(\gamma_{s/m,n}, \tilde{f}_{d/m,n})$$

Space-time steering vector

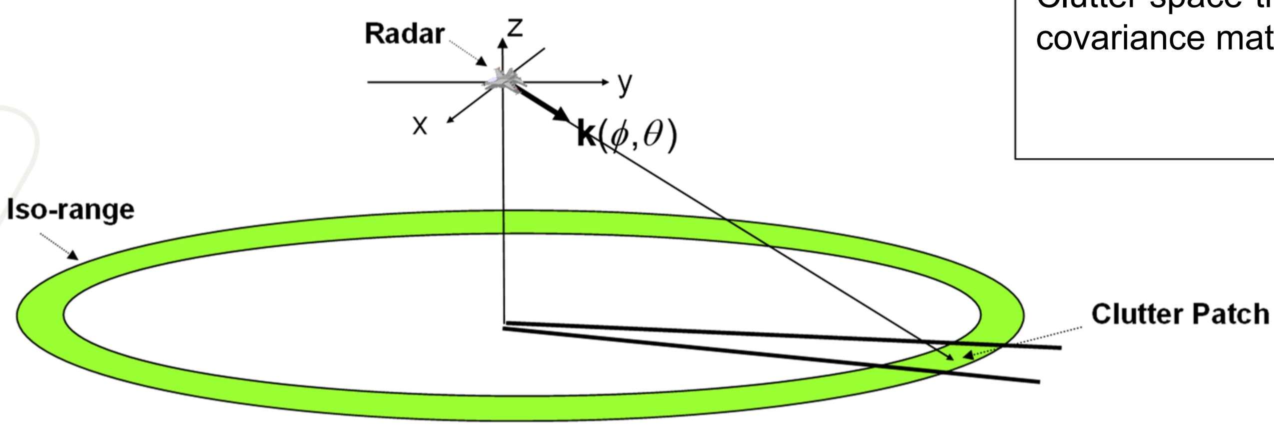
$$\mathbf{R}_{\mathbf{c/k}} = \sum_{m=1}^{N_c} \sum_{n=1}^{N_a} \sigma_{m,n}^2 \mathbf{s_{s\text{-}t}}(\gamma_{s/m,n}, \tilde{f}_{d/m,n}) \mathbf{s}_{\mathbf{s\text{-}t}}^H(\gamma_{s/m,n}, \tilde{f}_{d/m,n})$$

Clutter space-time covariance matrix

Clutter patch power

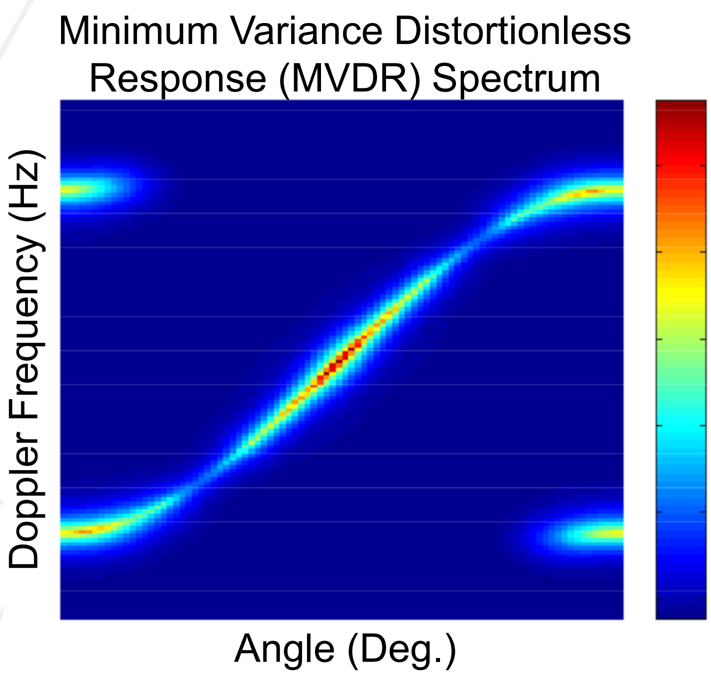
$$\sigma_{m,n}^2 = E\left[\left|\alpha_{m,n}\right|^2\right]$$

N_c = azimuthal granularity
N_a = # of range ambiguities
Narrowband Case

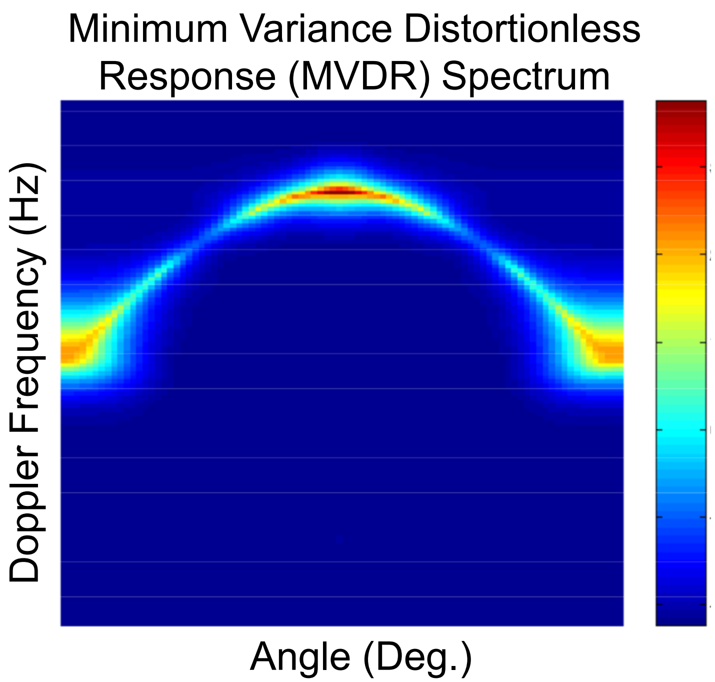


Angle-Doppler Characteristics for Side and Forward Looking Arrays

Side-Looking Array Radar (SLAR)



Forward-Looking Array Radar (FLAR)



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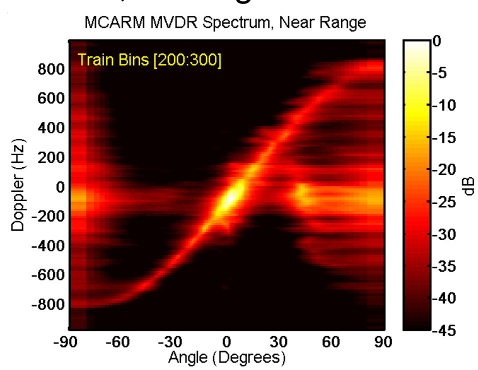
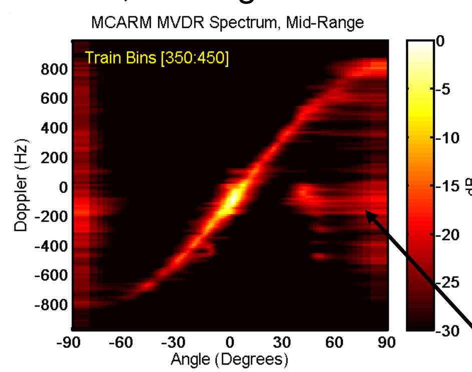
Multi-Channel Airborne Radar Measurements (MCARM) [13]

Measured MCARM MVDR spectrum estimate, training bins 200 to 300



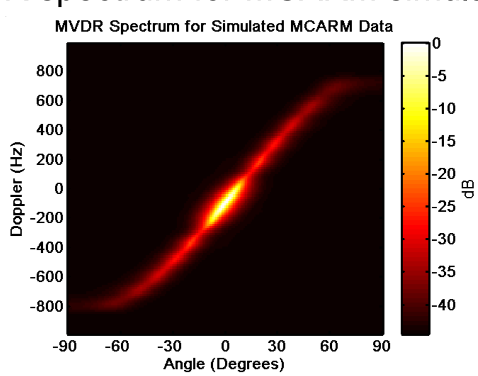
Measured MCARM MVDR spectrum estimate, training bins 350 to 450



Multipath from port-mounted radome struts

24 Channel, L-Band Radar Mounted on BAC 1-11

MVDR spectrum for MCARM simulation



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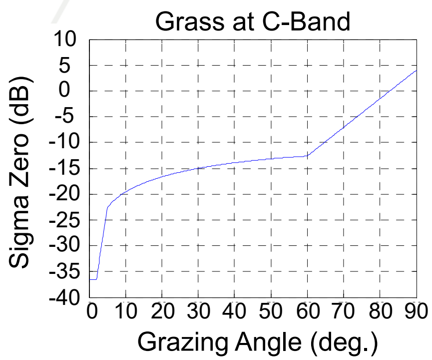
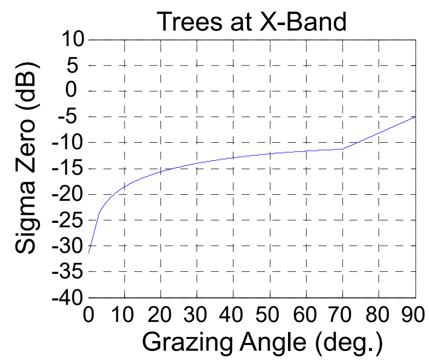
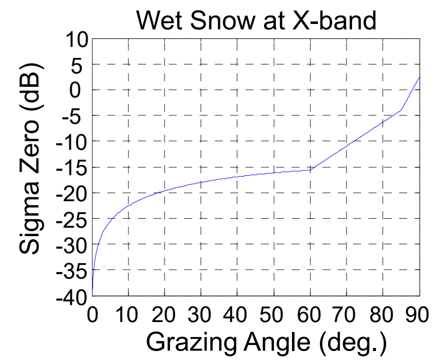
Clutter Sigma Zero and Reflectivity*

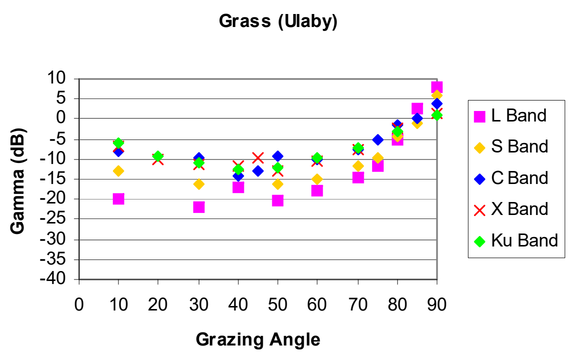
Sigma Zero

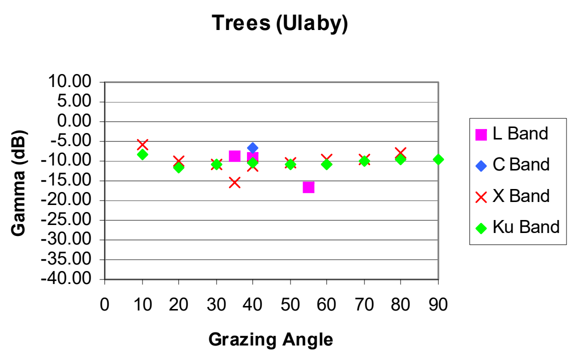


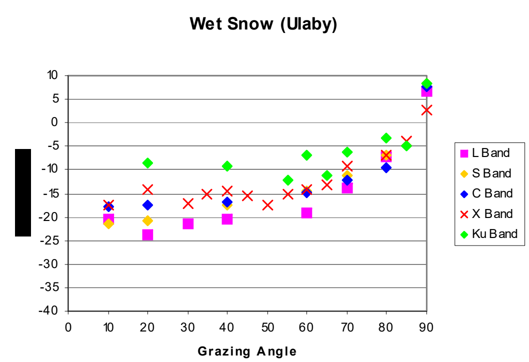




Reflectivity







* Compliments of Dr. Byron Keel, Georgia Tech Research Institute

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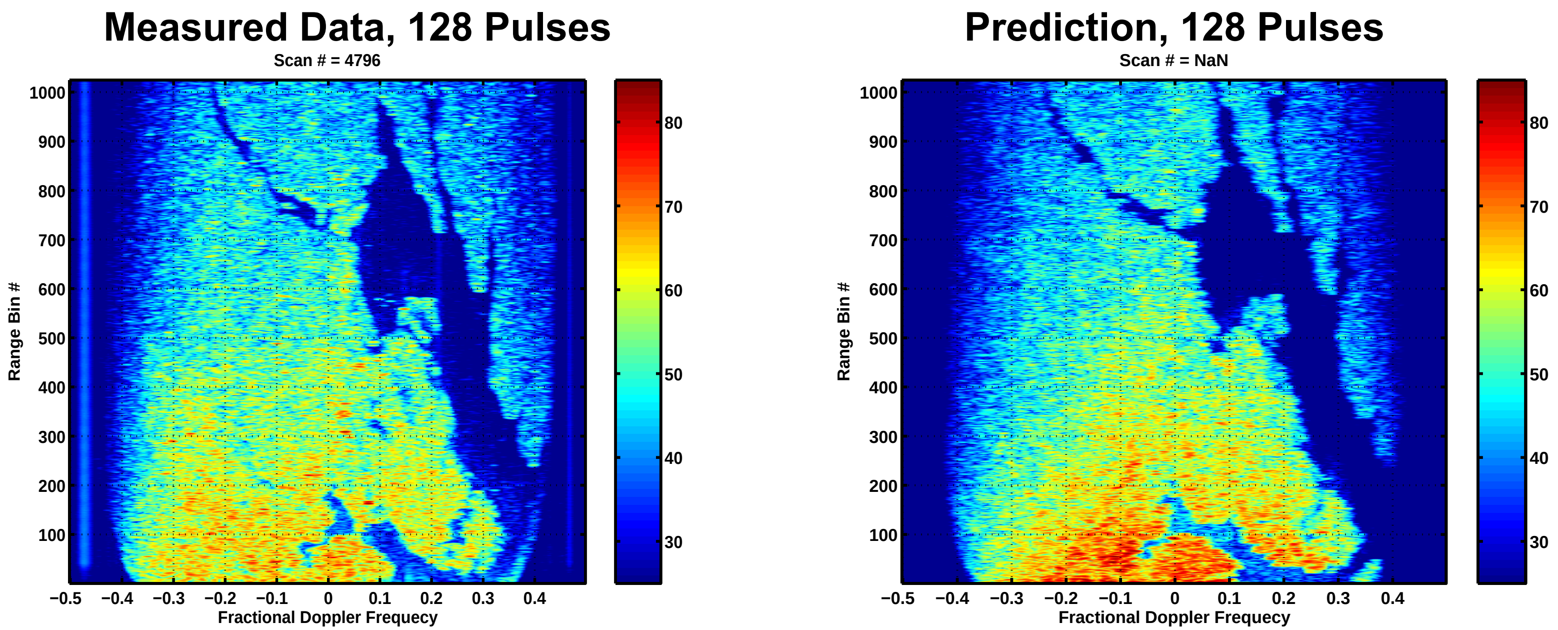
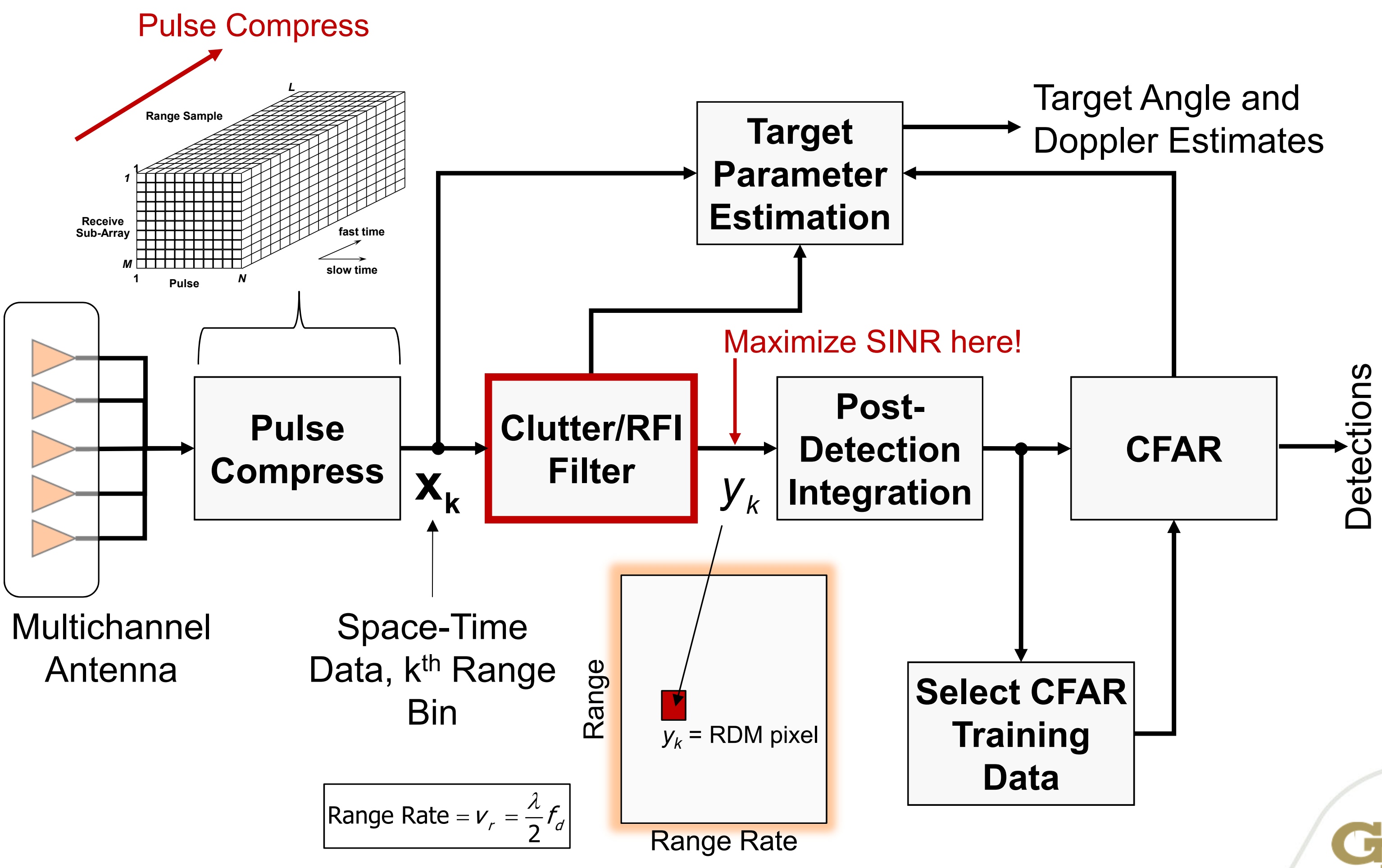
FOPEN Radar Range-Doppler Comparison



- Active targets (repeaters) in exo-clutter regions
- Radar saturates at near ranges
- Key element of knowledge-aided clutter mitigation techniques [12]
- FOPEN = foliage penetrating

Generic Radar Detection Processing Architecture



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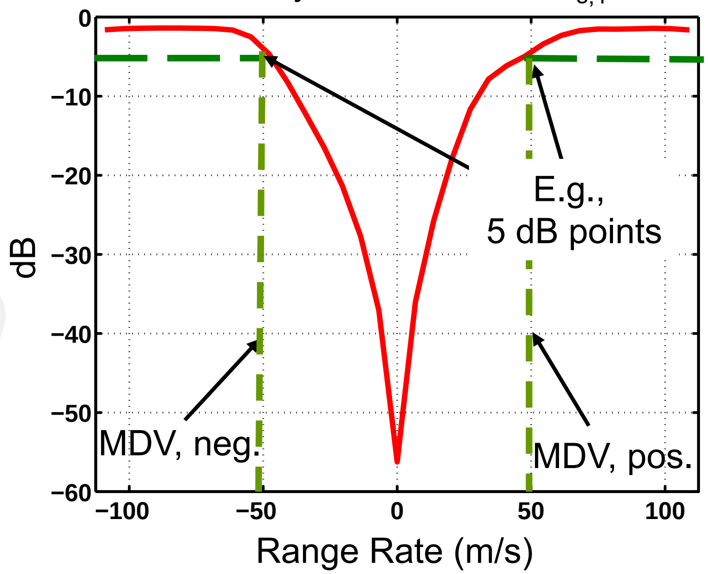
SINR Loss [6-8,11]

In Gaussian disturbance case, SINR relates directly to P_D and P_{FA} → SINR Loss is a key metric

$$SINR\left(\gamma_s,\tilde{f}_d\right) = \underbrace{SNR(\gamma_s)}_{\text{Noise-Limited, RRE}} \cdot \underbrace{\left(\frac{SINR_{clairvoyant}(\gamma_s,\tilde{f}_d)}{SNR(\gamma_s)}\right)}_{L_{s,1}(\gamma_s,\tilde{f}_d)} \cdot \underbrace{\left(\frac{SINR_{adaptive}(\gamma_s,\tilde{f}_d)}{SINR_{clairvoyant}(\gamma_s,\tilde{f}_d)}\right)}_{L_{s,2}(\gamma_s,\tilde{f}_d)}$$

Clairvoyant SINR Loss, $L_{s,1}$



SNR: Determines noise-limited detection performance

$L_{s,1}$: SINR loss due to colored noise

$L_{s,2}$: Adaptive SINR Loss, the SINR degradation due to estimation losses

$$0 \leq L_{s,1},\ L_{s,2} \leq 1$$

- RRE = radar range equation
- MDV = minimum detectable velocity
- Clairvoyant → details for implementation known, e.g., covariance matrix known (Clairvoyant can imply optimal)

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The Maximum SINR Weight Vector [2-9]

Signal and I+N snapshots: $\mathbf{s}, \mathbf{x_n} \in C^{NMx1}$

Target signal: $\mathbf{s} = \alpha_T \mathbf{s_{s\text{-}t}}(\gamma_s, \tilde{f}_d)$; $\sigma_s^2 = E\left[\left|\alpha_T / \sqrt{2}\right|^2\right]$

Interference-plus-noise signal: $\mathbf{x_n} \sim CN(\mathbf{0}, \mathbf{R_n} = \mathbf{R_{H_0}} = \mathbf{R_k})$

$$SINR = \frac{P_s}{P_n} = \frac{E\left[y_s y_s^*\right]}{E\left[y_n y_n^*\right]} = \frac{E\left[\left(\mathbf{w}^H\mathbf{s}\right)\left(\mathbf{s}^H\mathbf{w}\right)\right]}{E\left[\left(\mathbf{w}^H\mathbf{x_n}\right)\left(\mathbf{x_n}^H\mathbf{w}\right)\right]} = \frac{\mathbf{w}^H\mathbf{R_s}\mathbf{w}}{\mathbf{w}^H\mathbf{R_n}\mathbf{w}}$$

$$= \sigma_s^2 \frac{\left|\tilde{\mathbf{w}}^H\tilde{\mathbf{s}}\right|^2}{\tilde{\mathbf{w}}^H\tilde{\mathbf{w}}} \le \sigma_s^2 \frac{\left(\tilde{\mathbf{w}}^H\tilde{\mathbf{w}}\right)\left(\tilde{\mathbf{s}}^H\tilde{\mathbf{s}}\right)}{\tilde{\mathbf{w}}^H\tilde{\mathbf{w}}}$$

$\mathbf{R_s} = \sigma_s^2 \mathbf{s_{s\text{-}t}} \mathbf{s_{s\text{-}t}}^H$

$y_s = \mathbf{w}^H\mathbf{s}$

$y_n = \mathbf{w}^H\mathbf{x_n}$

$$\tilde{\mathbf{w}} = \mathbf{R_n}^{1/2}\mathbf{w}; \quad \tilde{\mathbf{s}} = \mathbf{R_n}^{-1/2}\mathbf{s_{s\text{-}t}}(\gamma_s, \tilde{f}_d)$$

Achieves the upper bound when $\tilde{\mathbf{w}} = \tilde{\mathbf{s}}$, or $\mathbf{w} = \mu \mathbf{R_n}^{-1}\mathbf{s_{s\text{-}t}}(\gamma_s, \tilde{f}_d)$...

Arbitrary scalar

$$SINR_{\max} = \sigma_s^2 \mathbf{s_{s\text{-}t}}^H \mathbf{R_n}^{-1} \mathbf{s_{s\text{-}t}}$$

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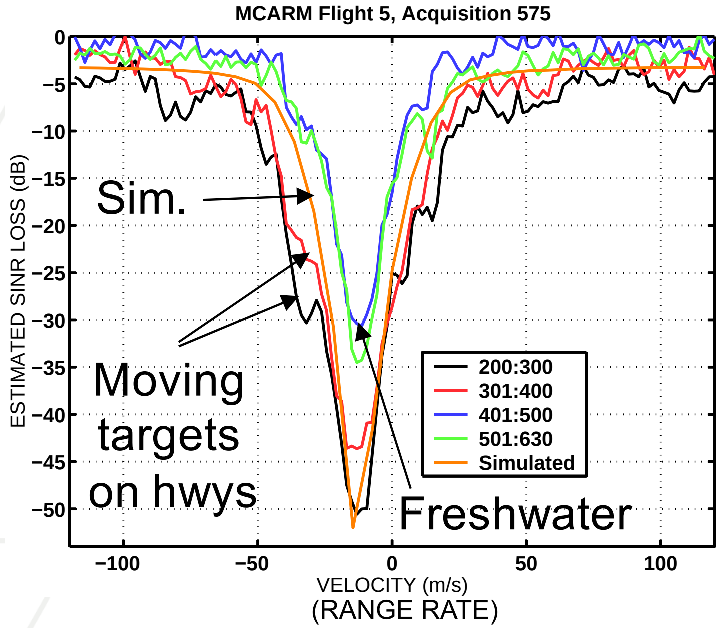
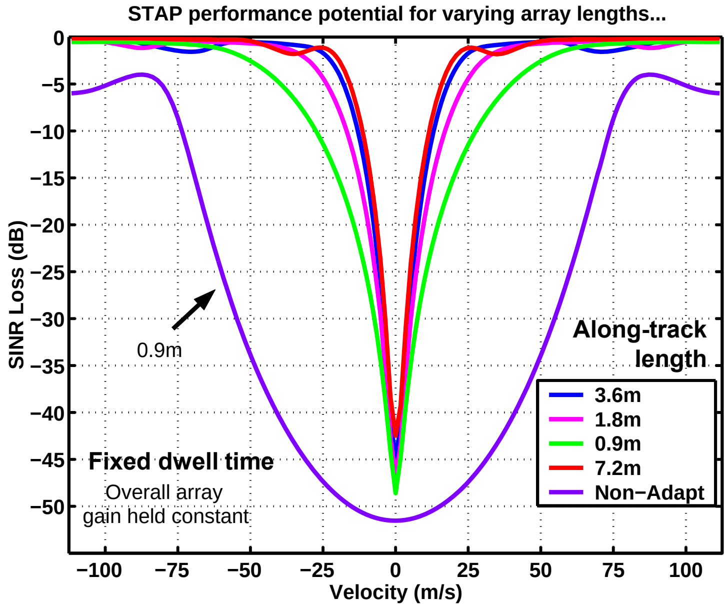
SINR Loss Examples

Estimated loss using MCARM data



- STAP versus non-STAP solution
- Impact of array length with STAP



Requirements to generate simulated response:
- Precise knowledge of platform velocity vector
- Platform pitch, roll and yaw
- Measured array normal

** See [12, 14] for additional info on heterogeneous clutter and solutions

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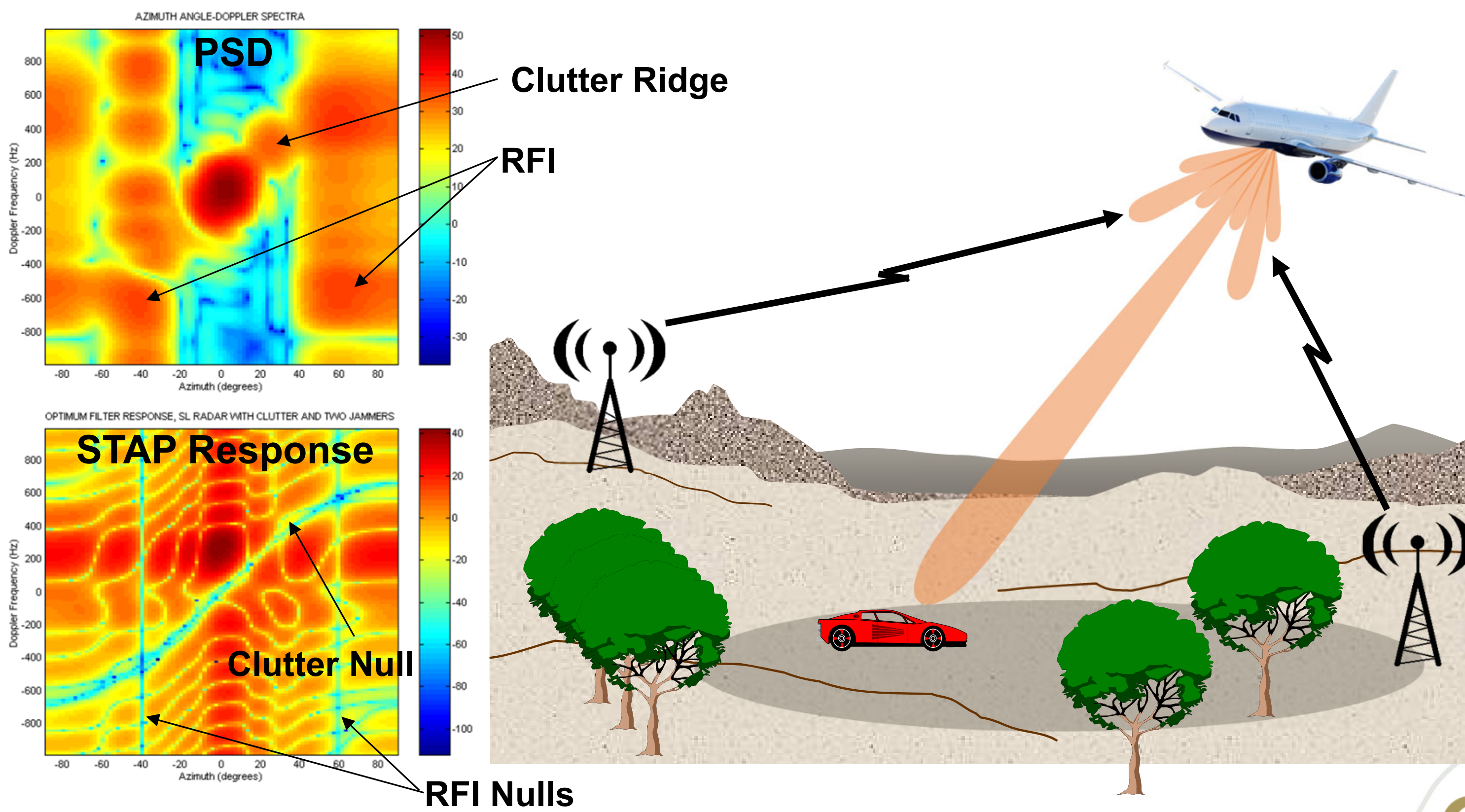
Space-Time Adaptive Processing (STAP)

Space-time adaptivity enables simultaneous clutter and RFI suppression **(Detection of interference-limited, moving targets)**



Summary

- Clutter → returns that are target-like, but aren't the target of interest
  - We talked about reflections from objects on the Earth's surface as viewed by an airborne or spaceborne radar (a.k.a., ground clutter)
- Ground clutter exhibits coupling in angle and Doppler, whereas moving target response has uncoupled angle and Doppler
- Radar systems incorporate complex mechanisms and approaches to mitigate the impact of clutter on system performance
  - Signal processing, antenna design, access to radar DoFs → STAP
    - STAP is a super-resolution technique; performance is often exceptional
  - Alternative approach is to resolve the target relative to the background clutter → this approach requires more bandwidth, time, and complex processing
- Ground clutter can be very complicated → spatially-varying clutter, clutter discretes, dense moving targets (heterogenous clutter impacts detection performance [14])

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Questions?

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References

[1] D.H. Johnson and D.E. Dudgeon, Array Signal Processing: Concepts and Techniques, Prentice-Hall, Englewood Cliffs, NJ, 1993.

[2] L.E. Brennan and I.S. Reed, "Theory of adaptive radar," *IEEE Trans. AES*, Vol. 9, No. 2, March 1973, pp. 237-252.

[3] R. Klemm, Space-Time Adaptive Processing: Principles and Applications, IEE Radar, Sonar, Navigation and Avionics 9, IEE Press, 1998.

[4] R. Klemm, Principles of Space-Time Adaptive Processing, 2nd Ed., IEE Radar, Sonar, Navigation and Avionics 12, IEE Press, UK, 2002.

[5] J.R. Guerci, Space-Time Adaptive Processing for Radar, Artech House, Norwood, MA, 2003.

[6] J. Ward, *Space-Time Adaptive Processing for Airborne Radar*, Lincoln Laboratory Tech. Rept., ESC-TR-94-109, December 1994.

[7] W.L. Melvin, "STAP overview," *IEEE AES Systems Magazine – Special Tutorials Issue*, Vol. 19, No. 1, January 2004, pp. 19-35.

[8] W.L. Melvin, "Space-time adaptive processing for radar," Academic Press Library in Signal Processing, Vol. 2, Communications and Radar Signal Processing, Eds. Rama Chellappa, Sergios Theodoridis, Academic Press, ISBN 978-0-12-396500-4, 2014, pp. 595-665.

[9] W.L. Melvin, "Clutter suppression using space-time adaptive processing," in Principles of Modern Radar: Advanced Techniques, ed. W. Melvin and J. Scheer, Sci-Tech Publishing, 2011.

[10] William Melvin, "Surface moving target indication," in Principles of Modern Radar: Radar Applications, Chapter 9, Eds. W.L. Melvin and J.A. Scheer, SciTech Publishing, 2013.

[11] I.S. Reed, J.D. Mallett, and L.E. Brennan, "Rapid convergence rate in adaptive arrays," *IEEE Trans. AES*, Vol. 10, No. 6, November 1974, pp. 853-863.

[12] W.L. Melvin and G.A. Showman, "Knowledge-aided parametric covariance estimation," *IEEE Trans. AES*, July 2006, pp. 1021-1042.

[13] D.K. Fenner and W.F. Hoover, "Test results of a space-time adaptive processing system for airborne early warning radar," in *Proc. 1996 IEEE Natl. Radar Conf.*, Ann Arbor, MI, 13-16 May 1996, pp. 88-93.

[14] W.L. Melvin, "Space-Time Adaptive Radar Performance in Heterogeneous Environments," *IEEE Trans. AES*, Vol. 36, No. 2, April 2000, pp. 621-633.

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Relevant IEEE AESS Paper

- A result of author’s musing after American Mid-Band Initiative (AMBIT) participation
- Discusses radar system reliance on spectrum
- Provides perspectives on using radar degrees of freedom (DoFs); emerging, configurable radar systems; and, decision support to harmonize radar’s use of spectrum (cognitive radar)

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Industry Insights

An Overview of Radar Operation in the Presence of Diminishing Spectrum

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INTRODUCTION

Monostatic radar systems actively interrogate the environment by transmitting a radiofrequency (RF) waveform and then receiving and processing the reflected signal to determine the presence of an object, its location, and other important features (e.g., motion, object type, or change in the object’s location) [1], [2], [3]. Radar has many civilian and military applications, including air traffic surveillance [4], severe weather detection and tracking [5], Earth resources management [6], automotive safety [7], missile defense [8], and haptic user interface [9]. These radar systems deploy on a plethora of platforms, including land-based pedestals and towers, automobiles and trucks, manned and unmanned aircraft and helicopters, marine vessels, satellites, dirigibles, person-held devices, etc.

Several key factors determine the radar system’s effectiveness in a given operating environment: detection capability; accuracy in estimating target parameters, such as range, angle, and Doppler frequency; and the ability to discriminate or characterize target type. The selection of operating center frequency and bandwidth plays a substantially important role in the radar’s effectiveness. Radar operating frequencies range from high frequency (HF), starting at 3 MHz, through millimeter wave (MMW) at over 100 GHz. Bandwidths vary greatly, with typical values from hundreds of kilohertz to 1 GHz or more. A number of factors influence the selection of radar operating frequency and bandwidth.

Radar detection, estimation, and characterization capability monotonically depend on signal-to-noise ratio (SNR). The radar range equation (RRE) characterizes basic radar performance [1], [2], [3]. Many variations of the RRE exist. A common version yielding output SNR is

$$SNR_o = \left(\frac{P_T G_T}{4\pi R_M^2}\right)\left(\frac{\sigma_T}{4\pi R_M^2}\right)\left(\frac{G_R \lambda_c^2 F_p}{4\pi k_B T_0 B F_n L_{sys}}\right) G_p \quad (1)$$

where P_T is peak transmit power in Watts, G_T is maximum transmit antenna gain, R_M is range to the target in meters, σ_T is radar cross section (RCS) in square meters, G_R is maximum receive antenna gain, λ_c is wavelength in meters, F_p is two-way propagation loss, k_B is Boltzmann’s constant (J/K), T_0 is standard temperature (290 K), B is bandwidth in Hertz, F_n is receiver noise figure, L_{sys} is RF system loss, and G_p is matched filtering gain from pulse compression and Doppler filtering. Wavelength and frequency are related as $f_c \lambda_c = c$, where f_c is the center frequency and c is taken as the speed of light. The maximum antenna gain G_x is nominally $G_x = 4\pi A_e / \lambda_c^2$, with A_e the effective antenna area. A number of factors in (1) exhibit explicit frequency dependence, including antenna gain, RCS, wavelength, and propagation loss. We consider both explicit and implicit frequency selection factors in more detail in the section “Frequency Selection and Use in Radar.”

Noise-limited performance is given by (1). However, radar systems necessarily operate in environments where clutter and other interference degrades capability. Clutter is any colored noise signal that is not the target of interest, and possesses target-like qualities; it is a form of interference impeding radar access to targets. For example, ground clutter returns exhibit an angle and Doppler response that spectrally competes with moving target returns [10]. Radio frequency interference (RFI) results from in-band signals emanating from specific angle-of-arrivals, but otherwise appearing uncorrelated in the temporal domain, thereby desensitizing radar performance by increasing the uncorrelated noise floor.

The signal-to-interference-plus-noise ratio (SINR) captures radar performance in an interference-limited

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