Improving Ground Moving Target Indication Performance

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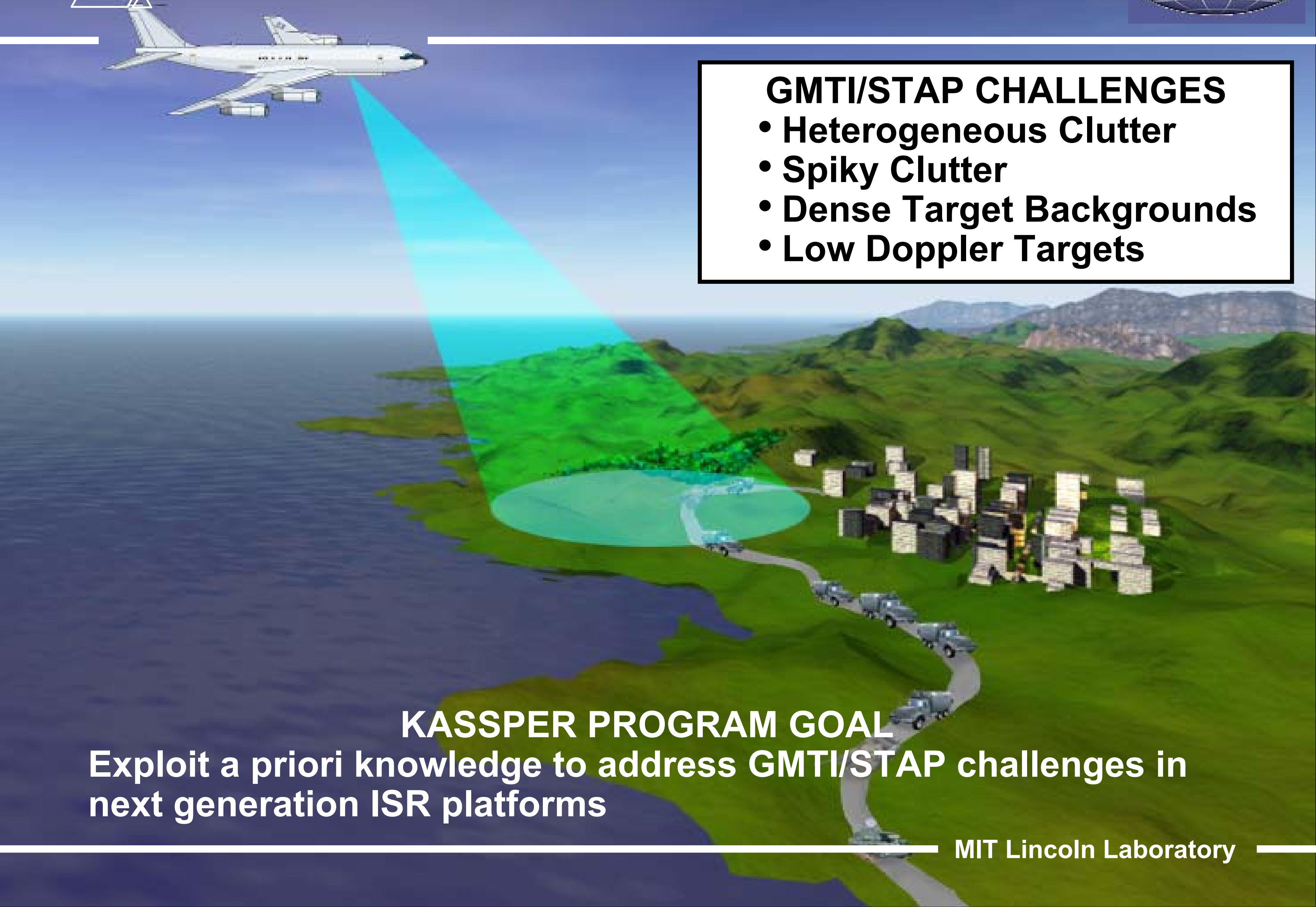
GMTI Scenario

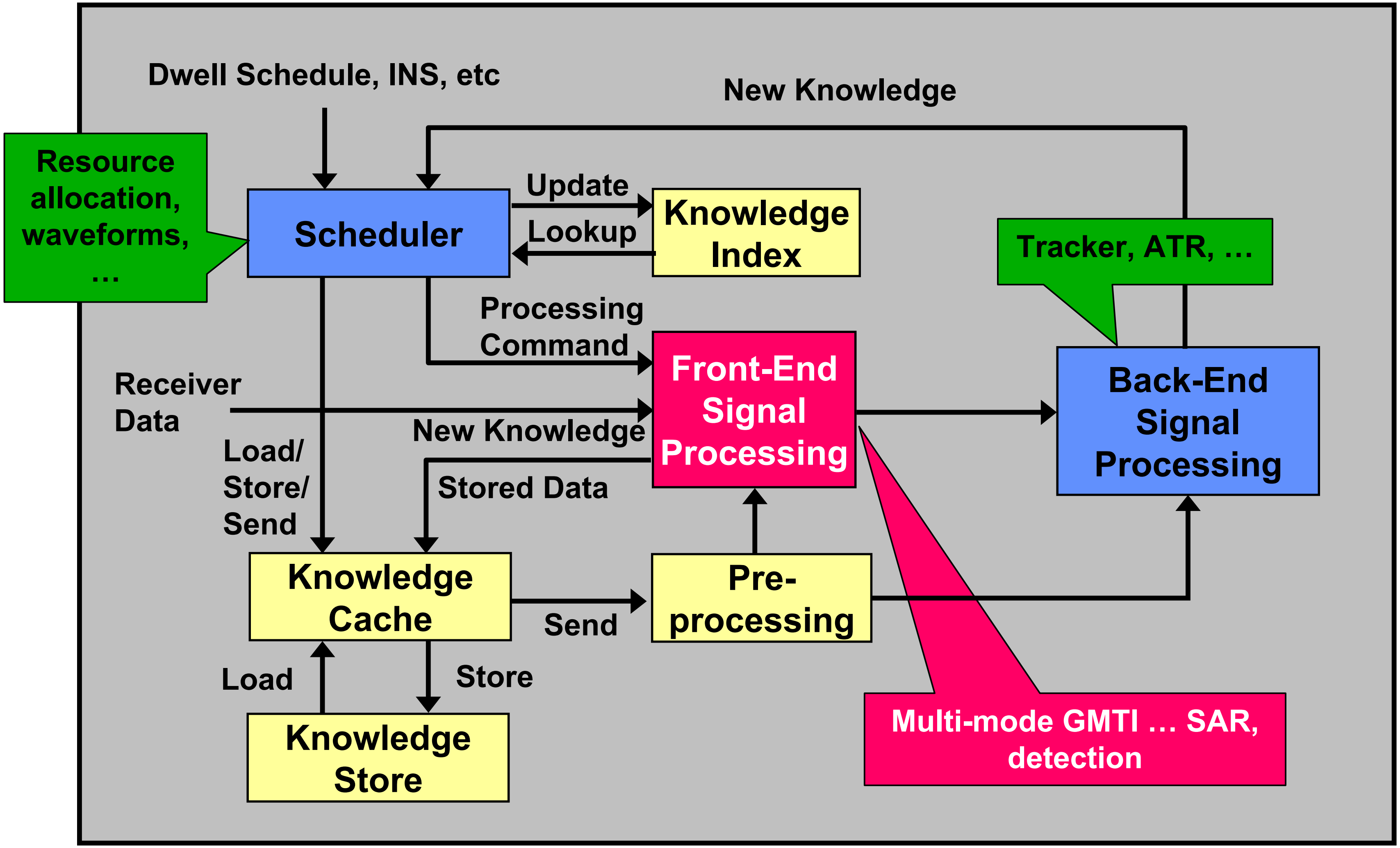


GMTI/STAP CHALLENGES
- Heterogeneous Clutter
- Spiky Clutter
- Dense Target Backgrounds
- Low Doppler Targets

KASSPER PROGRAM GOAL

Exploit a priori knowledge to address GMTI/STAP challenges in next generation ISR platforms

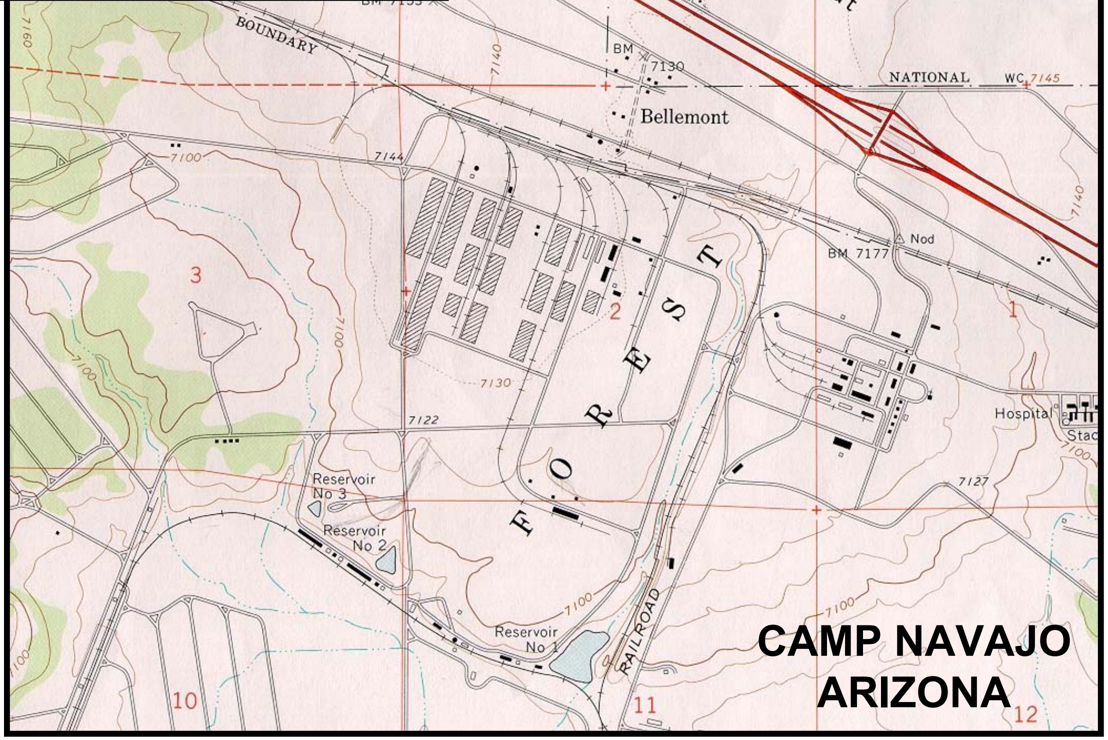
KASSPER Processing Architecture



Focus of talk will explore several front-end signal processing techniques

GMTI Scenario Example

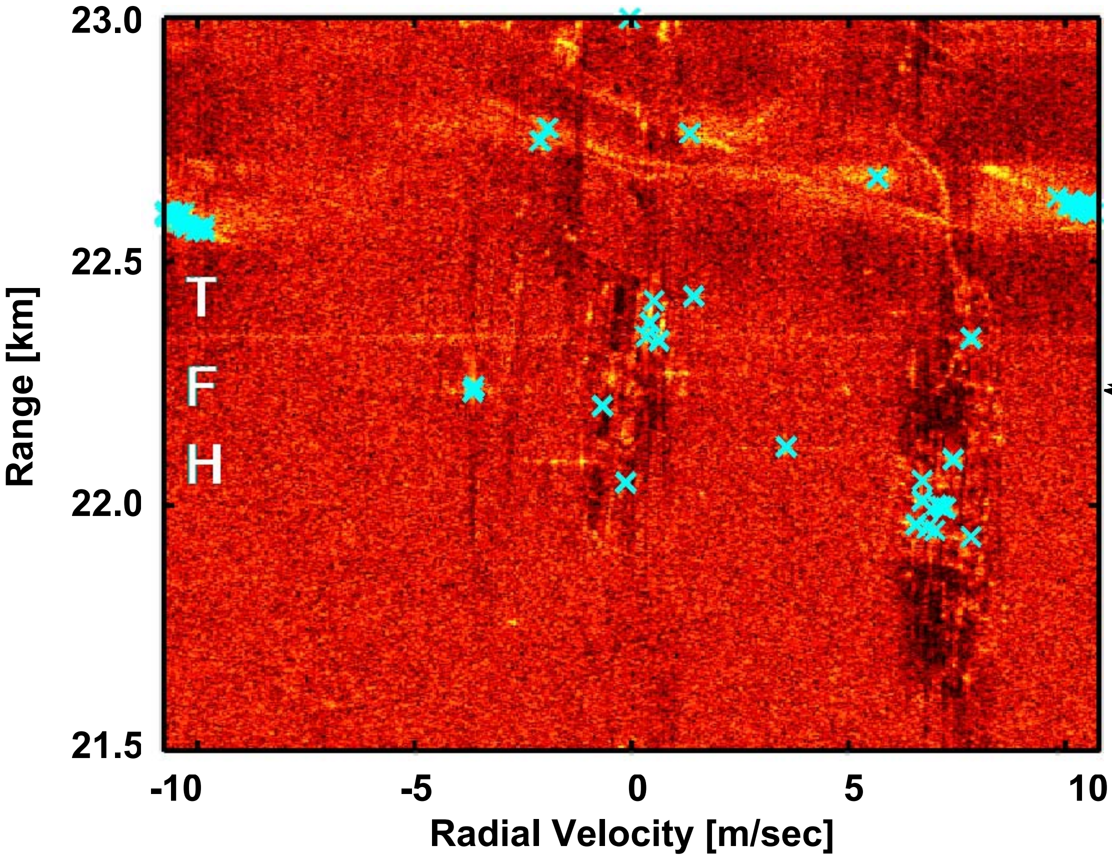
Tuxedo Sensor

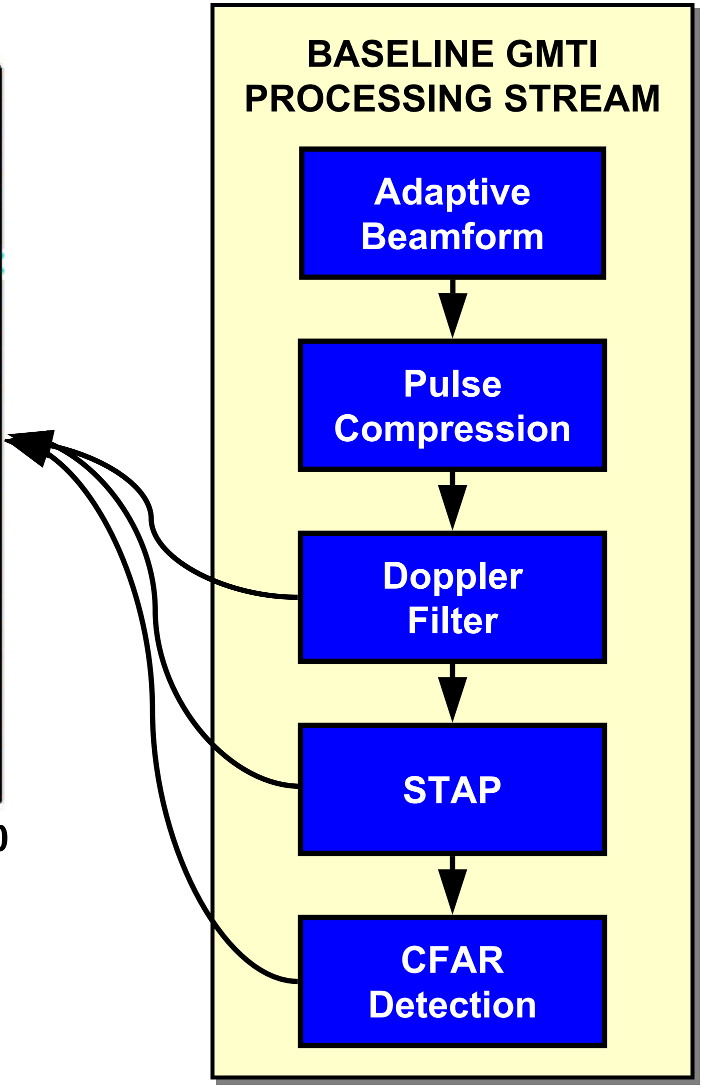


System Parameters for GMTI Mode

Center Freq.	9.6 GHz
Bandwidth	66 MHz
PRF	1,400 Hz
Tx Apertures	1
Rx Apertures	3
Az BW, Aperture	3.6 deg
El BW, Aperture	9.1 deg
Polarization	HH
A/C Heading	290 deg
Depr. Angle	15 deg
Recorded Time	40-60 sec

Example GMTI Output with Tuxedo Data



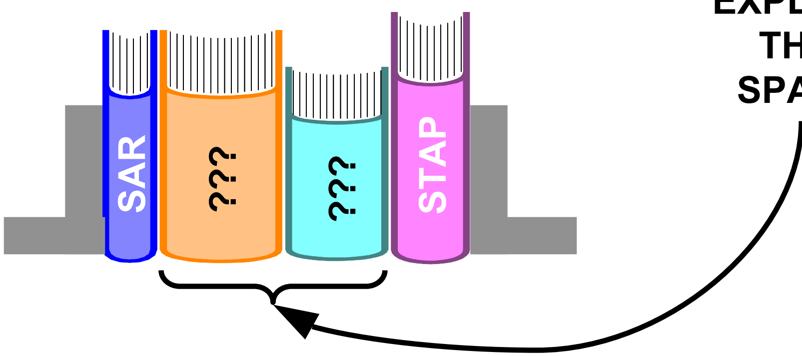


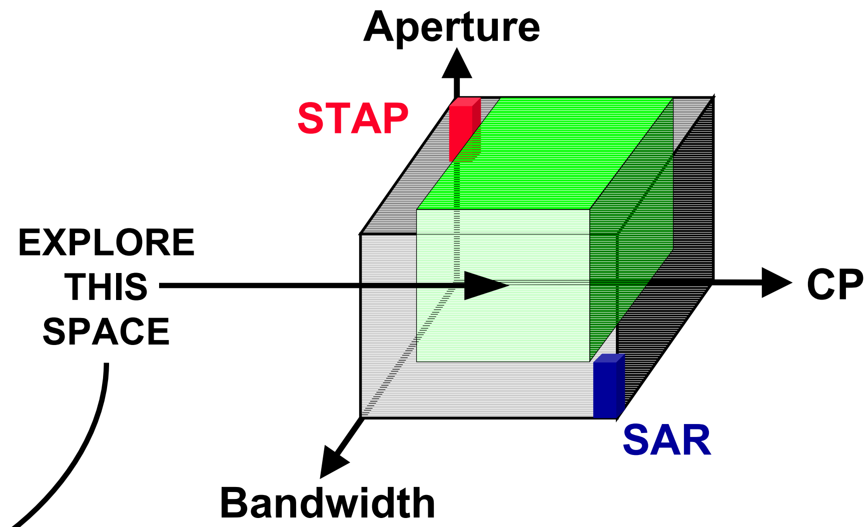
T = 2-ton Truck
F = Fuel Truck
H = HMMWV

× = Target Detection

Lincoln Laboratory Goals in the KASSPER Program

- **Develop signal processing architecture and algorithms that exploit a priori knowledge to overcome ISR challenges and improve performance**
  - Moving Target Focusing
  - Multi-channel adaptive SAR
  - Power Variable Training
  - Extended Array Receiver

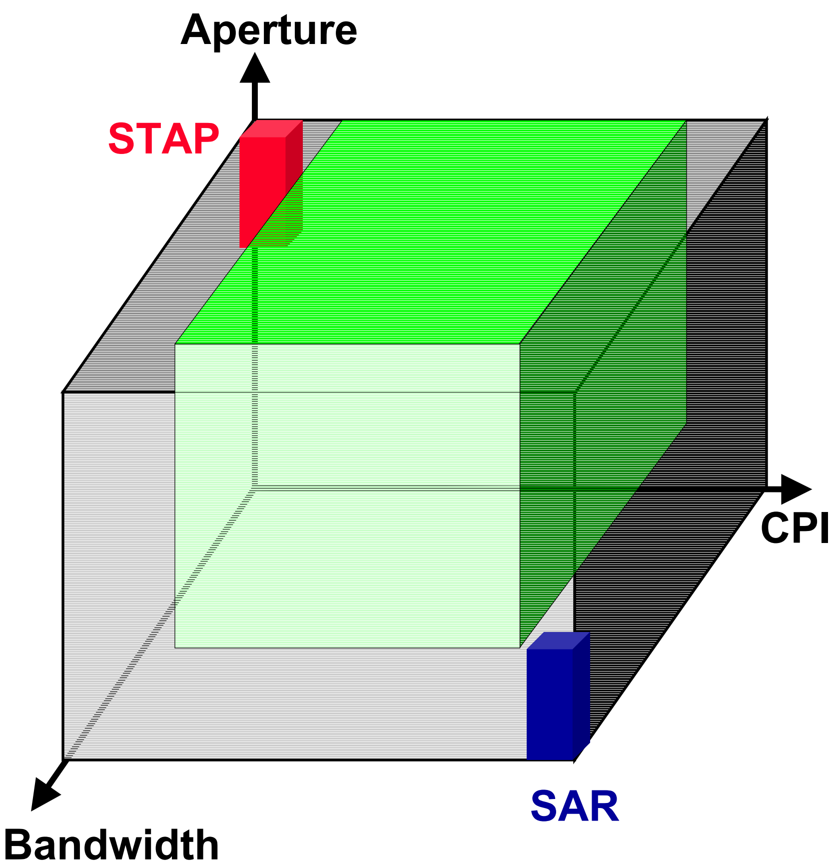




- **Develop new High Performance Embedded Computing (HPEC) architecture for real-time Intelligence, Surveillance, and Reconnaissance (ISR) applications**

- **Real-time flight demonstrations**

SAR versus STAP Processing*



- STAP adaptively nulls clutter and jammers to achieve noise-limited detection
  - Fast target revisit, high area search rate
  - Long aperture for low MDV
- High-resolution SAR employs long CPIs and high bandwidth to enhance target gain and reduce clutter strength
  - Clutter-limited detection
  - Slow target revisit, low area search rate
- Aperture size, CPI length and bandwidth may be selected to optimize MDV performance
- Adaptive array processing over long CPIs and large bandwidth needs to address
  - Spatial clutter heterogeneity
  - Clutter training sample support
  - Target migration

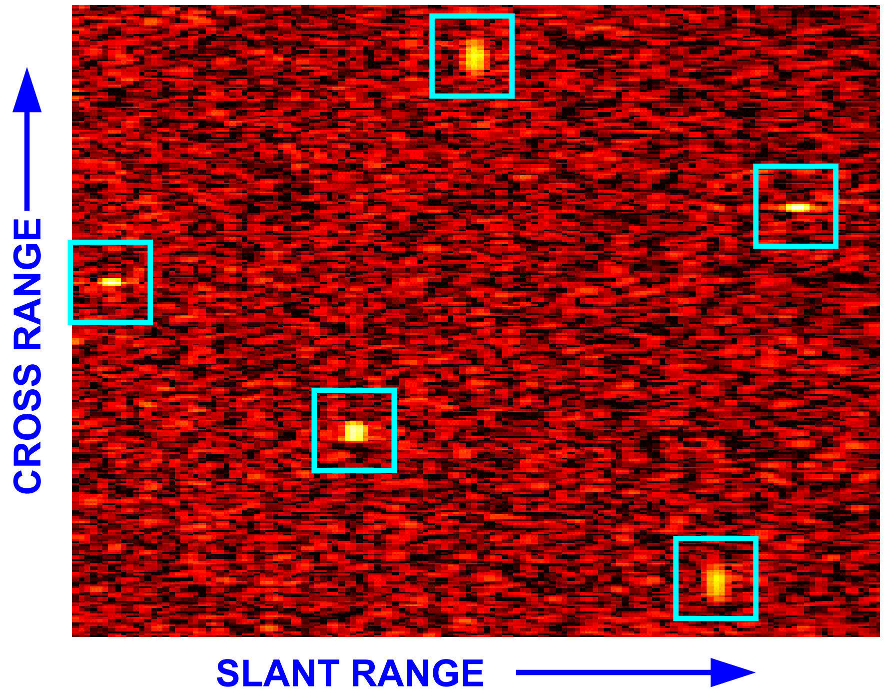
*Slide coutesy of Jen Jao

Outline

- Introduction
- New Concepts for GMTI Performance Improvements
  – Moving Target Focusing
  – Power Variable Training
  – Multi channel Adaptive SAR
  – Extended Array Receiver
- Summary

Defocus of Moving Targets with Cross-Range Motion

SIMULATED SAR IMAGE FOCUSED FOR STATIONARY TARGETS



STATIONARY CLUTTER

MOVING TARGETS WITH CROSS-RANGE MOTION

- Targets moving in slant-range dimension will appear displaced in cross-range relative to stationary clutter

EXPLORED HERE

- **Targets moving in cross-range dimension will appear smeared in doppler or cross-range**

Mechanism for Moving Target Smearing

Significant range walk with large *BW* and *T*

Range Resolution

$$\Delta r = \frac{1.81}{BW}\left(\frac{c}{2}\right)$$

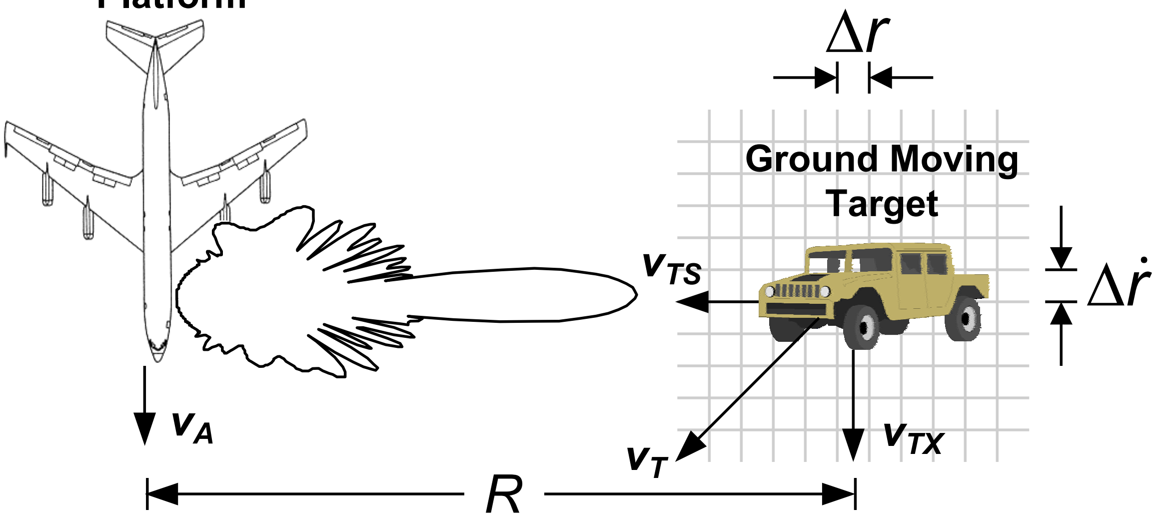
Significant doppler walk with large *T*

Doppler Resolution

$$\Delta \dot{r} = \frac{1.81}{T}\left(\frac{\lambda}{2}\right)$$

c	Speed of Light
BW	Bandwidth
λ	Wavelength
T	CPI Time
v_A	Aircraft Velocity
v_T	Target Velocity
R	Stand-off Range

Airborne Radar Platform



$$\gamma^2 \equiv \left(v_A - v_{TX}\right)^2 + v_{TS}^2$$

$$r(t) = \sqrt{R^2 + 2Rv_{TS}t + \gamma^2 t^2}$$

$$\dot{r}(t) = \left(Rv_{TS} + \gamma^2 t\right)/r(t)$$

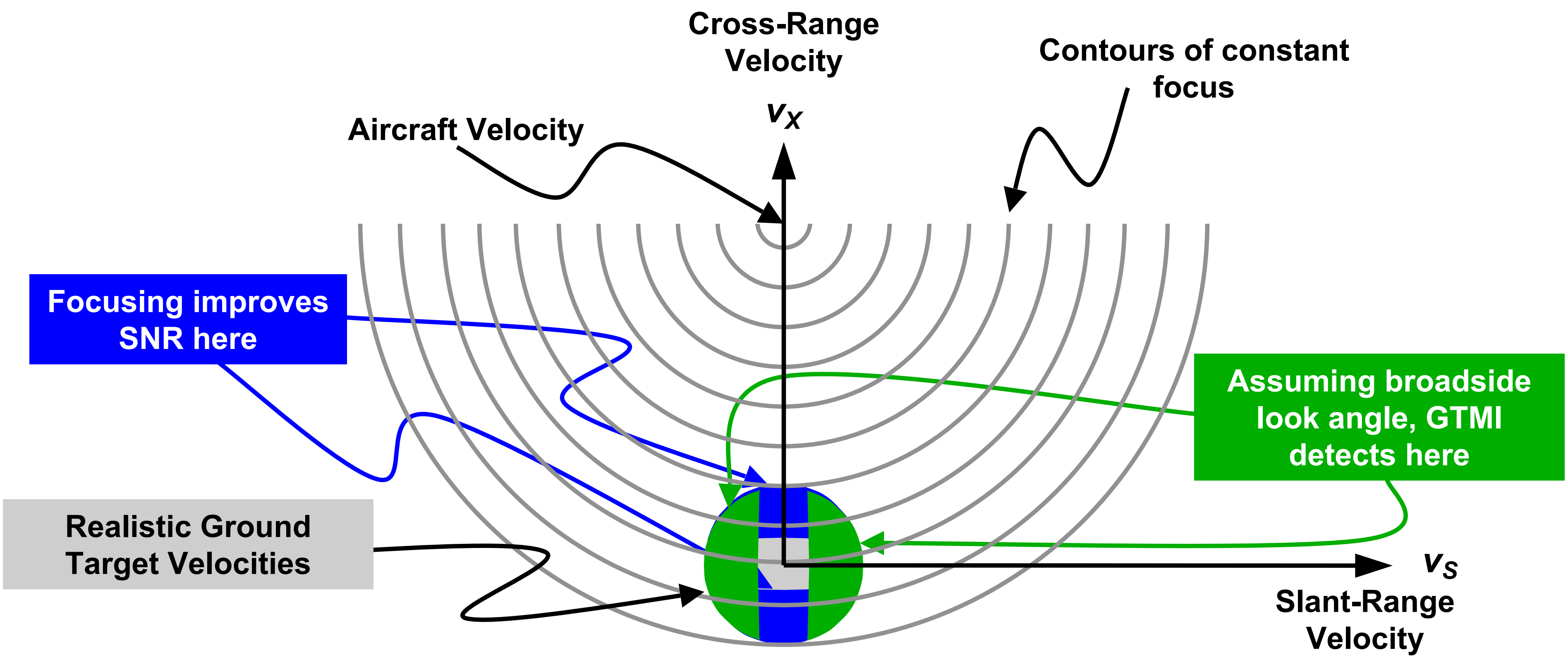
Long CPIs can lead to target doppler walk or smearing. The degree of smearing is a function of γ^2

Defocusing Factor

Defocusing Factor

$$\gamma \equiv \sqrt{\left(v_A - v_{TX}\right)^2 + v_{TS}^2}$$

Norm of the relative velocity vector



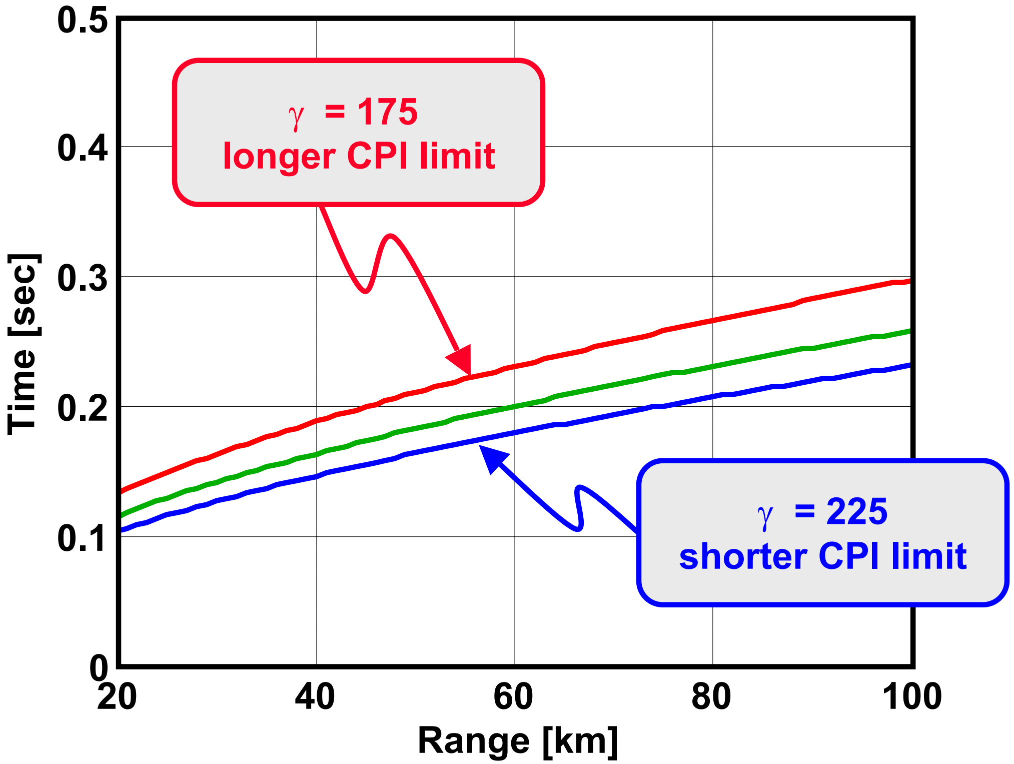
Focus of moving targets is parameterized with a single scalar quantity

Limits on CPI Time to Prevent Doppler-walk

$$\dot{r}(T/2) - \dot{r}(-T/2) \le \frac{1.81}{T}\left(\frac{\lambda}{2}\right)$$

Assume large *R*

$$T \le \sqrt{\frac{1.81R}{\gamma^2}\frac{\lambda}{2}}$$



- Center Frequency 10 GHz
- Platform Velocity 200 m/sec
- Target at broadside
- DFT with Hamming weighting

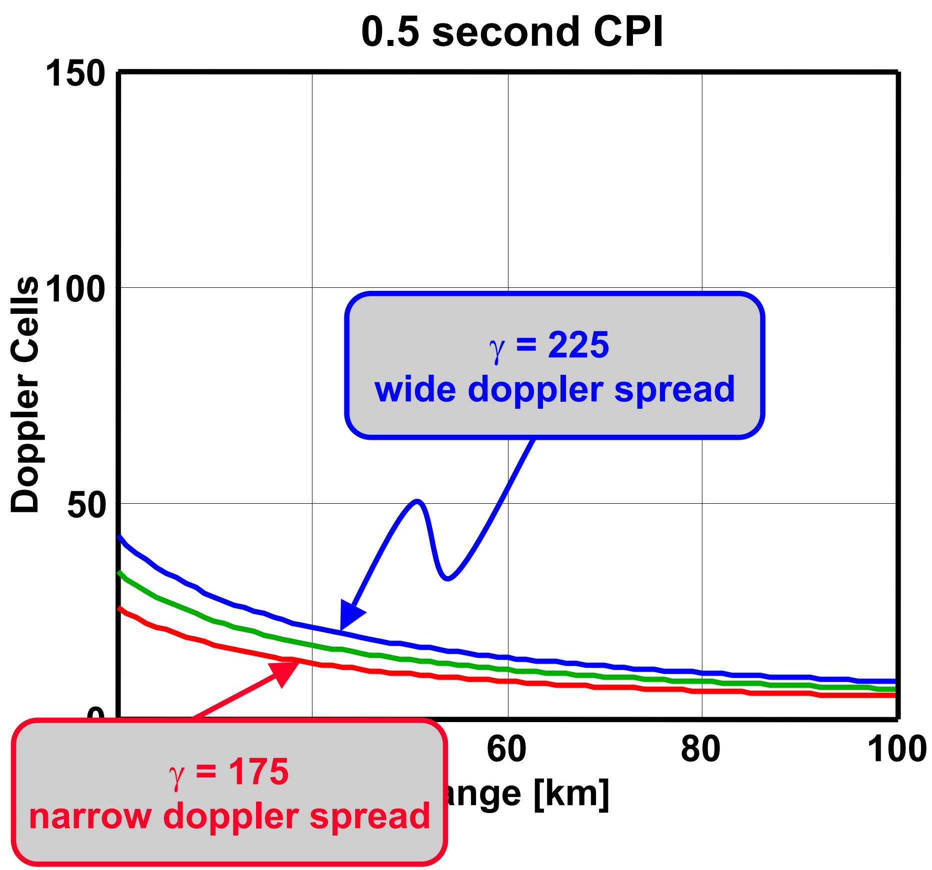
Velocities in m/sec

	v_x	γ
red	25	175
green	0	200
blue	-25	225

Moving Target Doppler Spread

$$\frac{\dot{r}(T/2) - \dot{r}(-T/2)}{\Delta \dot{r}} \approx \frac{2\gamma^2 T^2}{\lambda R}$$

Assume large *R*



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GMTI Focusing

$$\dot{r}(t) = \left(Rv_{TS} + \gamma^2 t\right) / r(t) \approx \left(Rv_{TS} + \gamma^2 t\right) / R \approx v_{TS} + \gamma^2 t / R$$

Constant term (v_{TS})

Term Affecting Defocus ($\gamma^2 t / R$)

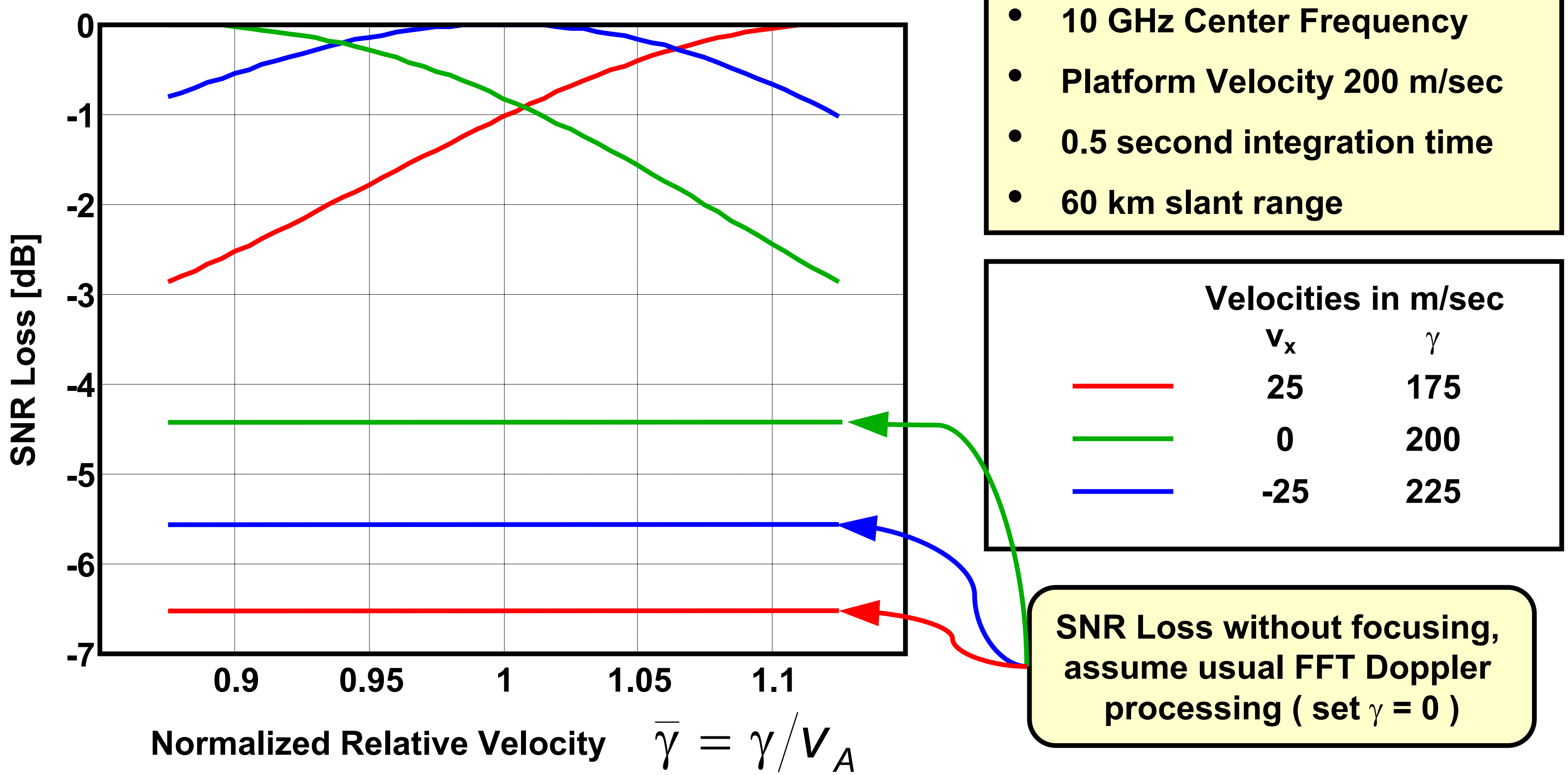
Moving Target Defocuses with:

- **Increasing CPI time**
- **Increasing γ**
- **Decreasing range**

$$\exp\left[\frac{j2\pi\gamma^2 t^2}{\lambda R}\right]$$

Correcting for target motion consists of applying a quadratic phase term to each pulse

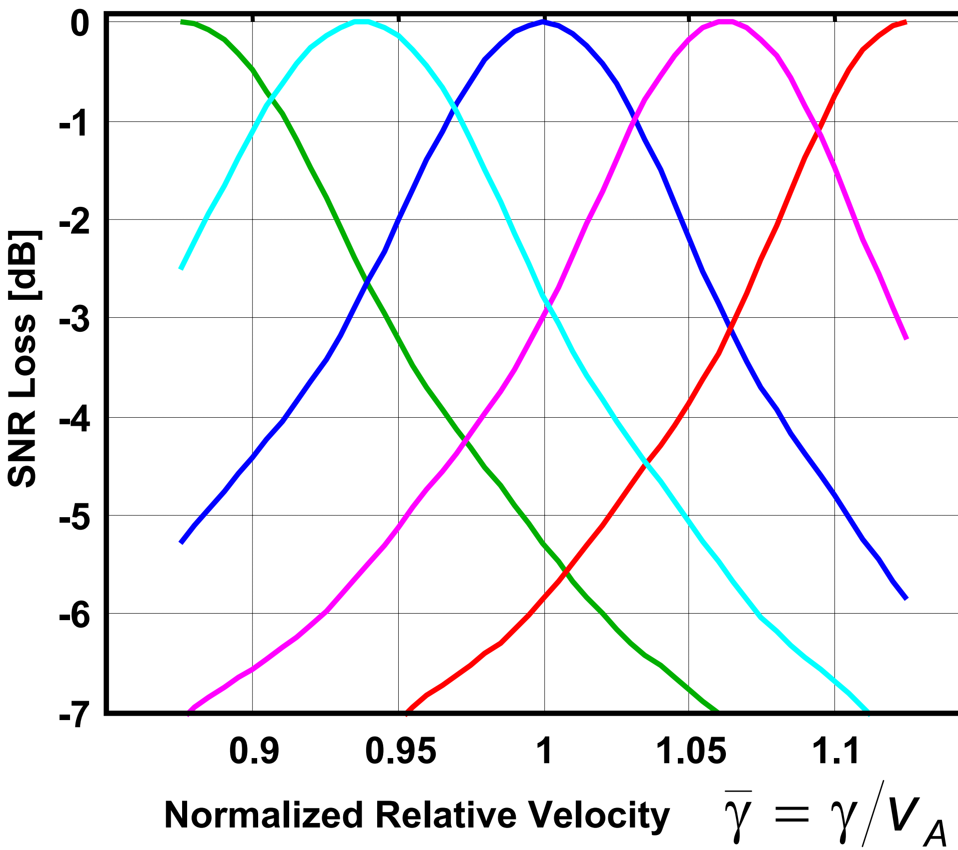
Sensitivity to γ



- 10 GHz Center Frequency
- Platform Velocity 200 m/sec
- 0.5 second integration time
- 60 km slant range

A bank of focusing filters (for different values of γ) is required. Analogous to Doppler filterbank architecture

Sensitivity to γ



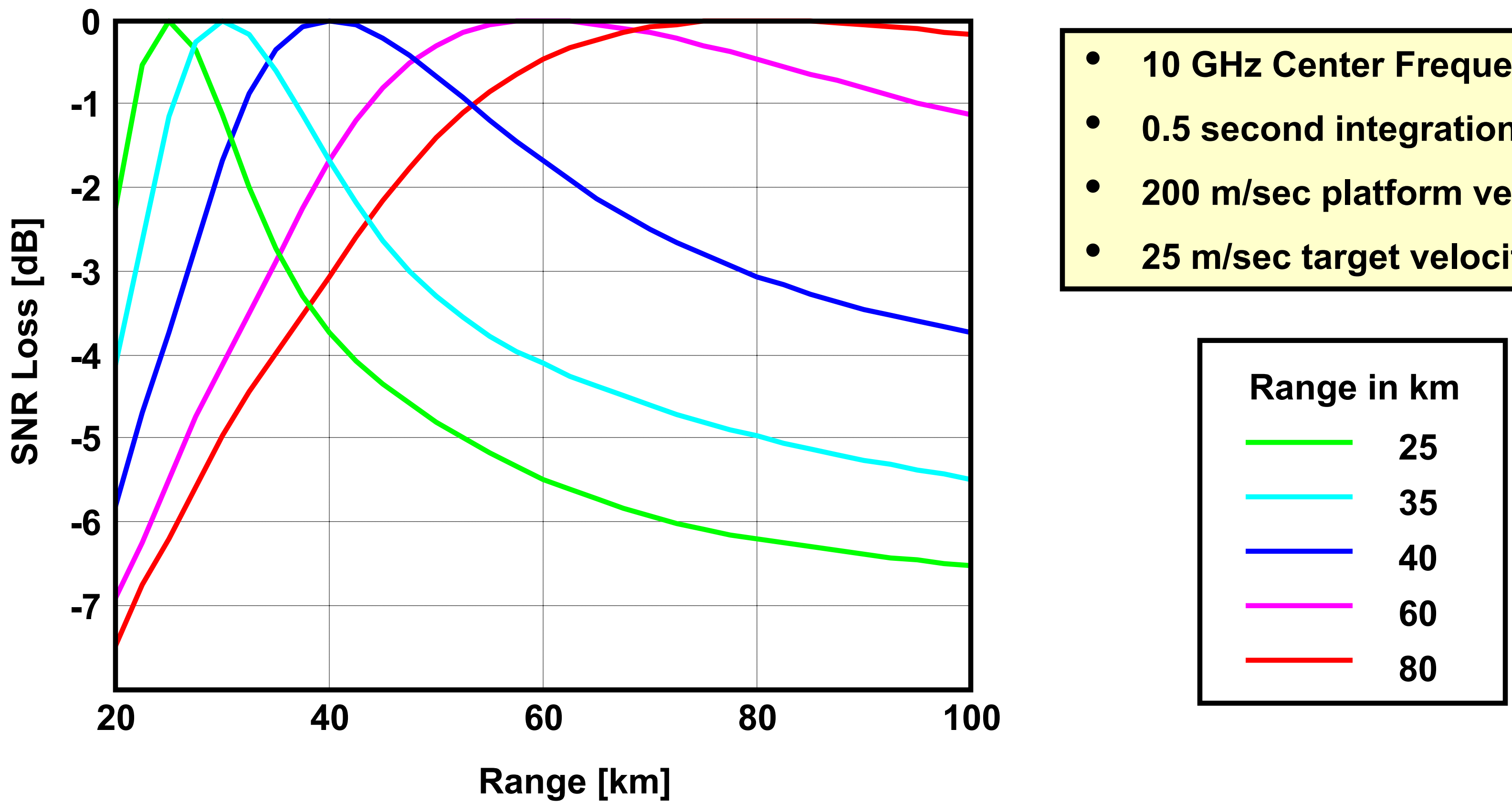
- 10 GHz Center Frequency
- Platform Velocity 200 m/sec
- 1.0 second integration time
- 60 km slant range

Velocities in m/sec

	v_x	γ
green	25.0	175
cyan	12.5	189
blue	0.0	200
magenta	-12.5	214
red	-25.0	225

With longer integration times, more filters are required.

Sensitivity to Range

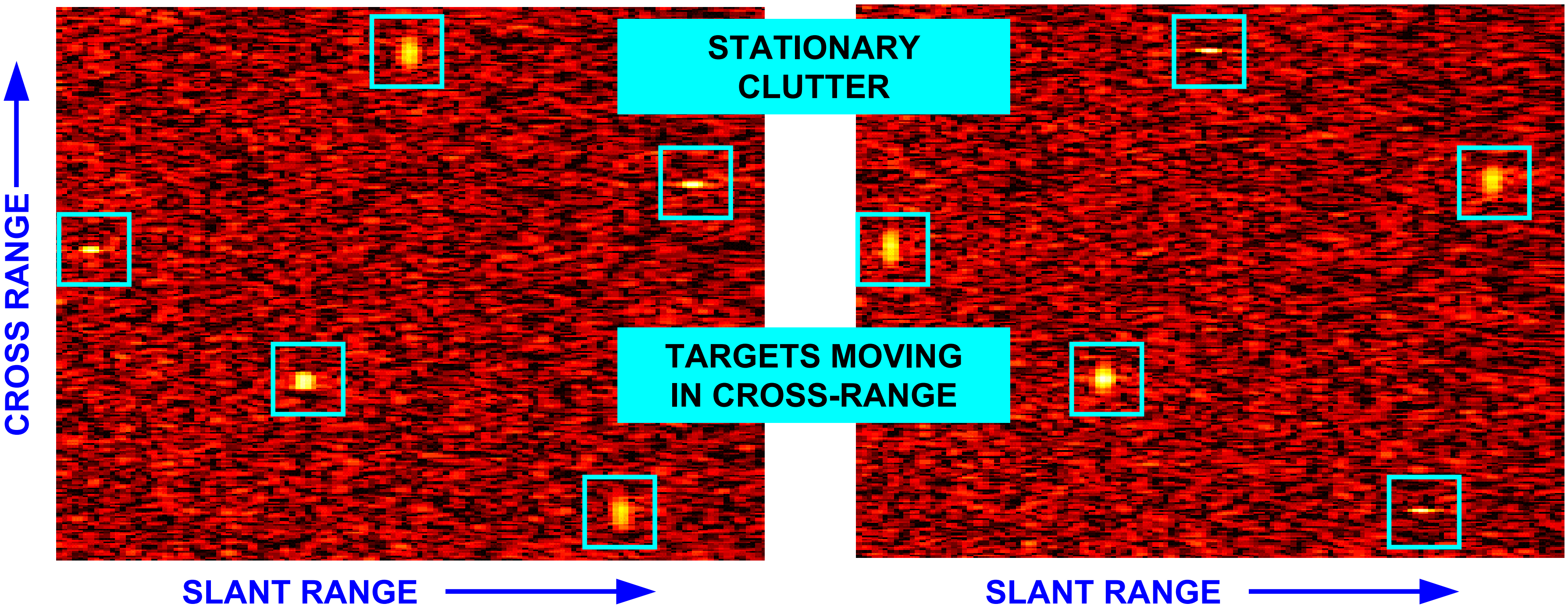


- 10 GHz Center Frequency
- 0.5 second integration time
- 200 m/sec platform velocity
- 25 m/sec target velocity

Phase correction may vary over long range swaths

Moving Target focusing for Targets with Transverse Motion

SIMULATED SAR IMAGE FOCUSED FOR STATIONARY TARGETS | **SIMULATED SAR IMAGE FOCUSED FOR MOVING TARGETS**



- Targets moving in cross range will appear smeared in a traditional SAR image and will “cohere-up” in a SAR image focused for moving targets
- If cross range motion is significant over integration time then comparing the two SAR images can separate moving targets from clutter (stationary targets)

REFERENCE J. Jao, “Theory of synthetic aperture radar imaging of a moving target,” IEEE Trans. on Geoscience and Remote Sensing, 2001.

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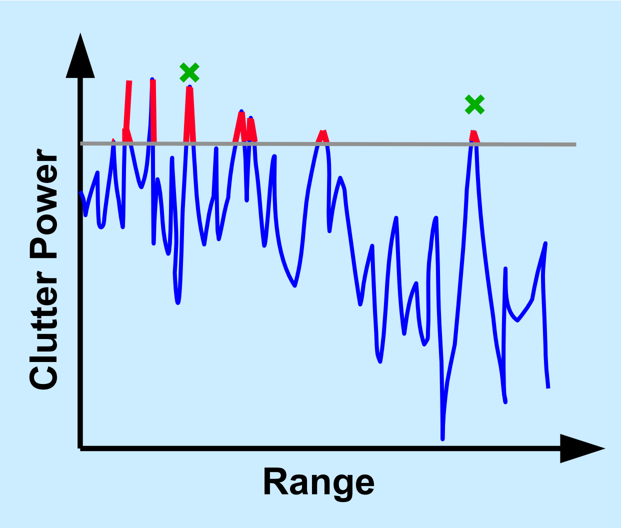
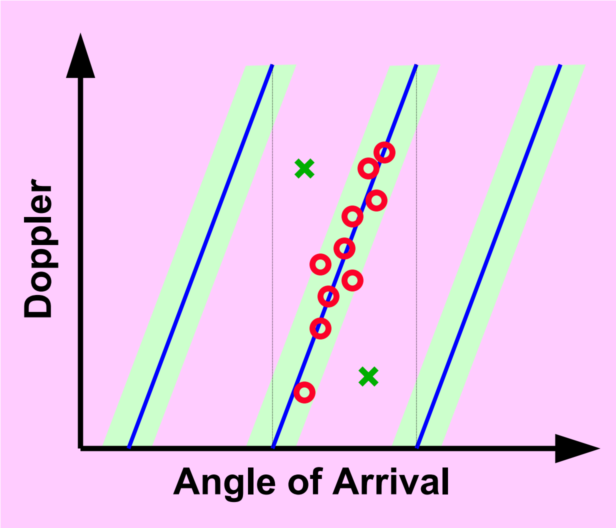
Power-Variable Training (Without Overnulling)

POWER SELECTIVE TRAINING



Select strongest clutter returns as candidate training samples

EXCISION



Excise samples away from clutter ridge (potential targets)

ESTIMATION

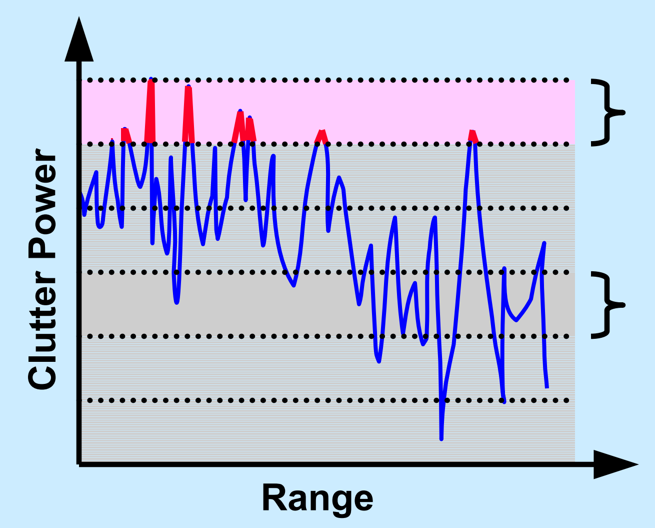
$$\mathbf{R}_M = \beta\left(\frac{1}{K}\sum \mathbf{x}_i \mathbf{x}_i^H\right) + \lambda \mathbf{I}$$

$\beta < 1$

Scale training samples to estimated CNR

- Power scaling provides lower MDV than power selective training
- Power scaling may generate more false alarms relative to power selective training but adaptive sidelobe blanking should remove most of them

Power Variable Training Procedure

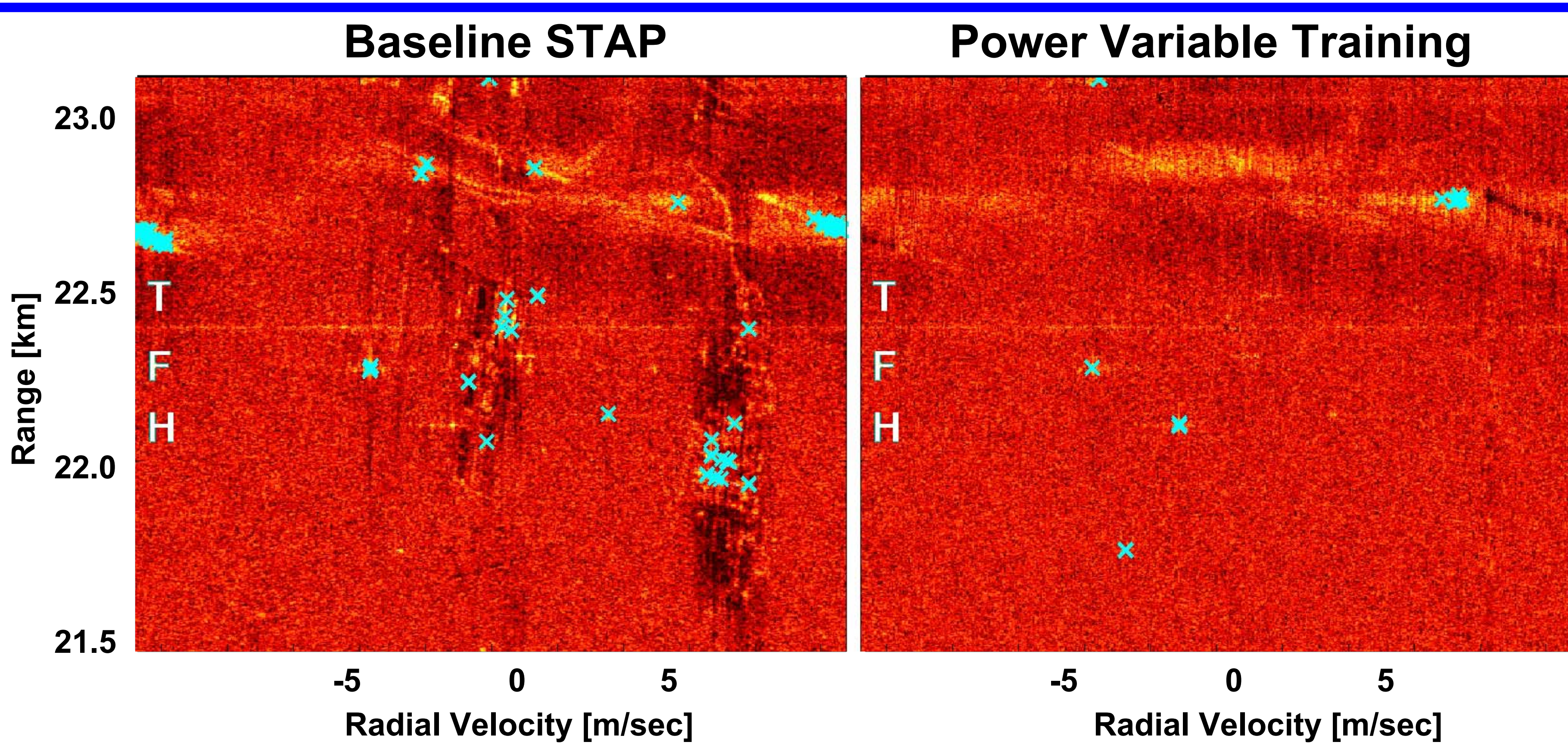


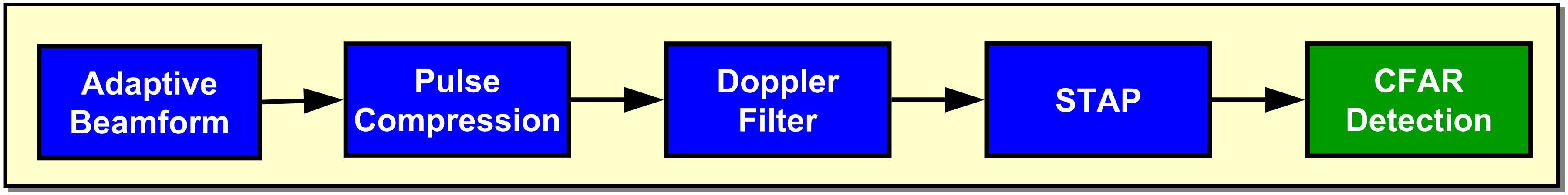
Training $\mathbf{R}_L = \frac{1}{K_L}\sum x_i x_i^H$

Tile "M" $e_M = \frac{1}{K_M}\sum x_i^H x_i$

Estimate Pure Clutter Covariance Matrix	$\mathbf{R}_C = \mathbf{R}_L - \lambda \mathbf{I}$	$\lambda =$ **Estimated Noise Floor**
Covariance Matrix for Tile "M"	$\mathbf{R}_M = \beta \mathbf{R}_C + \lambda \mathbf{I}$	$\beta = \frac{e_M - N\lambda}{tr[\mathbf{R}_L] - N\lambda}$
Adaptive Weight for Tile "M"	$w_M = \frac{[\mathbf{R}_M + \delta \mathbf{I}]^{-1} v}{\sqrt{v^H [\mathbf{R}_M + \delta \mathbf{I}]^{-1} v}}$	$\delta =$ **Diagonal Load Level**

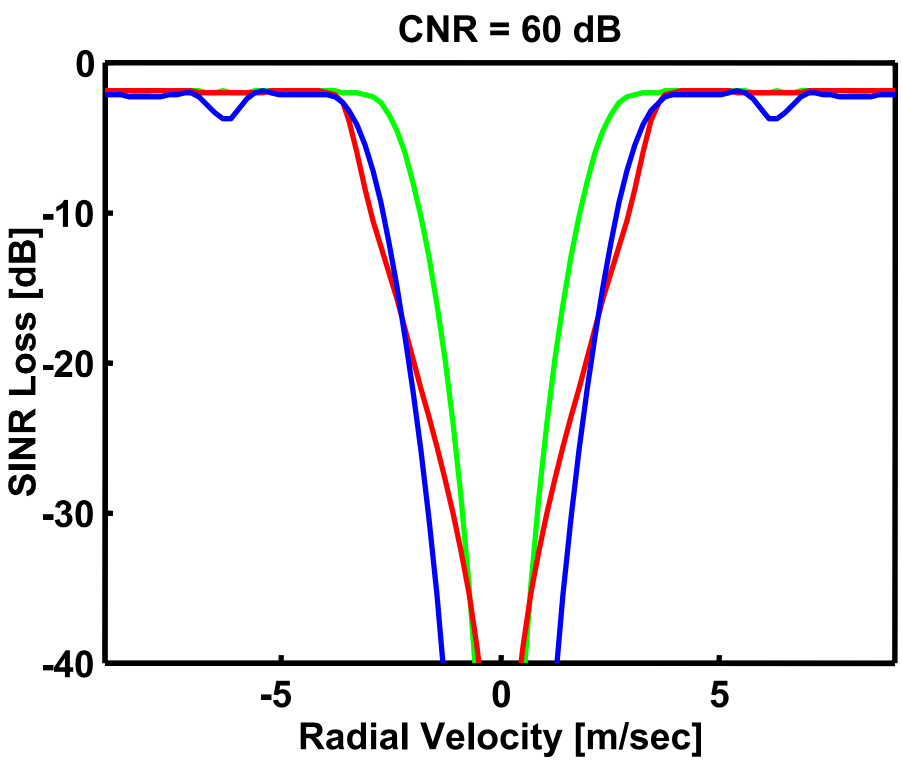
Example with Tuxedo Data





Power Variable Training SIGNIFICANTLY improves false alarm performance relative to baseline STAP approach

Overnulling / Undernulling Performance



PARAMETERS	
Aperture	4 m
Channels	7
Center Freq.	10 GHz
PRF	1.2 kHz
Sample Rate	20 MHz
Pulses	34
A/C Velocity	200 m/sec

- Matched
- 30 dB Undernulling
- 30 dB Overnulling

Matching CNR avoids unnecessary SINR Losses due to overnulling or undernulling

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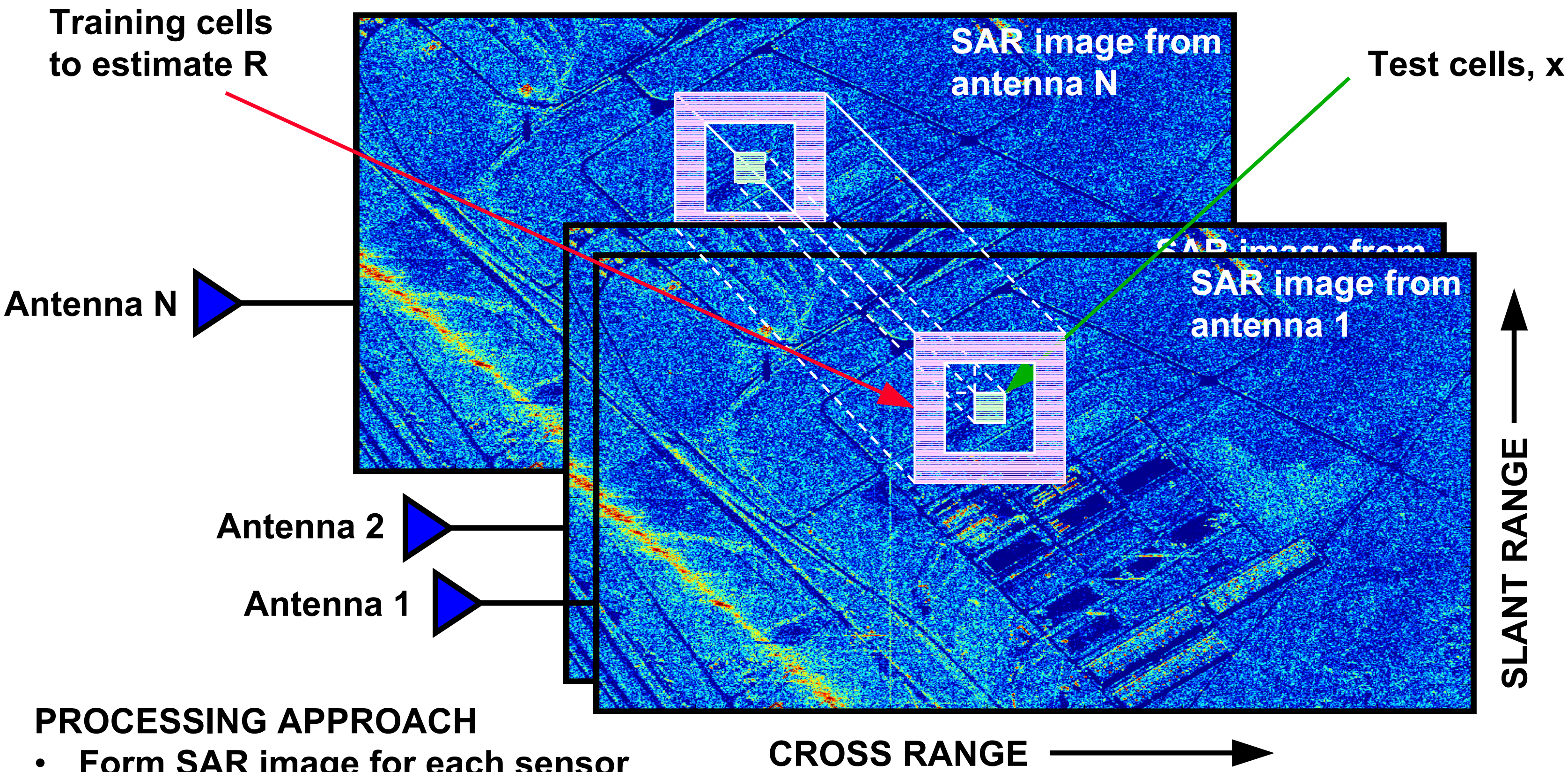
Multi-Channel Adaptive SAR



PROCESSING APPROACH
- Form SAR image for each sensor
- Compute estimated covariance
- Change detection
- Prune potential target data
- Recompute estimated covariance
- Change detection

$$x^H \hat{\mathbf{R}}^{-1} x > T$$

Compute change detection statistic using adjacent cross range and slant range pixels

REFERENCE A. Yegulalp, *FOPEN GMTI Using Multi-Channel Adaptive SAR*, Proceedings of the ASAP Workshop, March 2002.

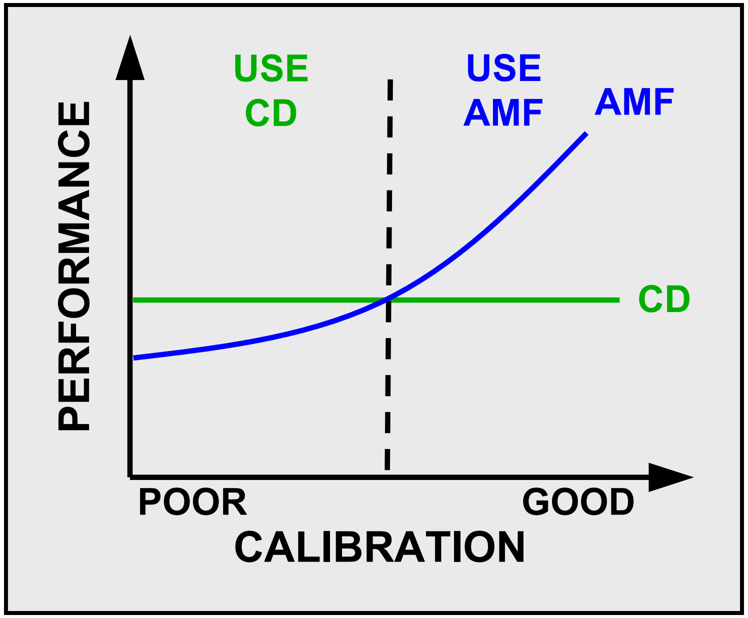
Open Issues with Multi-Channel Adaptive SAR Processing

CD TEST

$$x^H \hat{\mathbf{R}}^{-1} x > T$$

AMF TEST

$$\frac{| v^H \hat{\mathbf{R}}^{-1} x |^2}{v^H \hat{\mathbf{R}}^{-1} v} > T$$



- **For well calibrated arrays the adaptive matched filter (AMF) approach outperforms the change detection (CD) approach**
- **For what amount of array uncertainty does the change detection approach become more useful?**
- **Do we need to generate focused SAR images for each antenna element or will simple Doppler processing suffice?**

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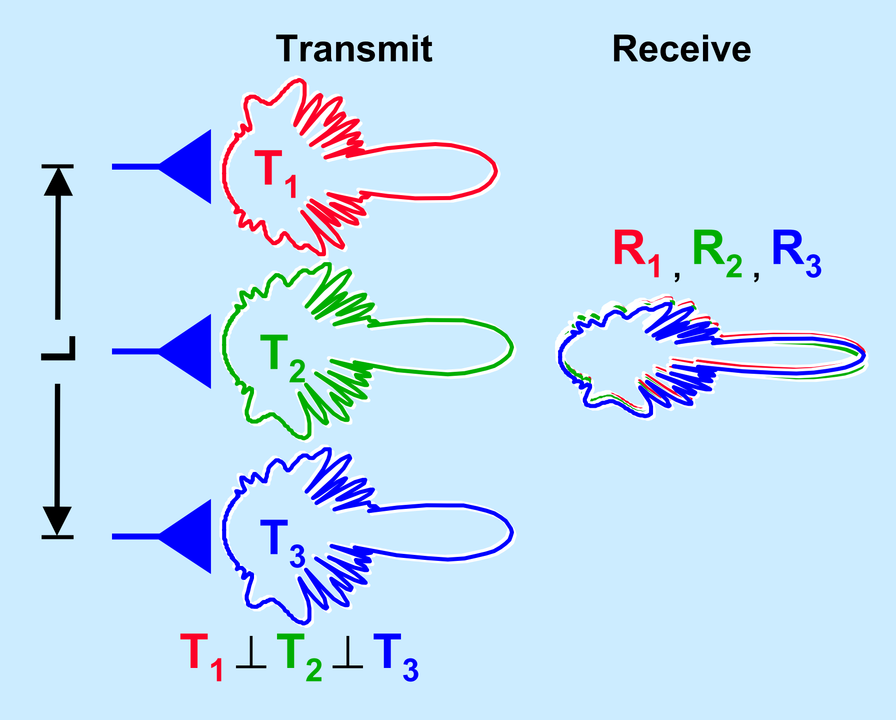
Extended Array Receiver

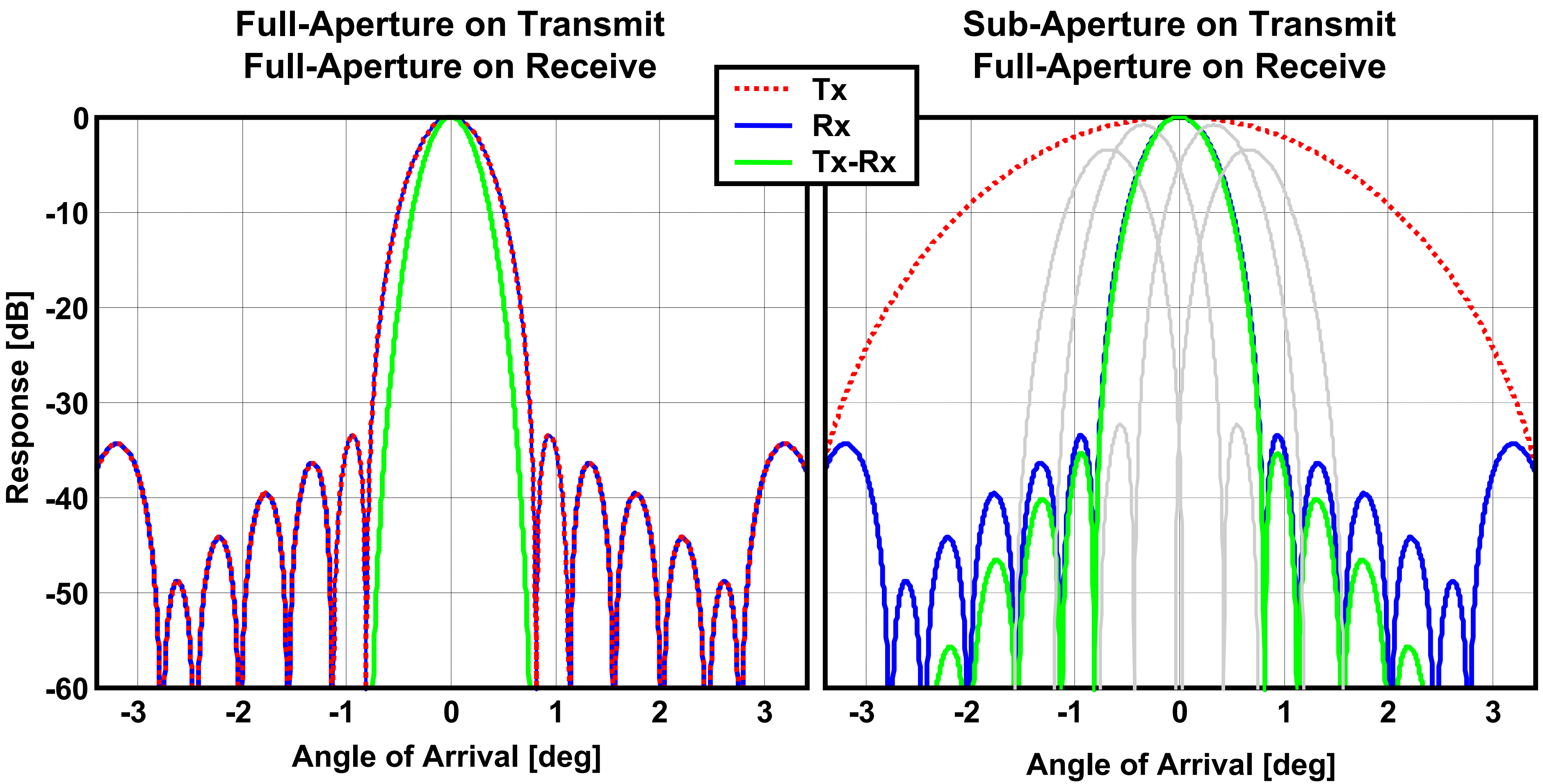
SYSTEM CONCEPT



- Transmit orthogonal waveforms on each subarray
- Receive and demodulate each waveform across the entire array
- This approach transfers the available transmit gain of the full aperture to the receiver, providing flexibility
- Note, some antenna systems spoil the gain on transmit for wider coverage

Provides narrow transmit-receive beampatterns over wide coverage area

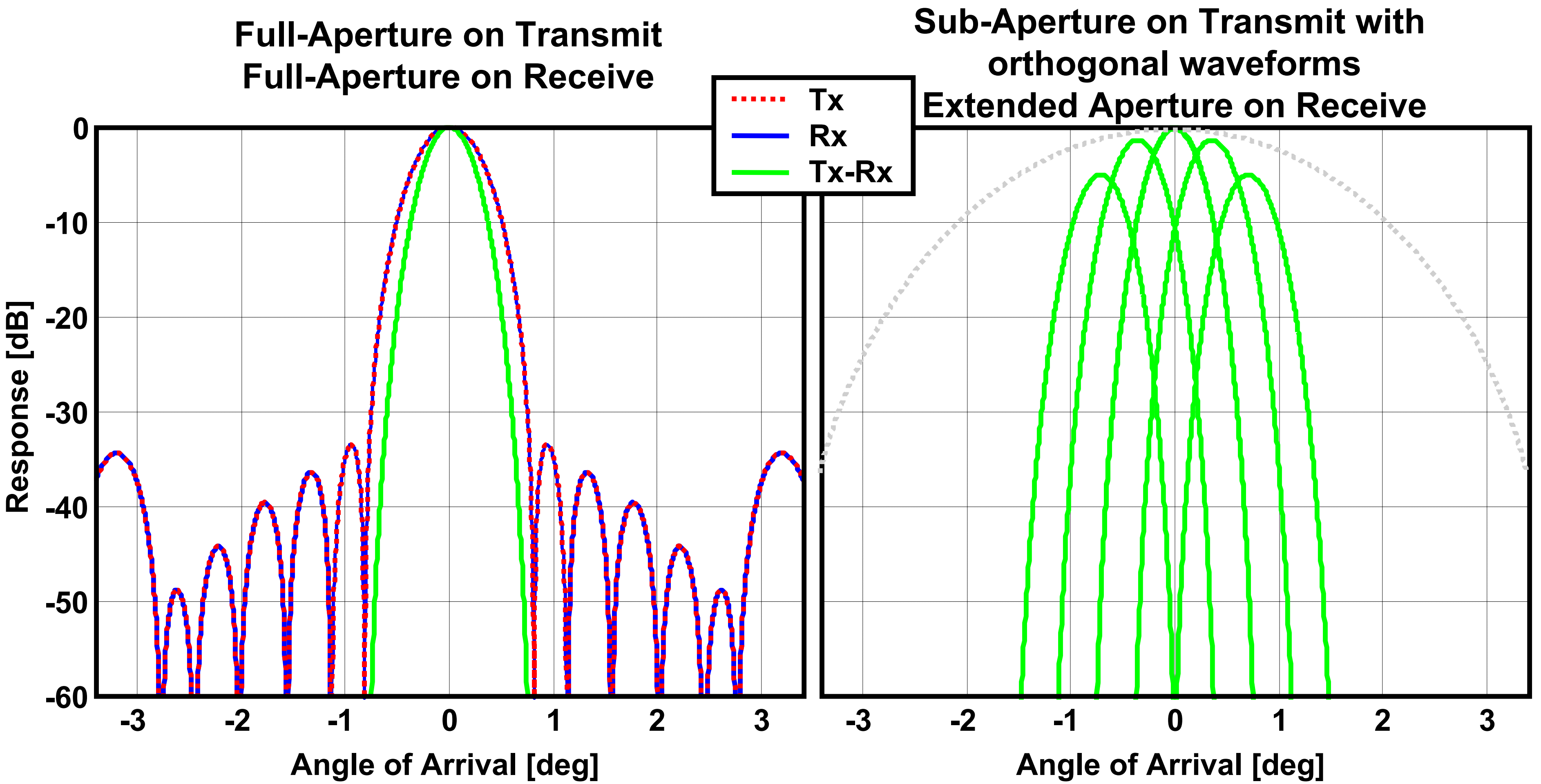
Theoretical Transmit-Receive Beampatterns



Narrow two-way beampatterns
Small coverage area

Wide two-way beampatterns
Large coverage area

Theoretical Transmit-Receive Beampatterns



Narrow two-way beampatterns
Small coverage area

Narrow two-way beampatterns
Large coverage area

Open Issues with Extended Array Receiver Concept

- Elevated receiver noise floor with multiple orthogonal waveforms
- Can a processor architecture support multiple orthogonal waveform decoding per subarray?
- How nearly orthogonal can multiple waveforms be over both delay and doppler?
- In some cases internal clutter motion may limit the benefit of an extended array receiver
- Need to investigate synchronization of orthogonal waveforms on reception

Summary of GMTI Performance Improvements

	Moving Target Focusing	Multi-channel Adaptive SAR	Power Variable Training	Training Data Excision	Extended Array Receiver
Controls False Alarms	■		■		
Improves MDV	■	■	■		■
Heterogeneous Clutter		■	■		
Avoids Target Self-nulling		■		■	

Summary

- GMTI is challenging in real-world applications
  – Excessive false alarms
  – Missed Detections (slow moving vehicles)
  – Dense target scenarios
  – Heterogeneous clutter environments
- Explored several approaches to improve GMTI performance
  – Moving target focusing for long CPIs
  – Excision of training data far from clutter ridge
  – Power variable training without overnulling
  – Multi-channel adaptive SAR
  – Extended array receiver
- Developing system-oriented approaches to exploit a priori knowledge with respect to front-end and back-end signal processing and scheduling
- Implementation on real-time testbed will be evaluated
- Ongoing evaluation with simulated and recorded radar data