Multichannel SAR-GMTI Clutter Cancellation Performance*

Challenges In Synthetic Aperture Radar
Institute for Pure and Applied Mathematics, UCLA

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Motivation And Objective

- **Motivation**
  - **Detection of very slow ground moving targets in clutter with radar on a moving airborne platform demands complex multichannel SAR-GMTI system, especially at low frequencies**
  - **Require support of large CPI-bandwidth, long aperture, and adaptive array processing to deliver strong clutter suppression**

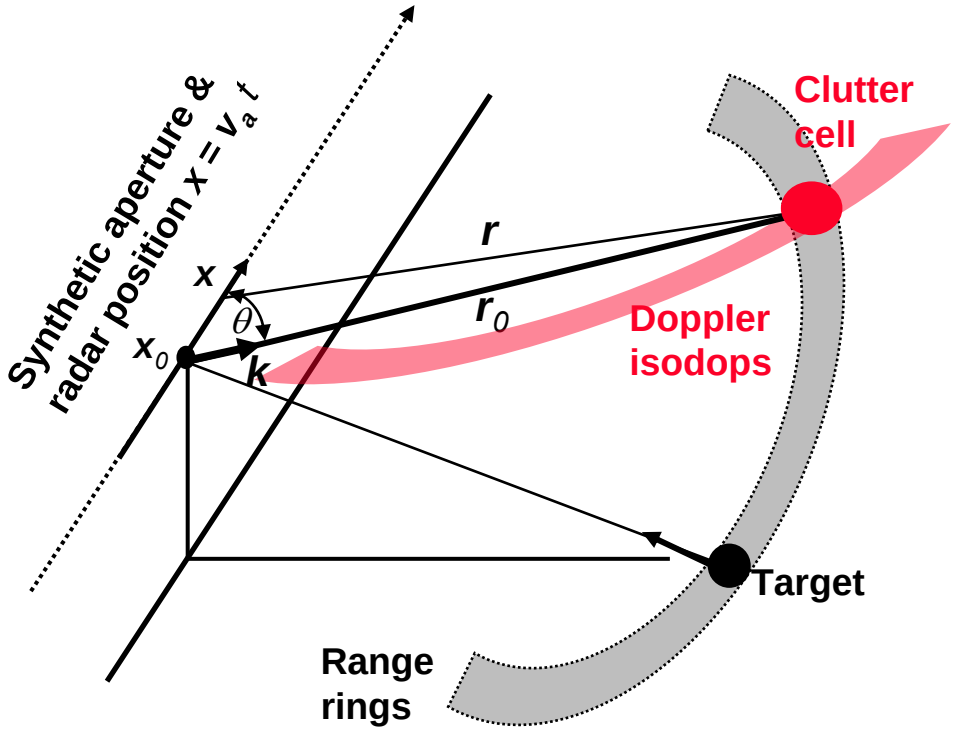
- **Objective**
  - **Develop efficient tools to quantify SAR-GMTI performance and to trade off system architecture**

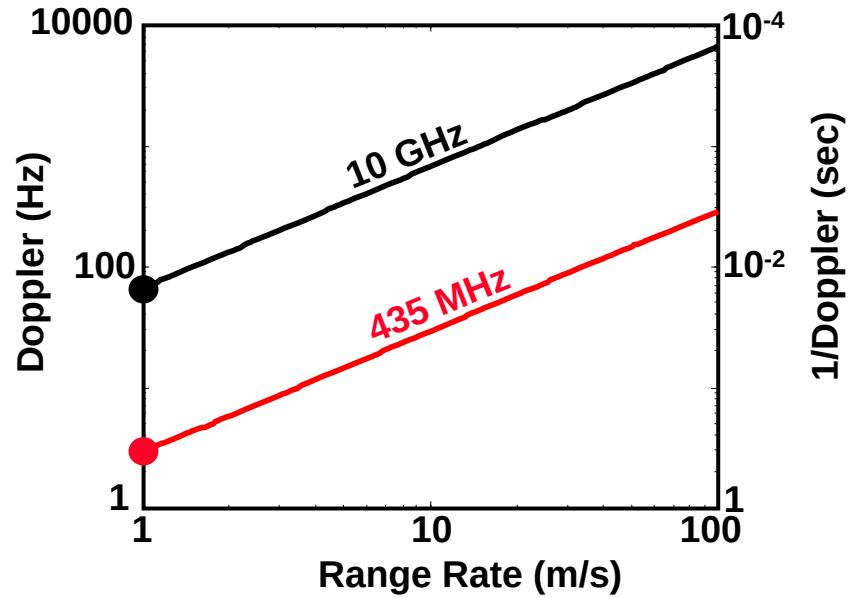
- **Presentation focus**
  - **Why multichannel SAR-GMTI?**
  - **How to do it**
  - **What's system trade off?**

Outline

- Motivation / objective
- Requirements for detecting slow ground targets in clutter
  - Long array aperture, large CPI-bandwidth, adaptive processing
- Adaptive array processing SCNR
- System parameter trade-off examples
- Summary

Side-Looking GMTI

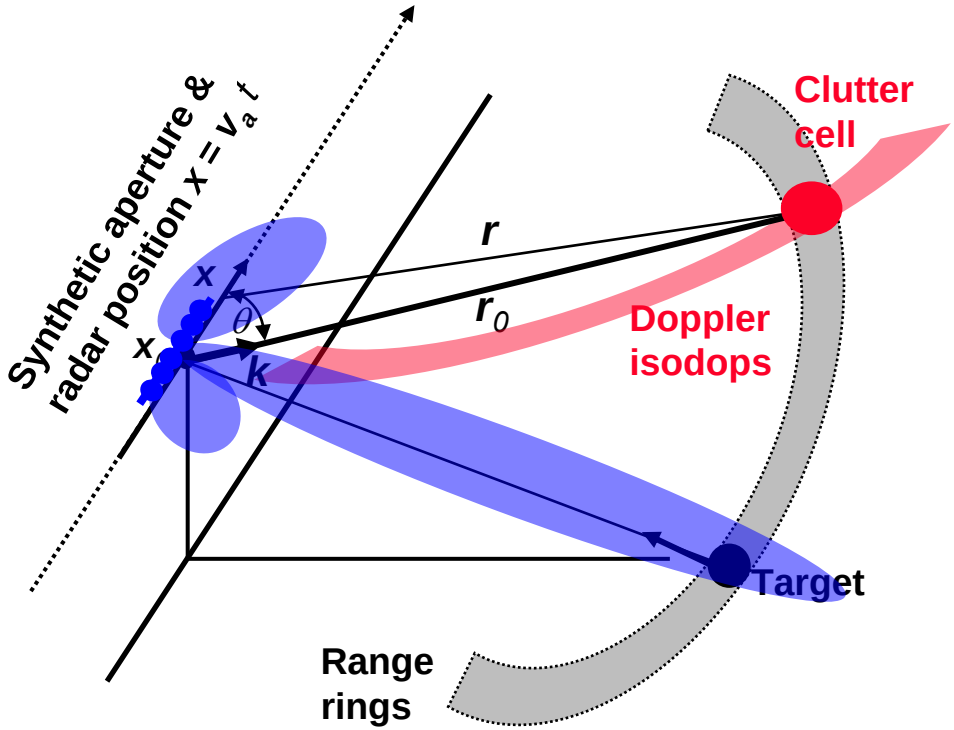


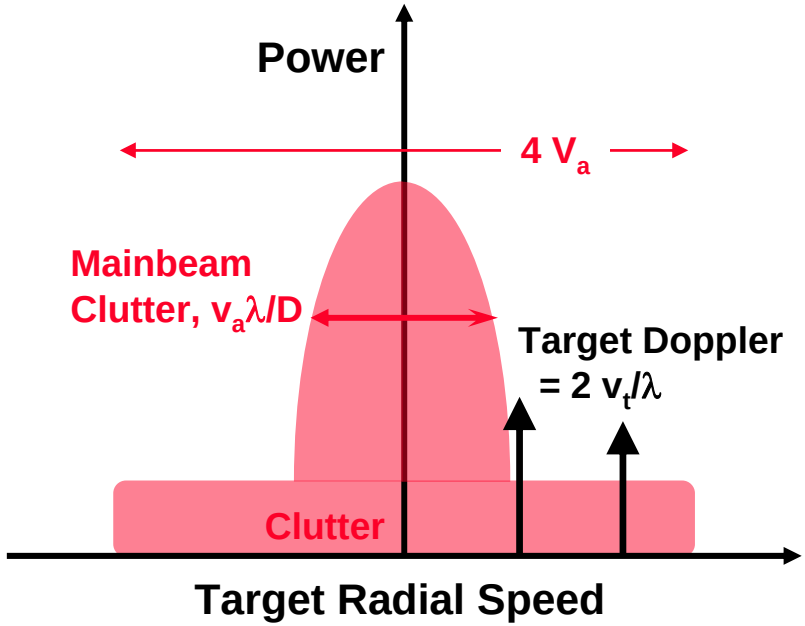


- **Conventional airborne GMTI is typically characterized by small CPI-bandwidth**
- **Doppler processing assumes linear approximation to the radar data phase history**

$$\phi = 2kr \sim 2kr_0 + \omega_d t \quad ; \quad \omega_d = -2kv_a \cos(\theta)$$

Side-Looking GMTI
(continued)





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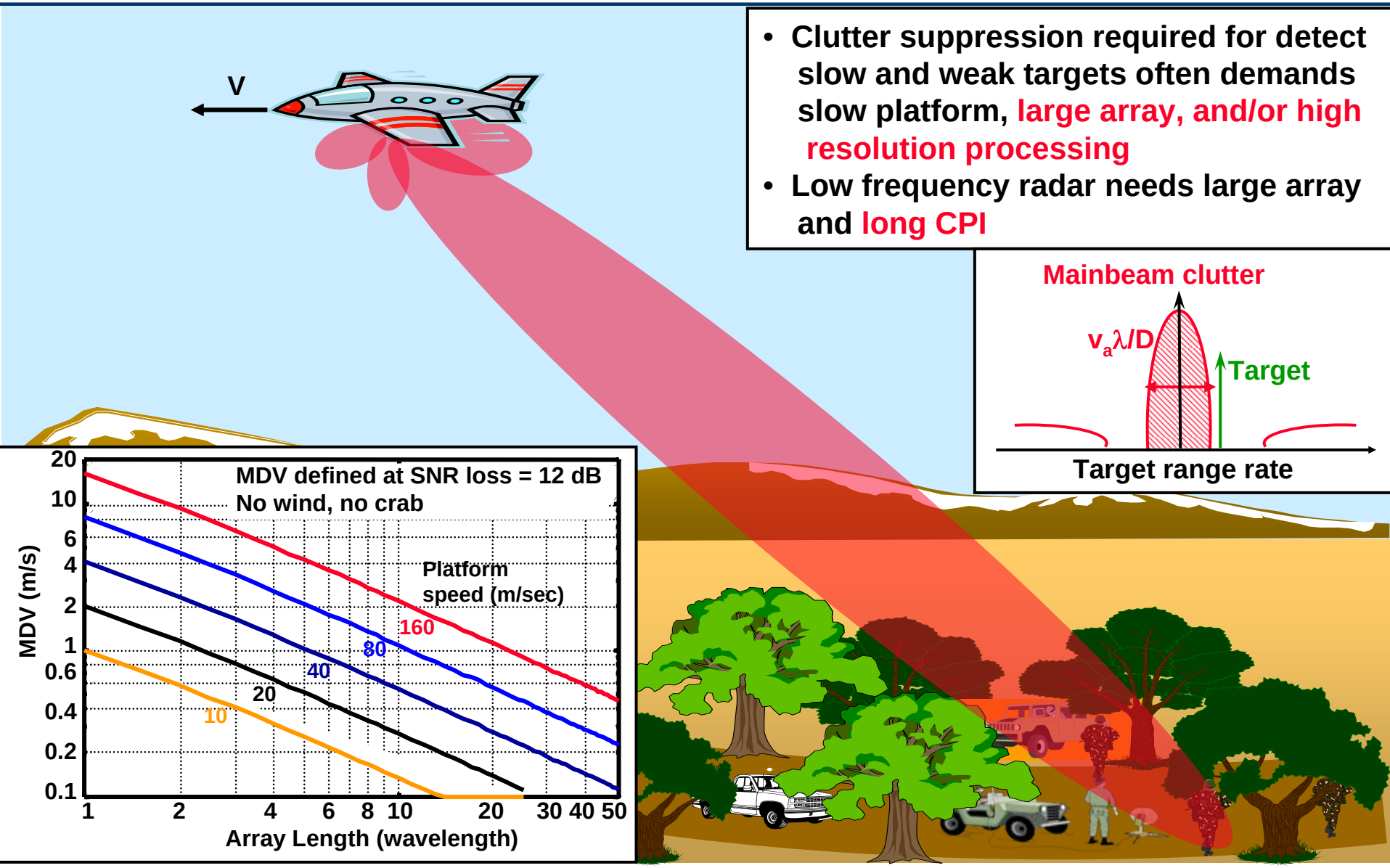
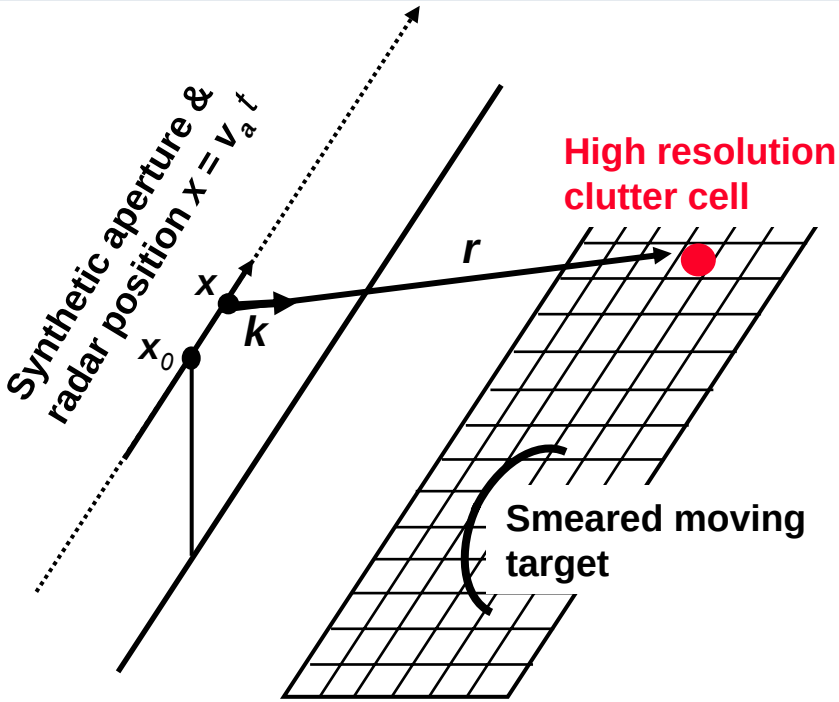
- Multichannel adaptive radar array processing improves slow target detection in endo-clutter by exploiting
  - > Angle-Doppler clutter correlation
  - > Different target and clutter angle-Doppler dependent signatures

GMTI Radar Technology Challenges

- Clutter suppression required for detect slow and weak targets often demands slow platform, large array, and/or high resolution processing
- Low frequency radar needs large array and long CPI



Side-Looking SAR

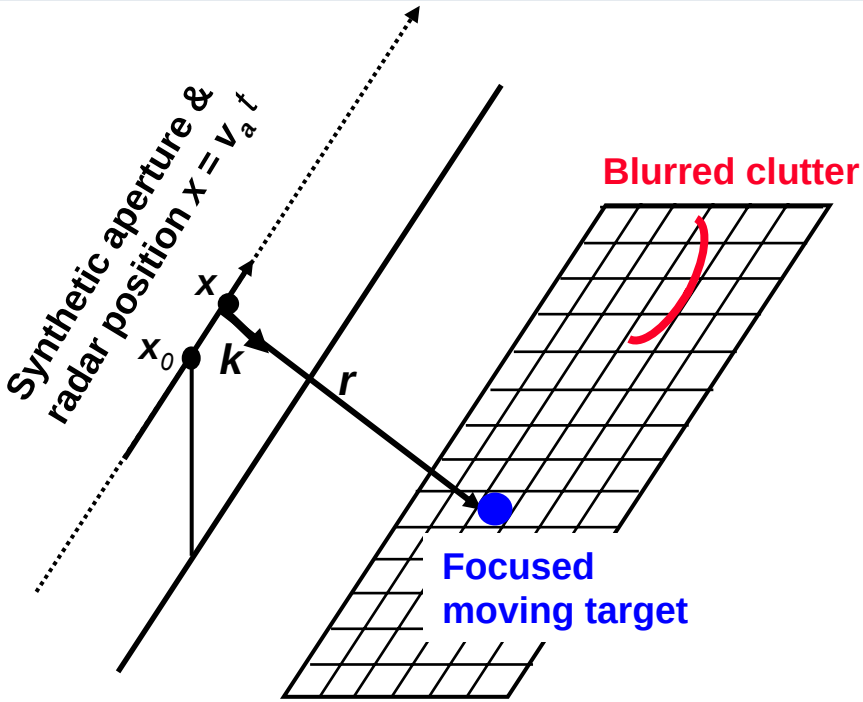


SAR processing faithfully compensate radar data phase history of each target over the entire synthetic aperture

$$\phi = 2kr = 2k|\boldsymbol{r} - \boldsymbol{x}| \quad ; \quad \boldsymbol{x} = \boldsymbol{v_a}\, t$$

- **SAR is characterized by large CPI-bandwidth and long synthetic aperture**
- **SAR imaging of stationary ground results in**
  - **High resolution ground image with reduced clutter strength and increased target-to-clutter ratios of stationary targets**
  - **Spatially displaced and blurred moving target trajectory**

Side-Looking SAR
(continued)



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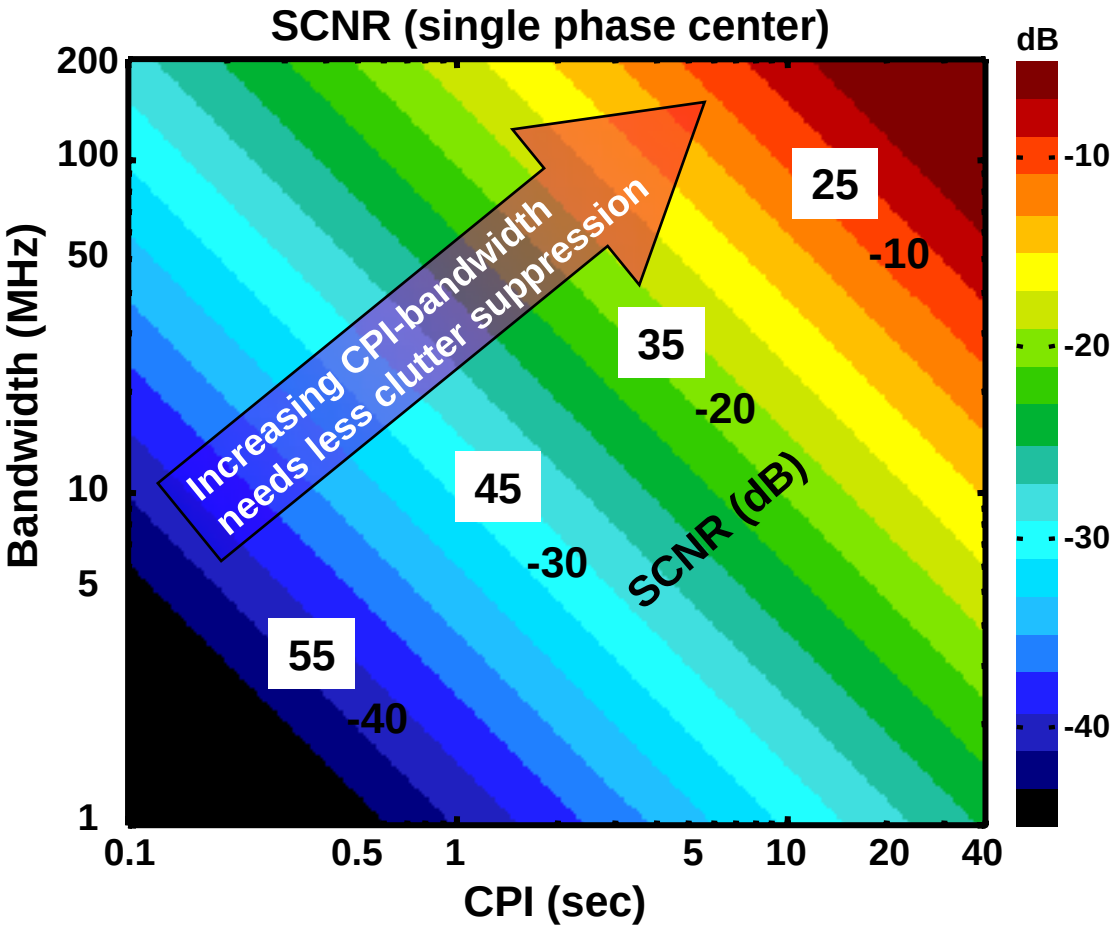
  - **Spatially displaced and blurred moving target trajectory**
- **SAR moving target imaging results in focused target and further improves target-to-clutter ratio**
- **Multichannel SAR supports adaptive array processing for clutter suppression**

Signal-to-Clutter Vs. CPI-Bandwidth



Example:

- Frequency: 430 MHz
- Radar speed: 100 m/sec
- Range: 20 km

- Target RCS: 0 dBm^2
- Target loss: 10 dB
- Tree backscatter σ_0: -10 dB

Clutter ~ inverse bandwidth
SCNR ~ CPI-bandwidth

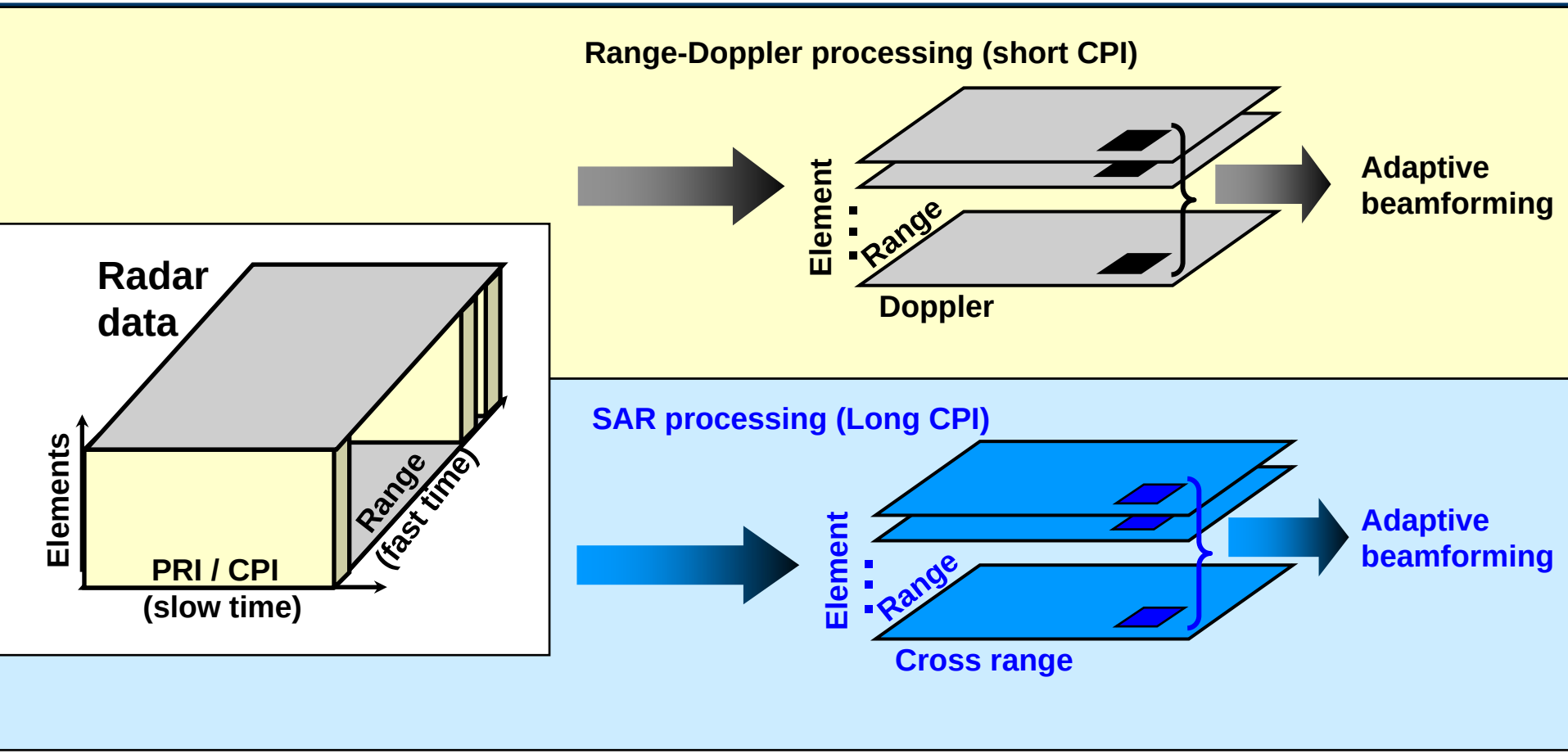
Large improvement in array SCNR required for detection (at threshold of ~15 dB)

Larger CPI-bandwidth reduces clutter suppression requirement

$$\mathrm{SCNR} = \left(\frac{\sigma_T(\text{Target loss})}{\sigma_0 \lambda^2}\right)\left(\frac{4VT_{CPI}}{R}\frac{B}{f}\right)$$

(Array gain x Clutter suppression)

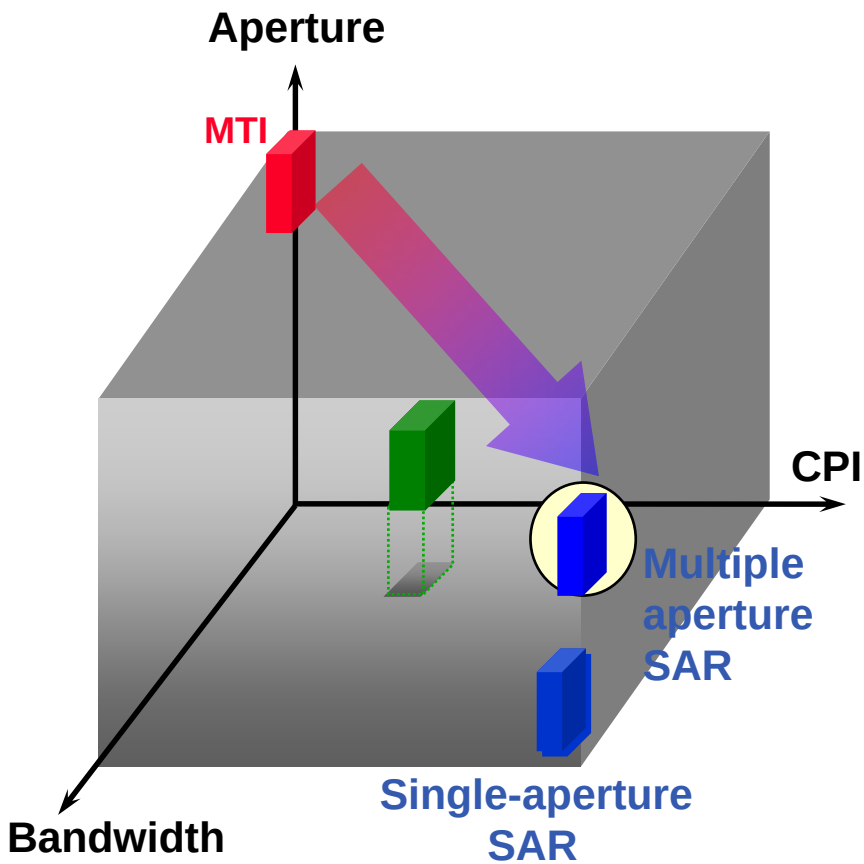
Post-Doppler / SAR Adaptive Processing



Post-SAR adaptive beamforming (ABF)

- Natural evolution of post-Doppler ABF, a degenerate case of 2D STAP
- Efficient, low DoFs 1D space-only adaptive processing, nearly optimal for long CPI
- High resolution SAR images provide ample sample support for adaptive clutter suppression and array calibration

SAR-GMTI Processing Trade Space



- Space-time adaptive processing (STAP) nulls clutter
  - Achieves noise-limited detection
  - Needs long array for low MDV
- High-resolution SAR reduces clutter strength, improves target-to-clutter
  - Requires large CPI-bandwidth
  - Enables clutter-limited detection
- Multichannel SAR-GMTI supports
  - High resolution imaging
  - Moving target focusing
  - Adaptive clutter suppression with ample sample support
  - Data-driven array calibration
- Array aperture and CPI-bandwidth may be selected to optimize performance

Outline

- Motivation / objective
- Requirements for slow ground target detection
- Adaptive array processing SCNR
  - SCNR provides one important measurement of GMTI performance
  - Inefficient numerical clutter simulation often employed for system parameter trade
  - Useful close-formed expressions derived for certain conditions to characterize SCNR dependence on arbitrary linear array structure and waveform spectrum*
- System parameter trade-off examples
- Summary

- J.K. Jao, A.F. Yegulalp, and S. Ayasli, "Unified Synthetic Aperture Space-Time Adaptive Radar Concept," MIT Lincoln Laboratory Report, NTI-4, 16 April 2004 (available from DTIC ADA423144).

Long CPI Adaptive Array Processing Loss

- **Assumptions and parameters:**

  Target with constant range rate v_r, angle-independent reflectivity

  Long CPI, unity clutter rank, *CNR* >> 1, no crab, no wind

  Aircraft velocity v_a

  Linear array, *N* elements, arbitrary placement, *nth* element at D_n, $n = 0, 1, \ldots N-1$

  Arbitrary, normalized waveform spectrum $p_B(\upsilon)$ centered at f_0

- **SNR processing loss: broad (sparse) band, large (sparse) array**

$$\text{SNR loss} \cong 1 - \left|\vec{\mathbf{t}}^{\mathrm{H}}\vec{\mathbf{c}}\right|^2 \quad ; \quad \text{Target-clutter correlation}: \vec{\mathbf{t}}^{\mathrm{H}}\vec{\mathbf{c}} = \frac{1}{\sqrt{N}\phi}\sum_{n=0}^{N-1}\phi_n(v) \quad , \quad \phi^2 = \sum_{n=0}^{N-1}\left|\phi_n(v_r)\right|^2 \quad ;$$

$$\phi_n(v_r) = \exp(-j2\pi f_0 t_n)\int_{Band} p_B(\upsilon)\exp(-j2\pi\upsilon t_n)d\upsilon \quad , \quad t_n = \frac{v_r}{v_a}\frac{D_n}{c} \qquad (c = \text{light speed}).$$

- **A special case: constant power over a bandwidth *B***

$$\mathbf{t}^H\mathbf{c} = \frac{1}{N}\sum_{n=0}^{N-1}\exp\left(-j2\pi f_0 t_n\right)\frac{\sin\left(\pi B t_n\right)}{\pi B t_n} \quad ; \quad p_B(u) = \frac{1}{\mathrm{B}}$$

Narrow Band Array Processing Loss

(A Limiting Case)

- **Assumptions:**
  - **Fully adaptive space-time processing (STAP) for clutter suppression**
  - **Narrow band, no wind, no aircraft crab**
  - **Long CPI,** $T_{CPI} >> D / v_a$
- **SNR loss bound of the MTI processing** L_{MTI}
  - **Linear, uniform, filled array**

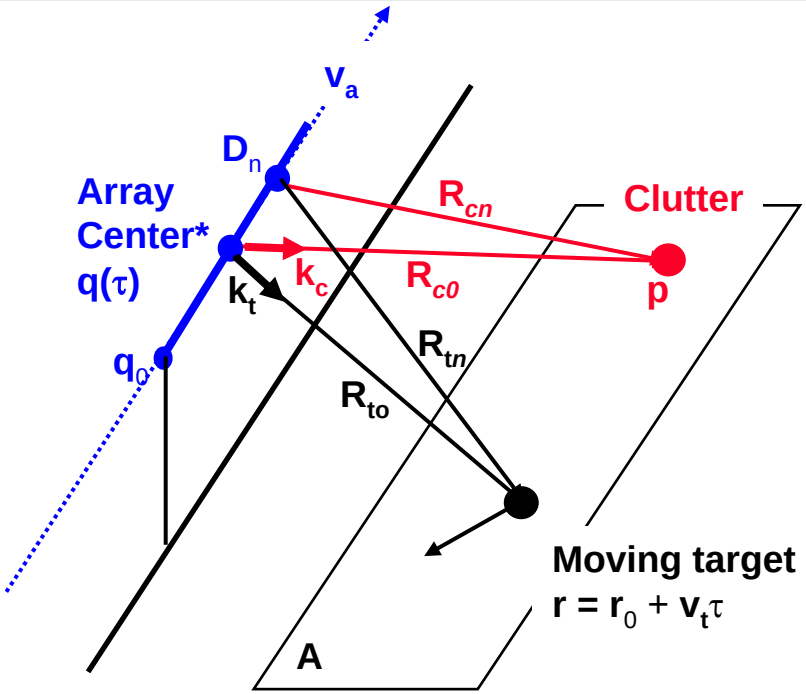
    N **array elements, element spacing** d

    D**: receiving antenna array length,** $D = (N - 1)d$
  - **Platform velocity** v_a**, target radial velocity** v_r

$$\text{SNR loss} \quad L_{MTI} \cong 1 - \frac{1}{N^2}\frac{\sin^2\left(\pi N \bar{f}_d\right)}{\sin^2\left(\pi \bar{f}_d\right)} \quad ; \quad CNR >> 1$$

$$\bar{f}_d = \frac{d}{\lambda_0}\frac{v_r}{v_a} = \left(\frac{2v_r}{\lambda_0}\right)\left(\frac{d}{2v_a}\right) \quad \text{(Normalized Doppler under DPCA condition)} .$$

Computation of Target-Clutter Correlation



Target-clutter correlation is computed as the clutter output of an ideal filter precisely matched to the target phase history

$$\phi_n(v_r) \sim \iint_A d^2\mathbf{p} \int_{CPI} d\tau \frac{c(\mathbf{p})}{R_{to}^2 R_{co}^2} \int_B df\; p_B(f) \exp\left[j\frac{2\pi f}{c}\left(R_{to} + R_{tn} - R_{co} - R_{cn}\right)\right]$$

$$\begin{aligned}
&\left(R_{to} + R_{tn}\right) - \left(R_{co} + R_{cn}\right) \\
&= \left|\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau\right| + \left|\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau + \mathbf{D}_n\right| - \left|\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau\right| - \left|\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau + \mathbf{D}_n\right| \\
&\cong 2\left(R_{to} - R_{co}\right) - \left(\mathbf{k}_t - \mathbf{k}_t\right)\cdot \mathbf{D}_n \quad ; \quad \mathbf{v} = \mathbf{v}_t - \mathbf{v}_a
\end{aligned}$$

*** Radar assumed to transmit from the array phase center. N-element receiving array, nth element at D_n**

Computation of Target-Clutter Correlation
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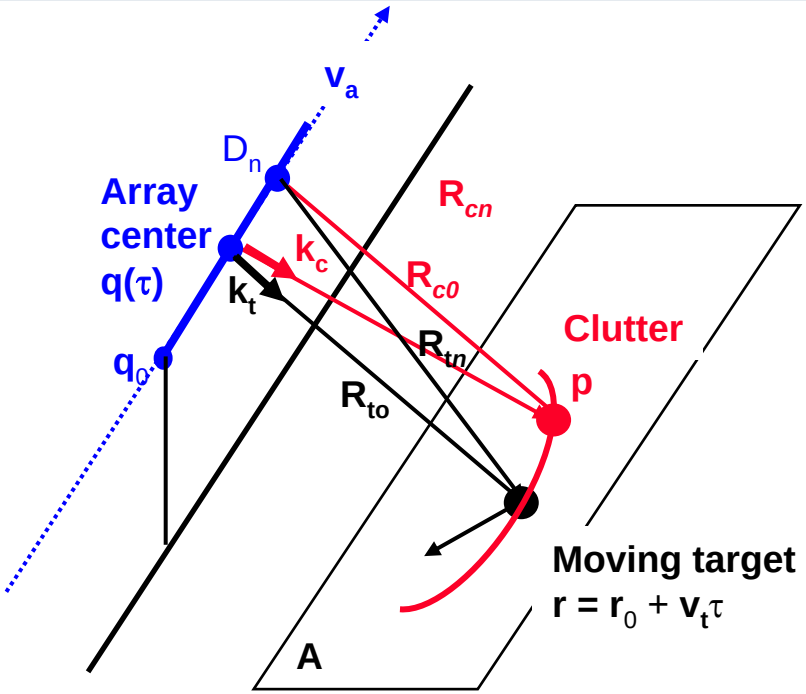


Target-clutter correlation may be approximated by the clutter integrated along the moving target migration trajectory in the SAR image domain under the stationary phase onditions

$$\phi_n(v_r) \sim \iint_A d^2\mathbf{p} \int_{CPI} d\tau \frac{c(\mathbf{p})}{R_{to}^2 R_{co}^2} \int_B df\, p_B(f) \exp\left[j\frac{4\pi f}{c} |\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau| - |\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau| \right] \exp\left[-j\frac{2\pi f}{c} (\mathbf{k}_t - \mathbf{k}_c)\cdot \mathbf{D}_n \right]$$

$$\sim \exp(-j2\pi f_0 t_n) \int_{Band} p_B(\upsilon) \exp(-j2\pi\upsilon t_n) d\upsilon \quad , \quad t_n = \frac{v_r}{v_a}\frac{D_n}{c} \quad ; \quad f = f_0 + \upsilon \ . \quad \text{(up to a scale factor)}$$

Moving target migration trajectory determined by the stationary phase conditions:

Equal range: $|\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau| = |\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau|$

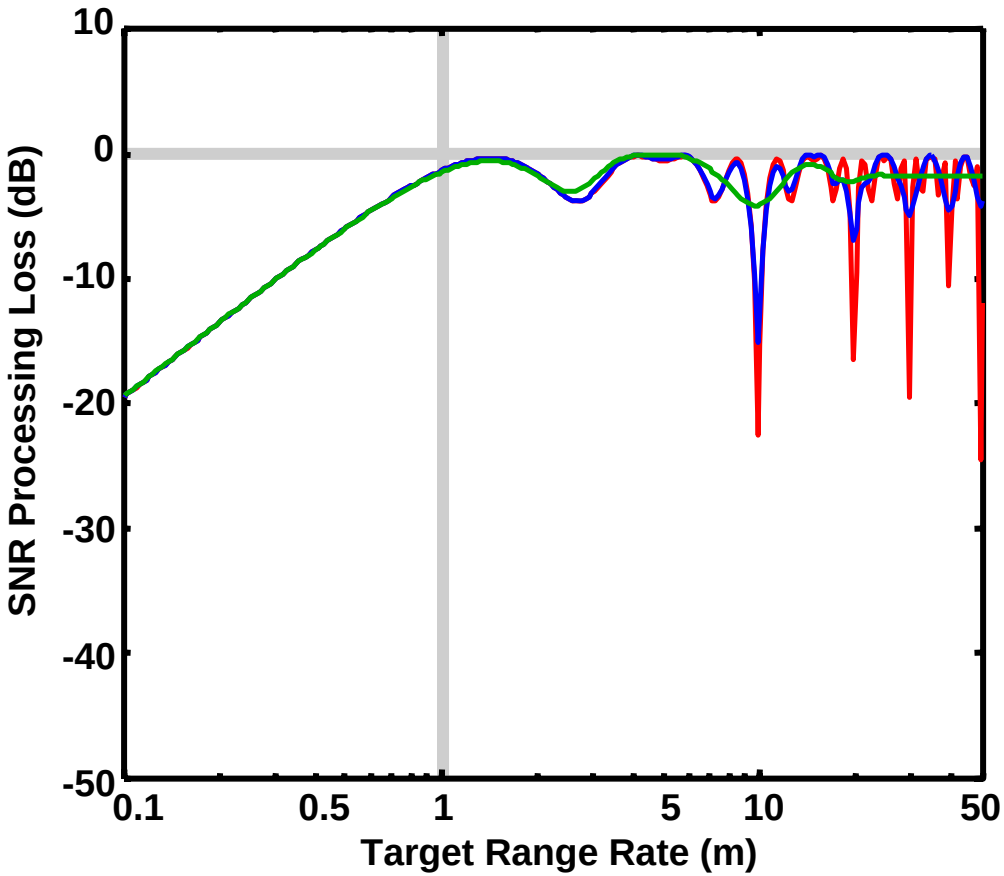
Equal Doppler: $\dfrac{\mathbf{v}\cdot(\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau)}{|\mathbf{r}_0 - \mathbf{q}_0 + \mathbf{v}\tau|} = -\dfrac{\mathbf{v}_a\cdot(\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau)}{|\mathbf{p} - \mathbf{q}_0 - \mathbf{v}_a\tau|}$ or $(\mathbf{v}_t - \mathbf{v}_a)\cdot\mathbf{k}_t = -\mathbf{v}_a\cdot\mathbf{k}_c$

Outline

- Motivation / objective
- Requirements for slow ground target detection
- Adaptive array processing SCNR
- System parameter trade-off examples
  - SCNR dependence on bandwidth
  - SCNR dependence on array structure
- Summary

SNR Loss in Adaptive Clutter Cancellation

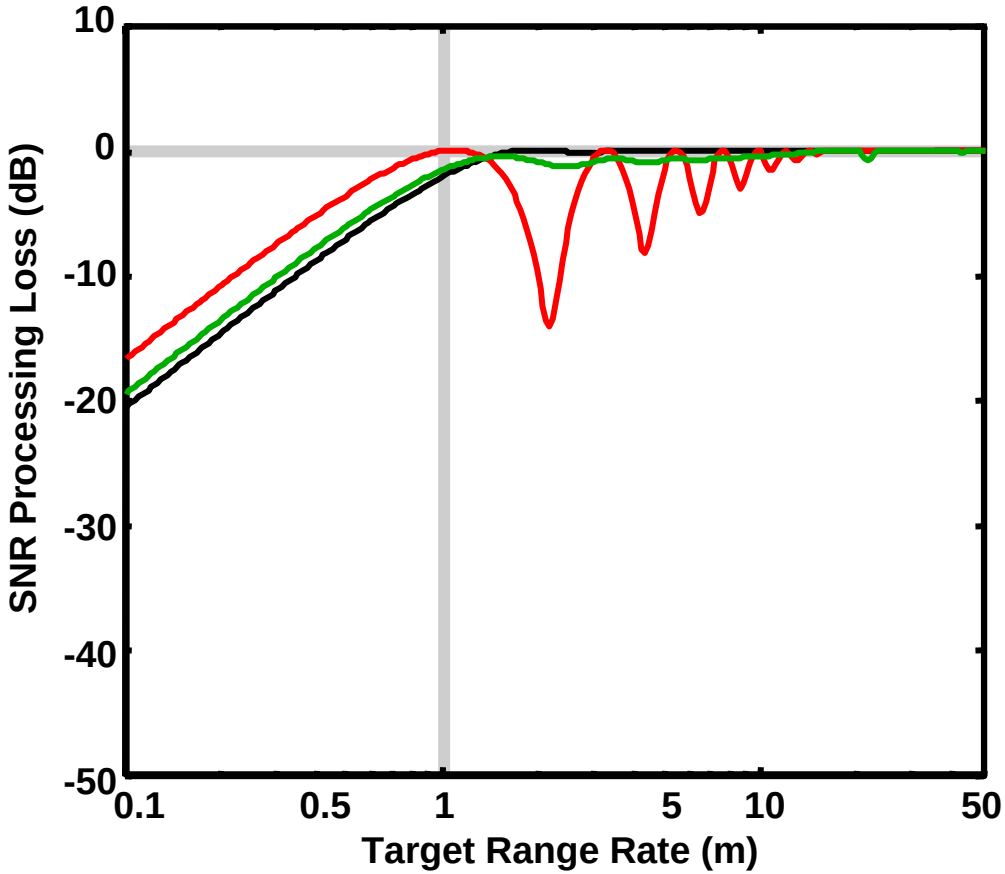
Dependence On Bandwidth

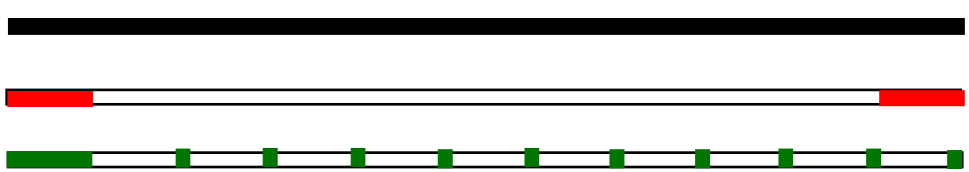


- **Platform speed: 100 m/s**
  - **Long CPI**
  - **3-element array, elements at [0 7.5 30] m**
- **Single band, various bandwidth centered at 400 MHz**
  - **1% bandwidth CNR: 50 dB**
  - **10% bandwidth CNR: 40 dB**
  - **50% bandwidth CNR: 33 dB**

SNR Loss in Adaptive Clutter Cancellation

Dependence on Array Structure



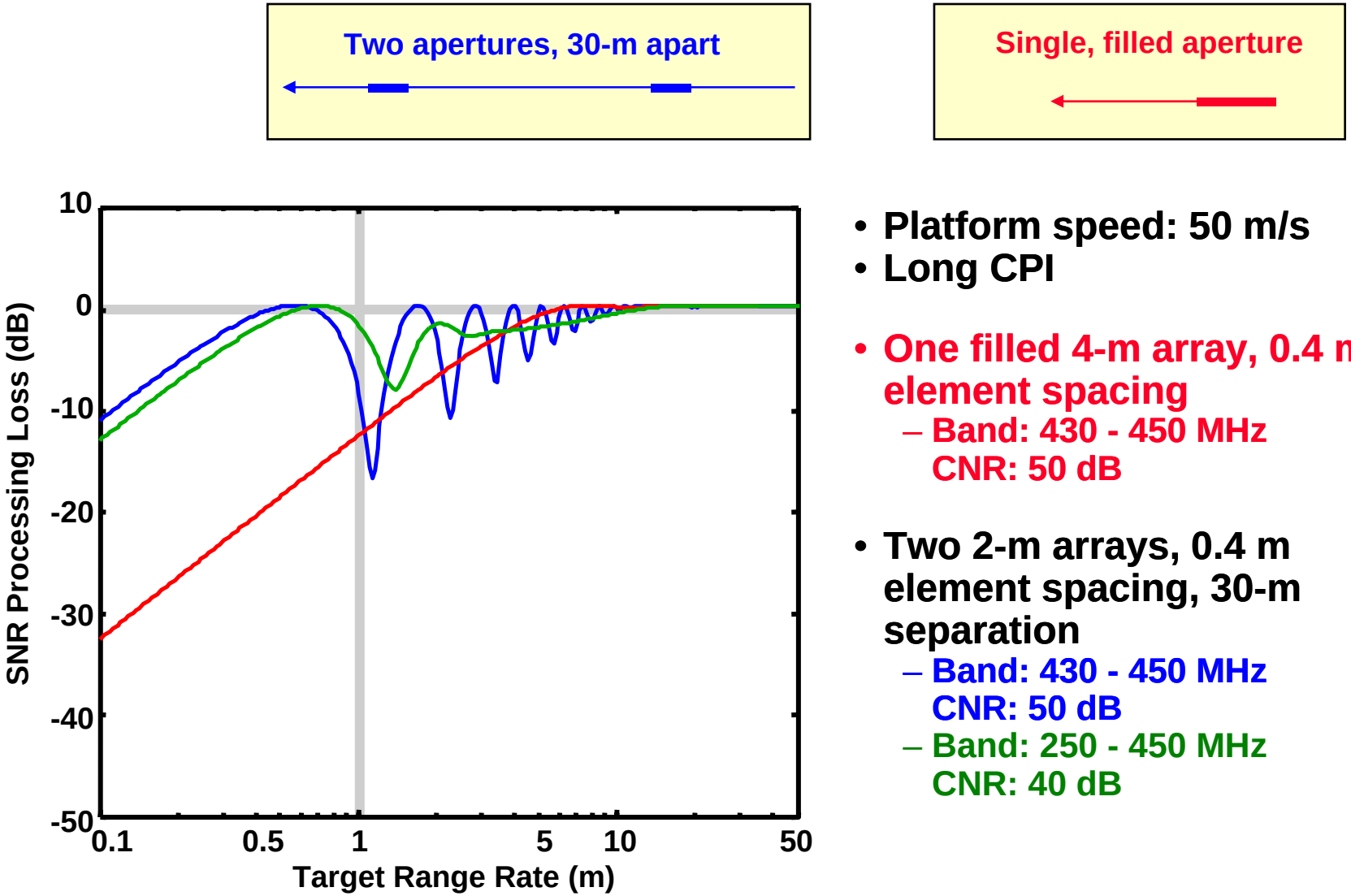


- Platform speed: 100 m/s
- 420 – 450 MHz
- Long CPI
- CNR = 50 dB
- Array length: 35 m

- One filled array
  - 101 elements, 0.35-m spacing
- Two subarrays at ends
  - 10 elements for each subarray
  - Elements at [0 : 0.35 : 3.15] and [31.85 : 0.35 : 35]
- 20-element sparse array
  - One 10-elment subarray, elements at [0 : 0.35 : 3.15]
  - 10 more elements with 3.15 m spacing at [6.65 : 3.5 : 35] m

SNR Loss in Adaptive Clutter Cancellation

Another Example



- Platform speed: 50 m/s
- Long CPI
- One filled 4-m array, 0.4 m element spacing
  - Band: 430 - 450 MHz
    CNR: 50 dB
- Two 2-m arrays, 0.4 m element spacing, 30-m separation
  - Band: 430 - 450 MHz
    CNR: 50 dB
  - Band: 250 - 450 MHz
    CNR: 40 dB

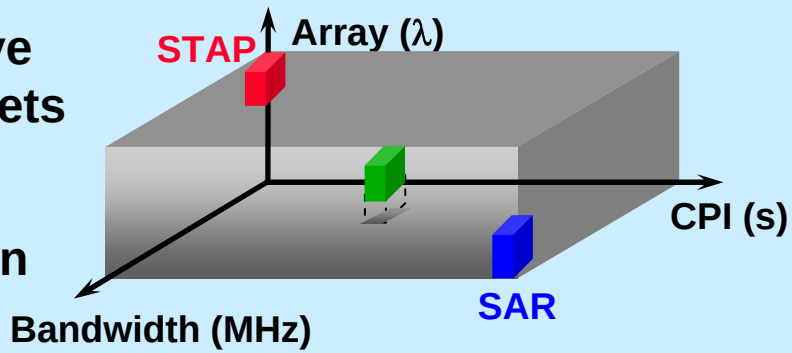
Wide-Area Multichannel SAR-GMTI Sensor

- **Airborne High- or low-frequency GMTI radar sensitivity often respectively favored by open or obscured target environment**
  - **High microwave frequency offers many benefits for detecting movers in the clear**
  - **UHF generally best for detecting movers under trees**

- **Adaptive multi-channel high-resolution array processing enables slow target detection**

Primary challenges	Solutions
All terrain (concealed, foliage-masked)	Low frequencies
Very slow targets (~< 1 m/sec)	Long array (sparse as necessary)
Velocity ambiguity	Broad band (sparse as necessary)
Low target RCS, slow motion	Long CPI
Strong clutter cancellation	Adaptive array processing
Target migration and movement	Moving target focusing, change detection

- **Previous field tests demonstrated effective SAR-GMTI detection of slow ground targets**
- **Efficient tools derived to facilitate optimization of system array configuration and waveform spectrum**



Summary

- **Detection of slow and weak targets demands SAR-GMTI processing with large aperture and CPI-bandwidth**

- **Multichannel SAR-GMTI extend conventional MTI processing to large CPI-bandwidth**
  - **Operating on same array element-range-pulse data**
  - **Transition of MTI to SAR requires better radar motion compensation**
  - **Fully time-delay compensated SAR may focus either moving or stationary target at high resolution**
  - **Adaptive clutter cancellation improves moving target MDV**
  - **Performance may depend on CPI-bandwidth and array**

- **Analytic SCNR expression useful for efficient optimization of multichannel SAR-GMTI array and waveform design**