Multichannel SAR-GMTI
Clutter Cancellation Performance*

Challenges In Synthetic Aperture Radar
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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
• Conventional airborne GMTI is typically characterized by small CPI-bandwidth
• Doppler processing assumes linear approximation to the radar data phase history

\[ \phi = 2kr \sim 2kr_0 + \omega_d t \quad ; \quad \omega_d = -2kv_a \cos(\theta) \]
• Conventional airborne GMTI is typically characterized by small CPI-bandwidth
• Doppler processing assumes linear approximation to the radar data phase history
  \[ \phi = 2kr \sim 2kr_0 + \omega_d t \quad ; \quad \omega_d = -2kv_a \cos(\theta) \]
• 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

![Diagram showing GMTI radar technology challenges with plots for MDV and platform speed](image)

- MDV defined at SNR loss = 12 dB
  - No wind, no crab

<table>
<thead>
<tr>
<th>MDV (m/s)</th>
<th>Platform speed (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
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<tr>
<td>10</td>
<td>20</td>
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<tr>
<td>6</td>
<td>40</td>
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<tr>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
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</tbody>
</table>

- Target range rate
- Mainbeam clutter
  - $v_a \lambda/D$

Jao 01/25/12
Side-Looking SAR

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

\[ \phi = 2kr = 2k|r - x| \quad ; \quad x = v_a t \]

- 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
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  - High resolution ground image with reduced clutter strength and increased target-to-clutter ratios of stationary targets
  - 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 dBm²
- Target loss: 10 dB
- Tree backscatter $\sigma_0$: -10 dB

Clutter $\sim$ inverse bandwidth
SCNR $\sim$ CPI-bandwidth

Large improvement in array SCNR required for detection
(at threshold of $\sim$15 dB)

Larger CPI-bandwidth reduces clutter suppression requirement

$$\text{SCNR} = \left( \frac{\sigma_T (\text{Target loss})}{\sigma_0 \lambda^2} \right) \left( \frac{4V T_{CPI} B}{R f} \right)$$ (Array gain x Clutter suppression)
Post-Doppler / SAR Adaptive Processing

Range-Doppler processing (short CPI)

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 processing (Long CPI)
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

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, $n$th element at $D_n$, $n = 0, 1, \ldots N-1$
- Arbitrary, normalized waveform spectrum $p_B(\nu)$ centered at $f_0$

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

\[
\text{SNR loss} \approx 1 - \left| \mathbf{t}^H \mathbf{c} \right|^2 ; \quad \text{Target-clutter correlation: } \mathbf{t}^H \mathbf{c} = \frac{1}{\sqrt{N\phi}} \sum_{n=0}^{N-1} \phi_n(\nu) , \quad \phi^2 = \sum_{n=0}^{N-1} |\phi_n(\nu)|^2 ;
\]

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

A special case: constant power over a bandwidth $B$

\[
\mathbf{t}^H \mathbf{c} = \frac{1}{N} \sum_{n=0}^{N-1} \exp(-j2\pi f_0 t_n) \frac{\sin(\pi B t_n)}{\pi B t_n} ; \quad p_B(\nu) = \frac{1}{B}
\]
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 $v_r$

\[
\text{SNR loss } L_{MTI} \approx 1 - \frac{1}{N^2} \frac{\sin^2 (\pi N \tilde{f}_d)}{\sin^2 (\pi \tilde{f}_d)} \quad ; \quad \text{CNR} >> 1
\]

\[
\tilde{f}_d = \frac{d}{\lambda_0} \frac{v_r}{v_a} = \left( \frac{2v_r}{\lambda_0} \right) \left( \frac{d}{2v_a} \right) \text{ (Normalize d Doppler under DPCA condition)}
\]
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.

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

\[
(R_{to} + R_{tn}) - (R_{co} + R_{cn}) = |r_0 - q_0 + v_\tau| + |r_0 - q_0 + v_\tau + D_n| - |p - q_0 - v_a\tau| - |p - q_0 - v_a\tau + D_n| \\
\approx 2(R_{to} - R_{co}) - (k_t - k_c) \cdot D_n ; \quad v = v_t - v_a
\]

* Radar assumed to transmit from the array phase center. N-element receiving array, nth element at \(D_n\)
Computation of Target-Clutter Correlation
(continued)

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 conditions.

\[
\phi_n(\nu) \sim \int_A \int_{\nu} \int_{\tau} \int_{f} \frac{c(p)}{R_{t0}^2 R_{c0}^2} p_B(f) \exp \left[ j \frac{4\pi f}{c} |r_0 - q_0 + v_\tau - |p - q_0 - v_a \tau| \right] \exp \left[ - j \frac{2\pi f}{c} (k_t - k_c) \cdot D_n \right] \]

\[
\sim \exp(-j2\pi f_0 t_n) \int_{\text{Band}} p_B(\nu) \exp(-j2\pi \nu t_n) d\nu \quad t_n = \frac{v_r}{v_a} \frac{D_n}{c} \quad f = f_0 + \nu \quad \text{(up to a scale factor)}
\]

Moving target migration trajectory determined by the stationary phase conditions:

Equal range:
\[
|r_0 - q_0 + v_\tau| = |p - q_0 - v_a \tau|
\]

Equal Doppler:
\[
\frac{v \cdot (r_0 - q_0 + v_\tau)}{|r_0 - q_0 + v_\tau|} = \frac{v_a \cdot (p - q_0 - v_a \tau)}{|p - q_0 - v_a \tau|} \quad \text{or} \quad (v_t - v_a) \cdot k_t = -v_a \cdot k_c
\]
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-element 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

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