Simulation and Analysis of Adaptive Interference Suppression for Bistatic Surveillance Radars*

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13 March 2001

*This work was sponsored under United States Air Force Contract F19628-00-C-002. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.
Outline

Problem Overview

- Bistatic Algorithms - Description and Analysis

- Summary and Future Work
Problem Overview

Bistatic geometry involves separate transmit and receive platforms
- Platforms are moving independently

Receive only platform for surveillance or strike
- Extend coverage area
- Improve target localization
- No transmitter on receive platform
  Reduce size, weight, power
  Improve stealthiness

Case 1
- Standoff Illuminator
  Altitude: 10 km
  Speed: 180 m/s

Case 2
- Satellite Illuminator
  Altitude: 800 km
  Speed: 7460 m/s
- Receive Platform
  Altitude: 6 - 16 km
  Speed: 180 m/s
Challenges for Bistatic Operation

- Benefits of bistatic operation come at a price
  - Azimuth / Doppler structure of clutter interference varies with range
- Challenge is to find training strategies to estimate covariance $R$
Algorithm Development Approach

- Covariance model is used to compare algorithms with
  - large number of geometries
  - coarse range sampling
- Modeling goal is to quickly survey algorithm performance
  - simplified scattering model
- Time series model is used to compare algorithms with
  - small number of geometries
  - fine scale range sampling
- Designed to examine “real world” effects on algorithm performance
Outline

• Problem Overview

• Bistatic Algorithms - Description and Analysis
  - Algorithm description
    - “Standard” 2 - bin Post - Doppler
    - 2 - bin Post - Doppler with Derivative Based Updating (DBU)
      - *Uses only radar data but doubles the degrees of freedom (DOF’s)*
        - Requires increased sample support
    - 2 - bin Post - Doppler with High Order Doppler Warping (HODW)
      - *Uses knowledge of bistatic clutter ridge*
        - Receiver must know position and velocity of transmitter
  - Algorithm performance

• Summary and Future Work
2 - Bin Post - Doppler Algorithm

- Two-Bin nulling algorithm:
  - Train on clutter in Doppler bin #’s 1 and 2 to null clutter at the target Doppler frequency
- Well established approach for monostatic STAP applications
  - Typically assume range invariance and estimate covariance with range average
Derivative-Based Updating Algorithm

- Derivative-Base Updating Algorithm (DBU):

- Assumes weight vector varies linearly with range
  - Effectiveness depends on accuracy of weight vector model

- Doubles the number of degrees of freedom (DOF) in the STAP problem
  - Covariance matrix size is doubled
  - Number of training samples required to estimate covariance is doubled

\[ w(r) = w_0 + r \frac{dw}{dr} \]
Derivative Based Updating - Interpretation

- Assume optimal filter \( w_k = w_0 + k w' \) (at \( k^{th} \) relative range gate)
- \( w_k^H x_k = w_0^H x_k + k w'^H x_k = [ w_0^H \ w'^H ] [ x_k ; k x_k ] \)
- Form sample set based on extended vector \( [ x_k ; k x_k ] \) to obtain extended covariance

\[
R_{est} = \left( \frac{1}{N} \right) \begin{bmatrix}
\sum_k x_k x_k^H & \sum_k k x_k x_k^H \\
\sum_k k x_k x_k^H & \sum_k k^2 x_k x_k^H
\end{bmatrix}
\rightarrow
\begin{bmatrix}
R_0 & \alpha & R' \\
\alpha & R' & \alpha R_0
\end{bmatrix}
\left( \alpha = \sum k^2 \right)
\]

\[
[ w_0^H \ w'^H ] [ x_k ; k x_k ] = [ v^H \ 0 ] (R_{est})^{-1} [ x_k ; k x_k ] = v^H D_k^{-1} x_k
\]

(have used sample set symmetry (\( \sum k = 0 \)) and \( R_k = < x_k x_k^H > = R_0 + k R' \))

**DBU equivalent to applying filter** \( w_k = D_k^{-1} v \) with \( D_k^{-1} = (I - k R_0^{-1} R') (R_0 - \alpha R' R_0^{-1} R')^{-1} \)

- First order perturbation: \( R_k^{-1} = (R_0 + k R')^{-1} \approx (I - k R_0^{-1} R') R_0^{-1} \)
  - DBU matches perturbation up to terms quadratic in \( R' \)
  - the \( \alpha \) term grows quadratically with the size of training set
High Order Doppler Warping (HODW)

- In each Doppler filter apply a range-dependent Doppler frequency shift
  - Shift is different in each Doppler filter, at each range
    
    Original warping algorithm used same shift in each Doppler filter

    Clutter ridge calculation requires knowledge of transmitter position and velocity
High-Order Doppler Warping
Bistatic Space to Air Example

Clutter Ridges Over 6 km at Target Range

- Frequency shift is derived from the clutter ridge geometry
  - Clutter ridge multiplicity (front lobe / back lobe, aliasing) resolved by choosing highest transmit power branch
- “High Order” Warping has made the clutter interference range invariant” on a bin by bin basis
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• Bistatic Algorithms - Description and Analysis
  – Algorithm description
    – “Standard” 2-bin Post - Doppler
    – Derivative Based Updating
    – High Order Doppler Warping
  ➔ Algorithm performance

• Summary and Future Work
Measuring Performance

- Standard measure of performance is \( \text{SINR Loss} \)
- For signal element response vector \( v \) ( \( |v|^2 = 1 \) ) and filter \( w \):
  
  \[
  \text{SINR} = \frac{|s|^2}{|w^H v|^2 / (w^H R w)}
  \]
  
  where \( R \) is the true “interference + noise” covariance matrix \( <x x^H> \) and \( s \) is the signal amplitude

- For uncorrelated noise (unit power) \( <n n^H> = I \) and with \( w = v \)
  
  \[
  \text{SNR} = \frac{|s|^2}{|v^H v|^2 / (v^H v)} = |s|^2
  \]

- For correlated noise \( <n n^H> = N \) and with \( w = N^{-1} v \)
  
  \[
  \text{SNR} = \frac{|s|^2}{|v^H N^{-1} v|^2 / (v^H N^{-1} v)} = |s|^2 \frac{v^H N^{-1} v}{v^H N^{-1} v}
  \]

- Ratio is \( \text{SINR Loss} = \frac{|w^H v|^2}{(w^H R w) (v^H N^{-1} v)} \leq 1 \)
  
  - Optimal \( w = R^{-1} v \) and \( \max(\text{SINR Loss}) = v^H R^{-1} v / (v^H N^{-1} v) \)
  
  - In practice use estimated \( R_{est} \) and \( w = R_{est}^{-1} v \)
Case 1:  Air to Air Geometry

Transmitter
- Altitude: 10 km
- Speed: 180 m/s
- Heading: North
- Freq.: 5.2 GHz
- Bandwidth: 5 MHz
- Array Elements: 8 Hor. X 24 Ver.

Receiver
- Altitude: 16 km
- Speed: 180 m/s
- Heading: North
- Array Elements: 32 Hor. X 1 Ver.
- # DOFs: 32

- Moderate variation of clutter ridge with range

Training Region - 20 km
Receiver Beamwidth - 4.6 deg.
Algorithm Performance - Bistatic Air to Air
(Case 1)

- Standard Sample Covariance Matrix approach significantly degraded
  - Only moderate variation of clutter interference structure across training region
  - Standard approach preserves 60% of useable Doppler space (UDSF)
- Both DBU and HODW methods yield near-ideal performance
  - DBU preserves 80% UDSF, HODW 85%, Ideal 85%
Case 2: Space to Air Geometry

Transmitter
- Altitude: 800 km
- Speed: 7540 m/s
- Heading: North
- Freq.: 5.2 GHz
- Bandwidth: 12 MHz
- Array Elements: 501 Hor. X 51 Ver.

Receiver
- Altitude: 6 km
- Speed: 200 m/s
- Heading: -86° wrt North
- Array Elements: 36 Hor. X 24 Ver.
- # DOFs: 36
- CNR: 40 dB

- Clutter ridge varies rapidly with range

Training Region - 4 km
Receiver Beamwidth - 2.8 deg.
3 dB Transmitter Beamwidth

- R
- T
- 75 km
- 569 km
- Target
• Standard Sample Covariance Matrix approach performs poorly
  – Very rapid variation of clutter interference structure across training region
  – Much worse performance than in air to air case
  – UDSF degrades from 45% with 4 km training to 25% with 6km training
• Both DBU and HODW methods again yield near - ideal performance
  – UDSF is 80% for both DBU and HODW, UDSF for ideal is 90%
Bistatic STAP Algorithms - Recap

• Standard training approach for STAP works poorly
  – Poor choice for non-stationary interference

• DBU approach
  – Advantages
    No knowledge of transmitter position and velocity required
  – Disadvantages
    Doubles the STAP degrees of freedom
    Doubles the number of training samples required
    Increases cost of weight computation by factor of 8
    No significant impact on weight application computation

• HODW Approach
  – Advantages
    No increase in degrees of freedom required
    Fully adaptive in spatial dimension
  – Disadvantages
    Requires knowledge of transmitter position and velocity
    Increased complexity of Doppler filtering
    FFT techniques may not be possible
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Summary

- Bistatic clutter interference suppression poses new challenges
  - Clutter interference exhibits strongly range dependent structure
- Doppler warping technique generalized
  - “High Order Doppler Warping” algorithm
- 2-bin Post- Doppler Algorithms examined both with covariance analysis and more realistic direct time series analysis
- Preliminary assessments of selected algorithms in Air - to - Air and Space - to - Air bistatic scenarios presented
  - All algorithms rely on sample average over range to estimate clutter interference covariance
  - Standard training - POOR
    (no attempt to address range variation)
  - Derivative Based Updating (DBU) - GOOD
    Requires doubling problem dimensionality
  - High Order Doppler Warping (HODW) - GOOD
    Requires knowledge of transmitter position and velocity
    Doppler filter implementation more complex
Future Directions

- Extend analyses to other engagement geometries
- Assess impact of imperfections
  - Array element calibration uncertainties
    - Both DBU and HODW are fully data adaptive in the spatial dimension
      - No deterministic spatial transformations
      - Anticipate impact similar to that on monostatic STAP
  - Engagement geometry uncertainties
    - HODW requires \textit{a priori} knowledge of transmitter position and velocity
- Develop computational complexity estimates for HODW
  - Determine optimal implementation strategy