Overview

- **STAP**: Detection of weak signals in stressful environments
  - The data cube
  - Steering Vectors
  - Beam Patterns
  - Components of the data
    - Clutter ridge, noise and discrete jammers, noise
  - Non-adaptive techniques
    - MTI, DPCA, Matched Filter
  - Optimal techniques
    - Wiener Filter, Minimum Output Energy
  - Fully Adaptive STAP
    - SMI, MSMI, Kelly’s Test
  - Reduced dimension techniques
    - Principal Components, CSM
    - Factored approaches
  - Original JDL, Sigma-Delta Σ-Δ
  - JDL for practical arrays
    - Transformation matrix
    - Implementation
  - Non-homogeneity detection
    - GIP
    - STAP based NHD
    - Implementation
  - D³ Processing
    - Sarkar’s original method
    - Two dimensional extension
    - Implementation
  - Hybrid Algorithm
    - Implementation
  - KB-STAP
    - Implementation
Space-Time Adaptive Processing

Goal: Find $w$

Airborne Interference Scenario
Airborne Moving Target Indication

AMTI: Discriminate between clutter and target using Doppler

Displaced Phased Center Antenna

- DPCA: Maintain constant phase center over successive pulses and subtract sections appropriately
- Follow with Doppler filtering
- Velocity and PRF must match

Pictures from "Introduction to Airborne Radar", G.W. Stimson, SciTech Publishing Inc.
Fully Adaptive STAP

Estimating the covariance matrix

- Issues of
  - Availability of secondary data
  - Computation load

- Fully adaptive STAP is impossible to implement in practice

STAP Processing Domains

Spatial Transform

Space-Time Data

Doppler Transform

Space-Doppler Data

2D Transform

Angle-Time Data

Doppler Transform

Angle-Doppler Data

JDL algorithm
(Wang and Cai 1994)
Joint Domain Localized Processing

Transformation shown for primary range only. All ranges are transformed.

Measured Steering Vectors

\[ \mathbf{s} = \begin{bmatrix} e^{jkd\sin(\theta)} & e^{2kd\sin(\theta)} & \cdots & e^{(N-1)kd\sin(\theta)} \end{bmatrix}^T \]

\(-\text{Constant Magnitude}\)

- Ideal Array
- MCARM Array
JDL For Real Arrays

Implementation of JDL

1. Choose the size of the LPR, i.e. $\eta_a$ and $\eta_d$. These numbers are usually odd. Common choices are 3, 5 or 7.
2. Choose the number of secondary data vectors that will be used to estimate the covariance matrix (usually of the order of $2\eta_a \eta_d - 4\eta_a \eta_d$) and the number of guard cells (usually 2-4).
3. If using tapers in space and time, choose a length $N$ taper in the space domain $t_a$ and a length $M$ taper $t_d$ in the temporal domain.
4. Set the angle bin to be the direction in which the radar signal is transmitted. Choose a set of $\eta_a$ angles centered around (and including) the look angle.
5. For each Doppler bin of interest, repeat the following steps:
6. Choose a set of $\eta_d$ Doppler bins centered around (and including) the look Doppler. Use the set of angles and Doppler bins to form the transformation matrix $T$.
7. Transform the entire datacube to the angle-Doppler space.
8. Form the JDL steering vector. This vector is fixed for all range bins.
9. For each range bin, repeat the following steps:
10. Estimate an angle-Doppler covariance matrix using transformed secondary data.
11. Obtain the angle-Doppler adaptive weights.
12. Obtain a decision statistic. The data vector is the transformed primary data.
13. Compare the decision statistic to the threshold. If statistic is greater than the threshold, declare a target to be present at the look angle-Doppler, if not a target is said to be absent.

Steps 5 and 9 form nested loops
The MCARM Array

Data Source
Example: Injected Target

- 22 elements, 128 pulses
- Amplitude $= 0.0003$
- Angle bin $= 0$ (broadside)
- Doppler bin $= -9$
- Range bin $= 290$
- 3x3 JDL Processing
- No window in space.
- $t_d = kaiser(M,\log_{10}(M));$

JDL For Real Arrays

Assuming ideal array  Accounting for array effects
JDL For Real Arrays

Accounting for array effects significantly improves STAP performance

Assuming ideal array

Accounting for array effects
MTS Tones

- Moving Target Simulator
- 22 elements, 128 pulses
- 5 simulated targets
  - Located at 0, -200, -400, -600, & -800 Hz
- 200 Hz ≡ 13 Doppler bins
- 3x3 JDL Processing
- No window in space.
- \( t_d = \text{kaiser}(M, \log_{10}(M)) \);

JDL For Real Arrays

*Assuming ideal array*  
*Accounting for array effects*
Sources of Non-Homogeneities

- Statistical outliers
- Real world radar returns contain
  - Changes in terrain over short distances
    - Urban areas
    - Land-Sea interfaces
  - Manmade non-homogeneities
    - Vehicular traffic
    - Corner reflectors
    - Blinking jammers
  - Dense target environments
    - Large sidelobe targets

Non-Homogeneities

- Incorrect estimate of covariance matrix
  - Poor interference suppression (more false alarms)
- Target-like signals
  - In secondary data, cause target nulling
  - In sidelobes, are false alarms and improper ID
- Non-Homogeneity Detection (NHD)
  - Identifies all cells that deviate from the “norm”
  - Separates data cube into homogeneous and non-homogeneous cells
    - Generalized Inner Product (GIP)
    - STAP as NHD
Generalized Inner Product

- Estimates $\mathbf{R}$ using all the data (entire data cube)
  \[ \eta_{\text{GIP}} = \mathbf{x}^H \mathbf{R} \mathbf{x} \]
- Find $K$ range cells closest to mean of GIP statistic
  - Estimate $\mathbf{R}$ using these $K$ range cells
- Can be applied in original or transform domains
  - Computationally efficient
  - Mathematically sound ($T^2$ test, Chen)
  - Loose local info.
    - Handles several clutter types?
  - Wasting a lot of data

GIP Variants

- Cell assumed homogeneous if within tolerance of mean
  - Use all homogeneous cells to estimate $\mathbf{R}$
    - good estimate of $\mathbf{R}$ (many, many cells used)
    - no local information
  - Use $K$ homogeneous cells close to the primary range cell to estimate $\mathbf{R}$
    - regain local information
    - is this local information valid
    - computationally more complex
STAP as NHD

- Apply STAP assuming homogeneous data
  - Choosing threshold for statistic sets tolerance to non-homogeneities
    - trade-off between sensitivity and numbers
  - Retains local information
  - Only cells *that impact* on STAP processing identified as non-homogeneous
  - Use $K$ homogeneous cells close to the primary range cell to estimate $R$
  - Computationally intensive

JDL-NHD

[Diagram of JDL-NHD process]

NHD Stage
- Transform to Angle-Doppler Space, $T$
- Compute LPR covariance matrix estimate about target, calculate weights
- Calculate statistic $MSMI$ within LPR region
- NHD Test Statistic

Adaptivity Stage
- Order Secondary Data
- Compute LPR covariance matrix estimate about target, using $K$ range cells
- Calculate weight via $SMI$ within LPR region
- Apply Weight
- Test Statistic
LPR GIP Performance

Assuming Ideal Array

Accounting for Array Effects

JDL-NHD Performance

Assuming Ideal Array

Accounting for Array Effects
Sample Support Selection in Homogeneous Data

Sample Support Selection in Non-Homogeneous Data

What do you do in non-homogeneous cells?

Non-statistical (D³) Processing

D³ Algorithm: Maximize gain of array while minimizing residual interference terms
Implementation of D³ Algorithm

1. If using measured data, "rotate" the data using the measured steering vector.
2. Arrange the data from the primary range cell in the form of a $N \times M$ matrix.
3. Choose the emphasis parameter $\kappa$.
4. Form matrix $A$ and matrix $[a(0:N-2) H a(0:N-2) - A^T A]$. If using rotated $a_{(0:N-2)} = [1 \ 1 \ 1 \ldots \ 1]^T$.
5. Find the eigenvector corresponding to the largest eigenvalue of this matrix. This is $w_s$.
6. For each Doppler bin, repeat the following steps:
   7. Form matrix $B$ and matrix $[b(0:M-2) H b(0:M-2) - B^T B]$.
   8. Find the eigenvector corresponding to the largest eigenvalue of this matrix. This is $w_t$.
9. The $D^3$ adaptive weights are given by

$$ w(\theta, f_d) = \left[ \begin{array}{c} w_1 \\ 0 \\ \otimes \\ 0 \\ \end{array} \right] $$

Simulation Example

- 18 elements, 18 pulses
- Mainbeam azimuth – broadside
- Jammer azimuth angles – $45^\circ$, $20^\circ$
- Normalized Doppler – 1/3
- Discrete Interferer
  - Azimuth angle – $-51^\circ$
  - Normalized Doppler – 1/3
Performance Simulations
JDJ Alone

Performance Simulations
Direct Data Domain Method Alone

Poor suppression of correlated interference
Array Effects (Mutual Coupling)

Ideal linear array

Using an array of dipoles

Deep nulls eliminate interference

Shallow, misplaced nulls do not suppress interference

Hybrid Algorithm

- Stage 1 uses data from primary range cell only
- Suppresses NIDs in primary range cell
- Poor suppression of correlated interference

- Statistical algorithm forms second stage
- Suppresses residual correlated interference

Detection Declarations
Stage 1: Repeated $D^3$

$$T = \left[ w(\theta_1, f_0) \, w(\theta_1, f_1) \, w(\theta_2, f_0) \, w(\theta_2, f_1) \, w(\theta_3, f_0) \, w(\theta_3, f_1) \right]$$

- $D^3$ applied $\eta_a \eta_d$ times using the *same* primary data
- $(\theta_0, f_0)$ the actual look angle and Doppler

Performance Simulations

Two-Stage Hybrid Method

Angle Response

Doppler Response
Implementation of Hybrid Algorithm

1. Choose the size of the LPR, i.e. $\eta_a$ and $\eta_d$. Choose the set of $\eta_a$ auxiliary look angles centered about look angle. Usually 3, 5, or 7
2. Choose $K$, the number of secondary data vectors to be used in estimating the angle-Doppler covariance matrix ($R$)
3. For each Doppler bin in each range bin, repeat the following steps:
4. Choose $\eta_d$ auxiliary Dopplers centered around the look Doppler
5. For each auxiliary Doppler and angle bin, execute the $D^3$ algorithm
   • The $\eta_a \eta_d$ weight vectors form the transformation matrix $T$
6. Choose $K$ homogeneous range cells closest to the primary range cell as secondary data. Transform the primary data, the secondary data and the steering vector using this transformation matrix
7. Estimate the angle-Doppler covariance matrix $R$
8. Obtain the adaptive weights using the transformed steering vector
9. Obtain a decision statistic

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MCARM Example

No target, non-homogeneity

![Graph 1](image1.png)

Target and non-homogeneity

![Graph 2](image2.png)

Non-homogeneity at angle bin $-35^\circ$, look angle: broadside
Hybrid Algorithm

- Very effective against discrete and correlated interference (clutter)
  - Non-statistical $D^3$ processing followed by statistical JDL processing
- Computationally intensive
  - $D^3$ algorithm must be executed $\eta_a \eta_d$ times
  - Use hybrid algorithm sparingly

Knowledge Based STAP

Put it all together, what do you get?
- A comprehensive, practical, approach to STAP
Implementation of KB-STAP

1. For each Doppler bin, repeat the following steps:
2. For all range bins, identify the homogeneous and non-homogeneous range bins using the JDL-NHD
3. For each range cell, repeat the following steps:
4. If the range cell is homogeneous, use JDL with other homogeneous cells for sample support
5. If the range cell is non-homogeneous, use the hybrid algorithm with other homogeneous range cells as sample support
6. In either case, compare with a threshold to determine if target is present or absent.

Data Source
Ground and Air Moving Target Indication

Classical STAP

KB-STAP

Note: the NHD identifies the first target range cell as homogeneous

GMTI/AMTI After Thresholding

Classical STAP

KB-STAP

Note: Aircraft approaching these targets at 250 mph.