REGISTRATION-BASED SOLUTIONS
TO THE RANGE-DEPENDENCE PROBLEM
IN STAP RADARS

Fabian D. Lapierre and Jacques G. Verly

Department of Electrical Engineering and Computer Science
University of Liège
Liège, Belgium
INTRODUCTION

• GOAL: TARGET DETECTION FOR ARBITRARY, POSSIBLY UNKNOWN BISTATIC CONFIGURATIONS

• DIFFICULTY: COMPLEX NATURE OF RANGE-DEPENDENT BISTATIC CLUTTER
OUTLINE

- INTRODUCTION
- CONFIGURATIONS AND SIGNALS
- RANGE-DEPENDENCE PROBLEM
- SNAPSHOT AND SPECTRUM
- STAP PROCESSOR
- EXISTING COMPENSATION METHODS
- NEW REGISTRATION-BASED METHODS
- SUMMARY
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RADAR-MEASUREMENT CONFIGURATION: BISTATIC

GROUND IS ASSUMED TO BE A FLAT (HORIZONTAL) PLANE
WHAT DOES THE RADAR MEASURE?
DUAL VIEW

\[ \lambda_c = \frac{c}{f_c} \]

\[ \lambda_s = \frac{\lambda_c}{\sin \xi} \]

\[ \tau_{rt} = \frac{R_b}{c} \]

\[ f_s = \frac{1}{\lambda_s} = \frac{\sin \xi}{\lambda_c} \]

\[ f_d = \frac{V_T}{\lambda_c} \cos \xi_d + \frac{V_R}{\lambda_c} \cos \xi_d \]

"ROUNDTRIP" DELAY
SPATIAL FREQUENCY
DOPPLER FREQUENCY

\[ \tau_{rt} \rightarrow v_s \]

\[ f_s \rightarrow v_d \]
ALTERNATE POSITIONING SYSTEM: ISOSURFACES AND ISOCURVES
ABSTRACTING CONFIGURATIONS AND SIGNALS: DIRECTION-DOPPLER (DD) CURVES

ISOCURVES
$(R_b, v_S, v_d)$

DIRECTION-DOPPLER (DD) CURVES
(for a given $R_b$)

WHAT HAPPENS WHEN $R_b$ CHANGES?
EXAMPLE DD CURVES: BISTATIC, IN-TRAIL, SIDELOOKING
EXAMPLE DD CURVES: BISTATIC, WING-TO-WING, SIDELOOKING
EXAMPLE DD CURVES:
BISTATIC, WING-TO-FUSELAGE, SIDELookING
PROBLEM: DD CURVES ARE RANGE-DEPENDENT! (EXCEPT FOR MONOSTATIC-SIDELookING CASE)
USEFUL CONCEPT: DD SURFACE

\[ R_b \]

\[ V_d \]

\[ V_s \]
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RADAR SNAPSHOT AND POWER SPECTRUM

LINEAR ANTENNA ARRAY

N ELEMENTS

SNAPSHOT

SPECTRAL ESTIMATION
e.g., MVE (or FFT)

M DOPPLER FREQ.

N SPATIAL FREQ.

SPECTRUM

MVE = MINIMUM VARIANCE ESTIMATOR
EXAMPLE POWER SPECTRUM:
CLUTTER ONLY

``CLUTTER RIDGE``

EXPECTED POWER

V

U

DOES THIS GRAPH TRIGGER ANY THOUGHT?
THE KEY LINK BETWEEN
THEORY AND MEASUREMENT

DD CURVE
(THEORETICAL !)

CLUTTER RIDGE
(MEASURED!)

\[ \nu_s \leftrightarrow U \]
\[ \nu_d \leftrightarrow V \]
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THE OPTIMUM STAP PROCESSOR

0  1  2  3  4  5  6  M-1
COHERENT PULSE TRAIN

AT EACH $R_b$
0  1  2  3  4  5  6  N-1
LINEAR ANTENNA ARRAY

$\mathbf{W} = \mathbf{R}^{-1} \mathbf{V}$

TRUE CLUTTER COVARIANCE MATRIX

HOW DO WE FIND $\mathbf{R}$?

$\sum w_{ij} y_{ij}$

$z = \mathbf{W}^H \mathbf{y}$

DECISION

TARGET PRESENT  TARGET ABSENT

THRESHOLD
WHAT VALUE DO WE USE FOR $\mathbf{R}$ IN

$$w = \mathbf{R}^{-1} v$$

<table>
<thead>
<tr>
<th>COVARIANCE MATRIX $\mathbf{R}(l)$</th>
<th>THEORETICAL &amp; BEST</th>
<th>PRACTICAL &amp; WORST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TRUE ESTIMATE</td>
<td>BIASED ESTIMATE</td>
</tr>
<tr>
<td></td>
<td>$\mathbf{R}(l) = \mathbb{E}{ \mathbf{y}_k \mathbf{y}_k^H }$</td>
<td>$\hat{\mathbf{R}}(l) = \frac{1}{N_l} \sum_{k \in S_l} \mathbf{R}(k)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mathbf{R}(k) = \mathbf{y}_k \mathbf{y}_k^H$</td>
</tr>
<tr>
<td>PROCESSOR</td>
<td>OPTIMUM PROCESSOR (OP)</td>
<td>STRAIGHT-AVERAGING PROCESSOR (SA)</td>
</tr>
</tbody>
</table>

TO GET UNBIASED ESTIMATE OF $\mathbf{R}(l)$,
WE MUST ALIGN CLUTTER RIDGES OF $\mathbf{R}(k)$'s!
THE CRUX OF STAP:
ALIGNING CLUTTER RIDGES, i.e., DD CURVES

FIXED CURVE AT $l$ (REFERENCE)

MOVING CURVE AT $k$

HOW DO WE ALIGN DD CURVES?
AN ABSOLUTE MUST:
A MATHEMATICAL THEORY OF DD CURVES

\[ C(v_s, v_d, R_b, \theta) = 0 \]

\[ \begin{align*}
(x_R, y_R, z_R) &= \text{RECEIVER POSITION} \\
\alpha_R &= \text{RECEIVER VELOCITY ANGLE} \\
\delta &= \text{ANTENNA ANGLE} \\
v_R &= \text{RECEIVER VELOCITY} \\
v_T &= \text{TRANSMITTER VELOCITY}
\end{align*} \]

WE HAVE DEVELOPED FORMULAS FOR ARBITRARY DD CURVES:
ONLY FOR THE MATHEMATICALLY-INCLINED!

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HOW TO QUANTIFY PROCESSOR PERFORMANCE?

SINR LOSS

\[ \text{SINR}_L = \frac{\text{SINR}}{\text{SINR}_0} \]

\[ = \frac{|w^H v|^2}{(w^H R w)(v^H v)} \]

\[ \Rightarrow \text{SINR}_L(v_s, v_d) \]
THE LINK BETWEEN
THEORY, MEASUREMENT AND PERFORMANCE

DD CURVE

CLUTTER RIDGE
(Power Spectrum)

CLUTTER NOTCH
(SINR LOSS)
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EXISTING RANGE-COMPENSATION METHODS:
(1) PRINCIPLE

DOPPLER WARPING (DW)

HIGH-ORDER DOPPLER WARPING (HODW)

DERIVATIVE-BASED UPDATING (DBU)

REFERENCE

\[ w(k) = w(l) + (k - l) \frac{d}{dl} w(l) \]

WEIGHT CONSISTS IN A RANGE-DEPENDENT DOPPLER SHIFT

WEIGHT GIVEN BY 1st-ORDER TAYLOR SERIES

INDEPENDENT OF \( v_s \)  DEPENDENT ON \( v_s \)


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## EXISTING RANGE-COMPENSATION METHODS: (2) COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>DW</th>
<th>HODW</th>
<th>DBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>• SIMPLE IMPLEMENTATION</td>
<td>• NEARLY-PERFECT COMPENSATION</td>
<td>• PARAMETERS NOT REQUIRED</td>
</tr>
<tr>
<td></td>
<td>• POOR PERFORMANCE FOR BS CONFIGURATION</td>
<td>• COMPLICATED DOPPLER FILTERING</td>
<td>• GOOD PERFORMANCE FOR SOME BS CONFIGURATIONS</td>
</tr>
<tr>
<td></td>
<td>• PARAMETERS REQUIRED</td>
<td>• PARAMETERS REQUIRED</td>
<td>• TWICE AS MANY DOF REQUIRED</td>
</tr>
</tbody>
</table>

**OUR GOAL:** GENERAL BS CONFIGURATIONS, UNKNOWN PARAMETERS, LOW COMPLEXITY WITHOUT ANY INCREASE IN NUMBER OF DOF
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PEAK-MAPPING RANGE-DEPENDENCE COMPENSATION: (1) Principle

CONFIGURATION PARAMETERS

\[ \Gamma(k) \rightarrow \Gamma'(k) \]

MC\((k)\) = MOVING CURVE AT RANGE GATE \(k\)

FC\((l)\) = FIXED CURVE AT REFERENCE RANGE GATE \(l\)

\[ \hat{\Gamma}(l) = \frac{1}{N_l} \sum_{k \in S_l} T'^{\Gamma}_{lk} \{ \Gamma(k) \} \]

HOW DO WE FIND \( T'^{\Gamma}_{lk} \) FOR ALL \( k \) AND \( l \) ?
PEAK-MAPPING RANGE-DEPENDENCE COMPENSATION: (2) System

\[ \Gamma(k) \]

SNAPSHOT DOMAIN

ZERO PADDING \((k < l\) only) \rightarrow FFT

CONFIGURATION PARAMETERS \(\theta\)

SPECTRUM DOMAIN

PEAK EXTRACTION (1) \rightarrow PEAK MAPPING \rightarrow PEAK INTERPOLATION

WE PROPOSE THREE PEAK-MAPPINGS METHODS

\[ \Gamma'(k) \]

WINDOWING \((k < l\) only) \rightarrow IFFT
PEAK-MAPPING BY SCALING TRANSFORMATION (ST): (1) PRINCIPLE
PEAK-MAPPING BY SCALING TRANSFORMATION (ST): (2) PERFORMANCE

BEFORE ST

AFTER ST

WORKS ONLY FOR MONOSTATIC CONFIGURATIONS

HOW DO WE EXTEND RANGE OF APPLICABILITY?

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PEAK-MAPPING BY AFFINE TRANSFORMATION (AT): PRINCIPLE

WORKS ONLY FOR MONOSTATIC AND SOME BISTATIC CONFIGURATIONS

HOW DO WE EXTEND RANGE OF APPLICABILITY?
PEAK-MAPPING BY WARping TRANSFORMATION (WT): (1) PRINCIPLE

EXAMPLE FLOW LINES

\[ V_d \]
\[ V_s \]

WARping TRANSFORMATION

\[ V_d \]
\[ V_s \]

MC(k)

FC(l)
PEAK-MAPPING BY WARPING TRANSFORMATION (WT): (2) PERFORMANCE

WORKS FOR ALL MONOSTATIC AND BISTATIC CONFIGURATIONS

HOW DO WE FIND CONFIGURATION PARAMETERS IF UNKNOWN?

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HOW DO WE FIND THE CONFIGURATION PARAMETERS?

\[ \Gamma(k) \xrightarrow{\text{ZERO-PADDING (BS CONFIG. ONLY)}} \text{FFT} \xrightarrow{\text{PEAK EXTRACTION (2)}} \text{CURVE FITTING} \xrightarrow{} \hat{\theta} \]

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>PEAK EXTRACTION (2)</th>
<th>CURVE FITTING</th>
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<tbody>
<tr>
<td>MS</td>
<td>THRESHOLDING</td>
<td>SIMPLE MMSE</td>
</tr>
<tr>
<td>BS</td>
<td>WATERSHED SEGMENT (Image processing)</td>
<td>DIFFICULT MMSE (Theory of DD curves)</td>
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</table>
RANGE COMPENSATION METHODS COME IN TWO TYPES AND SIX FLAVORS!

OPEN-LOOP (OL)

\[ \Gamma(k) \rightarrow \text{PEAK-MAPPING COMPENSATION} \rightarrow \Gamma'(k) \]

DATA-ADAPTIVE (DA)

\[ \Gamma(k) \rightarrow \hat{\theta} \rightarrow \text{CONFIGURATION PARAMETER ESTIMATION} \rightarrow \text{PEAK-MAPPING COMPENSATION} \rightarrow \Gamma'(k) \]

<table>
<thead>
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<th>PEAK-MAPPING COMPENSATION</th>
<th>OPEN-LOOP (OL)</th>
<th>DATA-ADAPTIVE (DA)</th>
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<tr>
<td>SCALING TRANSFORMATION (MS)</td>
<td>OL-ST-MS</td>
<td>DA-ST-MS</td>
</tr>
<tr>
<td>AFFINE TRANSFORMATION (BS)</td>
<td>OL-AT-BS</td>
<td>DA-AT-BS</td>
</tr>
<tr>
<td>WARPING TRANSFORMATION (BS)</td>
<td>OL-WT-BS</td>
<td>DA-WT-BS</td>
</tr>
</tbody>
</table>
PERFORMANCE COMPARISON:
(1) ST-MS

--- SA
--- OL-ST-MS
--- OP

--- DA-ST-MS
--- OL-ST-MS
--- OP

SINR LOSS (dB)

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PERFORMANCE COMPARISON:
(2) AT-BS

--- SA
--- OL-AT-BS
--- OP

--- DA-AT-BS
--- OL-AT-BS
--- OP

SINR LOSS (dB)

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PERFORMANCE COMPARISON:
(3) WT-BS

-- SA
-- OL-WT-BS
-- OP

-- DA-WT-BS
-- OL-WT-BS
-- OP

SINR LOSS (dB)

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PERFORMANCE COMPARISON:
(4) AT vs BT

-- OL-AT-BS
-- OL-WT-BS
-- OP

-- DA-AT-BS
-- DA-WT-BS
-- OP

SINR LOSS (dB)

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PERFORMANCE COMPARISON:
(5) DIRECTIVE SENSORS, MONOSTATIC

- SA
- OL-ST-MS
- OP

- DA-ST-MS
- OL-ST-MS
- OP

- SAME RESULTS FOR BS CONFIGURATIONS WITH DIRECTIVE SENSORS
- POOR PERFORMANCE FOR BS DA METHODS WITH DIRECTIVE SENSORS
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SUMMARY

- RANGE-DEPENDENCE OF BS CLUTTER SPECTRUM MAKES BS CLUTTER REJECTION A CHALLENGE IN STAP

- WE REVIEWED EXISTING COMPENSATION METHODS
  - DOPPLER WARPING (DW)
  - HIGH-ORDER DOPPLER WARPING (HODW)
    - Configuration parameters required
  - DERIVATIVE-BASED UPDATING (DBU)
    - Doubling of number of DOF

- WE PROPOSED NEW REGISTRATION-BASED COMPENSATION METHODS
  - Nearly perfect compensation for all MS and BS configurations
  - Configuration parameters not required
  - No increase of number of DOF
  - High computational load
  - Complex implementation
  - Robustness