Side-Looking Airborne Adaptive Operation in Hot Clutter

Timothy W. Lawson

Follow this and additional works at: https://scholar.afit.edu/etd

Part of the Signal Processing Commons

Recommended Citation
https://scholar.afit.edu/etd/3492

This Thesis is brought to you for free and open access by the Student Graduate Works at AFIT Scholar. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of AFIT Scholar. For more information, please contact richard.mansfield@afit.edu.
SIDE-LOOKING AIRBORNE ADAPTIVE RADAR OPERATION IN HOT CLUTTER

THESIS

Timothy William Lawson, Second Lieutenant, USAF

AFIT/GE/ENG/06-33

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY
Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.
The views expressed in this research are those of the author and do not reflect official policy or position of the United States Air Force, Department of Defense or the U.S. Government
SIDE-LOOKING AIRBORNE
ADAPTIVE RADAR OPERATION IN HOT CLUTTER

THESIS

Presented to the Faculty
Department of Electrical and Computer Engineering
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Electrical Engineering

Timothy William Lawson, B.S.E.E.
Second Lieutenant, USAF

March 2006

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.
SIDE-LOOKING AIRBORNE
ADAPTIVE RADAR OPERATION IN HOT CLUTTER

Timothy William Lawson, B.S.E.E.
Second Lieutenant, USAF

Approved:

/signed/

Maj Todd B. Hale, PhD (Chairman)
24 Feb 2006

/signed/

Dr. Michael A. Temple (Member)
24 Feb 2006

/signed/

Dr. Richard K. Martin (Member)
24 Feb 2006
Abstract

This research effort examines side-looking airborne radar operation in hot clutter. In this context, hot clutter is an electronic counter-measure used to degrade airborne radar performance. Hot clutter occurs by illuminating the ground with an airborne jammer at some velocity, azimuth, elevation, and range from the airborne radar. This research uses a simplifying assumption where the bistatic hot clutter radar cross section (RCS) scattering statistics are identical to the monostatic clutter RCS scattering statistics. When the airborne jammer waveform scattered returns are perfectly coherent with the radar waveform, the radar cannot distinguish between the returns transmitted by the jammer and returns transmitted by the radar. Hot clutter is shown to degrade radar performance at different locations in azimuth and Doppler depending on the jammer velocity and location in the radar environment.

The Joint Domain Localized (JDL) and Factored Time Space (FTS) adaptive filters are shown to improve radar performance in hot clutter when compared to non-adaptive processing. Adaptive filters can mitigate hot clutter not in the radar look direction. FTS and JDL adaptive filters are shown to improve radar performance 32 and 36 dB per element per pulse, respectively, over non-adaptive processing in the jammer mainbeam Doppler location when the jammer mainbeam is not in the radar look direction in azimuth. JDL and FTS adaptive filter performance are shown only to degrade at locations of hot clutter in the radar look direction in azimuth and Doppler. In addition, the sample support is no longer independently and identically distributed (iid) when the jammer is close to the range cell under test (RUT). This research shows if the sample support used to create adaptive filters occupies a small range extent, the interference estimate used to create adaptive filters is not seriously corrupted due to heterogeneities within the sample support.
Acknowledgements

I would like to thank my thesis advisor, Major Todd B. Hale, for his invaluable knowledge and guidance.

Timothy William Lawson
# Table of Contents

Abstract .......................................................... iv

Acknowledgements .................................................. v

List of Figures ........................................................ viii

List of Tables .......................................................... xiv

List of Symbols .......................................................... xv

List of Abbreviations .................................................. xviii

I. Introduction ......................................................... 1
   1.1 Objective ....................................................... 1
   1.2 Purpose ......................................................... 1
   1.3 Notation ......................................................... 2
   1.4 Materials and Resources ....................................... 2
   1.5 Organization ................................................... 2

II. Literature Review .................................................. 4
   2.1 Geometry ......................................................... 4
   2.2 Data Format ..................................................... 6
   2.3 Clutter Model Review .......................................... 10
   2.4 Adaptive Radar Detection ...................................... 13
      2.4.1 Joint Domain Localized ................................... 14
      2.4.2 Factored Time Space ...................................... 16
   2.5 Previous Hot Clutter Research. .............................. 17

III. Hot Clutter Model ................................................ 18
   3.1 Introduction .................................................... 18
   3.2 Model Development ............................................. 18
   3.3 Non-Homogeneity Detection ................................. 28
   3.4 Interference Covariance Matrix Rank ...................... 30
   3.5 Summary ......................................................... 33
IV. Hot Clutter Radar Interference Environment ............................................. 34
  4.1 Interference From a TN Jammer ......................................................... 34
    4.1.1 Range Dependence ...................................................................... 36
    4.1.2 Azimuthal Dependence .................................................................. 43
  4.2 Interference From an OC Jammer ......................................................... 50
    4.2.1 Range Dependence ...................................................................... 50
    4.2.2 Azimuthal Dependence .................................................................. 57
  4.3 Radar Interference Summary ................................................................. 59

V. Tangential Hot Clutter Jammer Impact on Side-Looking Radar Performance ......................................................... 61
  5.1 Non-Adaptive Radar Performance ....................................................... 62
    5.1.1 TN Jammer at Radar Boresight ...................................................... 62
    5.1.2 TN Jammer at 45 Degrees Azimuth ................................................ 68
  5.2 Adaptive Radar Performance ............................................................... 71
    5.2.1 Radar Performance Using Known Interference .............................. 71
    5.2.2 Radar Performance Using Estimated Interference .......................... 83
  5.3 TN Jammer Performance Impact Summary ............................................ 110

VI. Oncoming Hot Clutter Jammer Impact on Side-Looking Radar Performance ......................................................... 113
  6.1 Non-Adaptive Radar Performance ....................................................... 113
    6.1.1 OC Jammer at Boresight ............................................................... 113
    6.1.2 OC Jammer at 45 Degrees Azimuth ............................................... 117
  6.2 Adaptive Radar Performance ............................................................... 117
    6.2.1 Radar Performance Using Known Interference .............................. 119
    6.2.2 Radar Performance Using Estimated Interference .......................... 132
  6.3 OC Jammer Performance Impact Summary .......................................... 152

VII. Conclusions ......................................................................................... 153
  7.1 Hot Clutter Results ............................................................................. 153
  7.2 Recommendations for Future Work ..................................................... 156

Bibliography ............................................................................................... 158
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>SL radar planar array geometry.</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Radar platform geometry.</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>Radar data cube.</td>
<td>8</td>
</tr>
<tr>
<td>2.4</td>
<td>Fast-time sampling.</td>
<td>8</td>
</tr>
<tr>
<td>2.5</td>
<td>Radar clutter geometry.</td>
<td>11</td>
</tr>
<tr>
<td>2.6</td>
<td>$3 \times 3$ Localized Processing Region.</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>One-way radar equation.</td>
<td>19</td>
</tr>
<tr>
<td>3.2</td>
<td>Relationship between jammer range and radar look direction.</td>
<td>21</td>
</tr>
<tr>
<td>3.3</td>
<td>Illustration of jammer range and azimuth dependence to a radar clutter patch.</td>
<td>23</td>
</tr>
<tr>
<td>3.4</td>
<td>Relationship between jammer and radar azimuth.</td>
<td>24</td>
</tr>
<tr>
<td>3.5</td>
<td>Generalized Inner Product using known covariance $\mathbf{R}$.</td>
<td>31</td>
</tr>
<tr>
<td>3.6</td>
<td>Interference Covariance Matrix Rank for an OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>32</td>
</tr>
<tr>
<td>4.1</td>
<td>MVE interference containing cold clutter and thermal noise.</td>
<td>35</td>
</tr>
<tr>
<td>4.2</td>
<td>SM interference containing cold clutter and thermal noise.</td>
<td>37</td>
</tr>
<tr>
<td>4.3</td>
<td>Doppler frequency of hot clutter.</td>
<td>39</td>
</tr>
<tr>
<td>4.4</td>
<td>MVE interference for a TN jammer at $\phi = 0^\circ$ for different locations in range.</td>
<td>40</td>
</tr>
<tr>
<td>4.5</td>
<td>SM interference for a TN jammer at $\phi = 0^\circ$ for $R_j = 132$ Km.</td>
<td>41</td>
</tr>
<tr>
<td>4.6</td>
<td>SM interference for a TN jammer at $\phi = 0^\circ$ for $R_j = 72$ Km.</td>
<td>42</td>
</tr>
<tr>
<td>4.7</td>
<td>MVE interference for a TN jammer at $\phi = 45^\circ$ for different locations in range.</td>
<td>44</td>
</tr>
<tr>
<td>4.8</td>
<td>SM interference for a TN jammer at $\phi = 45^\circ$ for the jammer at 72 Km.</td>
<td>45</td>
</tr>
<tr>
<td>4.9</td>
<td>TN jamming scenario.</td>
<td>47</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.10.</td>
<td>MVE interference for different TN jammer azimuth locations when $R_j = 132$ Km.</td>
<td>48</td>
</tr>
<tr>
<td>4.11.</td>
<td>MVE interference for a TN jammer for various azimuth at 72 Km.</td>
<td>49</td>
</tr>
<tr>
<td>4.12.</td>
<td>OC jamming scenario.</td>
<td>51</td>
</tr>
<tr>
<td>4.13.</td>
<td>MVE interference for an OC jammer at $\phi = 0^\circ$ for various ranges.</td>
<td>53</td>
</tr>
<tr>
<td>4.14.</td>
<td>SM interference for an OC jammer at $\phi = 0^\circ$ for $R_j = 132$ Km.</td>
<td>54</td>
</tr>
<tr>
<td>4.15.</td>
<td>SM interference for an OC jammer at $\phi = 0^\circ$ for $R_j = 72$ Km.</td>
<td>55</td>
</tr>
<tr>
<td>4.16.</td>
<td>MVE interference for an OC jammer at $\phi = 45^\circ$ for various jammer locations in range.</td>
<td>56</td>
</tr>
<tr>
<td>4.17.</td>
<td>MVE interference for an OC jammer at 132 Km for different azimuth locations.</td>
<td>58</td>
</tr>
<tr>
<td>4.18.</td>
<td>MVE interference for an OC jammer at 72 Km for various azimuth locations.</td>
<td>59</td>
</tr>
<tr>
<td>5.1.</td>
<td>Non-adaptive Range-Doppler output under homogeneous interference for range cells 60 to 72 Km.</td>
<td>63</td>
</tr>
<tr>
<td>5.2.</td>
<td>Non-adaptive Range-Doppler output with a TN jammer at $\phi = 0^\circ$, $R_j = 132$ Km.</td>
<td>64</td>
</tr>
<tr>
<td>5.3.</td>
<td>Non-adaptive Range-Doppler output with a TN jammer at $\phi = 0^\circ$, $R_j = 72$ Km.</td>
<td>65</td>
</tr>
<tr>
<td>5.4.</td>
<td>Non-adaptive Output SINR for a TN jammer at $\phi = 0^\circ$, at ranges of 72 and 132 Km.</td>
<td>66</td>
</tr>
<tr>
<td>5.5.</td>
<td>Probability of detection of a target at $(\phi = 0^\circ, \bar{\omega} = 0.25)$ with a TN jammer at $\phi = 0^\circ$, $R_j = 72,132$ Km using non-adaptive processing.</td>
<td>67</td>
</tr>
<tr>
<td>5.6.</td>
<td>Non-adaptive Range-Doppler output with a TN jammer at $\phi = 45^\circ$, $R_j = 132$ Km.</td>
<td>68</td>
</tr>
<tr>
<td>5.7.</td>
<td>Non-adaptive Range-Doppler output with a TN jammer at $\phi = 45^\circ$, $R_j = 72$ Km.</td>
<td>69</td>
</tr>
<tr>
<td>5.8.</td>
<td>Non-adaptive Output SINR for a TN jammer at $\phi = 45^\circ$, at ranges of 72 and 132 Km.</td>
<td>70</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>5.9.</td>
<td>Probability of Detection of a target at ((\phi = 0^\circ, \bar{\omega} = -0.36)) with a TN jammer at (\phi = 0^\circ, R_j = 72,132) Km using non-adaptive processing.</td>
<td></td>
</tr>
<tr>
<td>5.10.</td>
<td>Output SINR for the MF, TN jammer at (\phi = 0^\circ, R_j = 132) Km.</td>
<td></td>
</tr>
<tr>
<td>5.11.</td>
<td>Output SINR for the MF, TN jammer at (\phi = 0^\circ, R_j = 72) Km.</td>
<td></td>
</tr>
<tr>
<td>5.12.</td>
<td>Output SINR for the MF, TN jammer at (\phi = 45^\circ, R_j = 132) Km.</td>
<td></td>
</tr>
<tr>
<td>5.13.</td>
<td>Output SINR for the MF, TN jammer at (\phi = 45^\circ, R_j = 72) Km.</td>
<td></td>
</tr>
<tr>
<td>5.14.</td>
<td>Output SINR for a TN jammer at (\phi = 0^\circ, R_j = 132) Km for the FTS adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.15.</td>
<td>Output SINR for a TN jammer at (\phi = 0^\circ, R_j = 72) Km for the FTS adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.16.</td>
<td>Output SINR for a TN jammer at (\phi = 45^\circ, R_j = 132) Km for the FTS adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.17.</td>
<td>Output SINR for a TN jammer at (\phi = 45^\circ, R_j = 72) Km for the FTS adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.18.</td>
<td>Output SINR for a TN jammer at (\phi = 0^\circ, R_j = 132) Km for the JDL adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.19.</td>
<td>Output SINR for a TN jammer at (\phi = 0^\circ, R_j = 72) Km for the JDL adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.20.</td>
<td>Output SINR for a TN jammer at (\phi = 45^\circ, R_j = 132) Km for the JDL adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.21.</td>
<td>Output SINR for a TN jammer at (\phi = 45^\circ, R_j = 72) Km for the JDL adaptive filter.</td>
<td></td>
</tr>
<tr>
<td>5.22.</td>
<td>MF SINR Loss, TN jammer at (\phi = 0^\circ) at different ranges, (\text{RUT}= 66) Km.</td>
<td></td>
</tr>
<tr>
<td>5.23.</td>
<td>MF SINR loss, TN jammer at (\phi = 0^\circ, R_j = 72) Km for 150 range cells close to the jammer.</td>
<td></td>
</tr>
<tr>
<td>5.24.</td>
<td>SINR Loss, TN jammer at (\phi = 0^\circ, R_j = 132) Km, for the range cell sample support.</td>
<td></td>
</tr>
<tr>
<td>5.25.</td>
<td>SINR Loss, TN jammer at (\phi = 0^\circ, R_j = 72) Km, for the range cell sample support.</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.26.</td>
<td>Output SINR using estimated interference for JDL construction. TN jammer at $\phi = 0^\circ$, 72 Km from the jammer.</td>
<td>95</td>
</tr>
<tr>
<td>5.27.</td>
<td>$P_d$, TN jammer at $\phi = 0^\circ$, $R_j = 132$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.1563$), for the JDL adaptive filter.</td>
<td>96</td>
</tr>
<tr>
<td>5.28.</td>
<td>$P_d$, TN jammer at $\phi = 0^\circ$, $R_j = 72$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.1563$), for the JDL adaptive filter.</td>
<td>97</td>
</tr>
<tr>
<td>5.29.</td>
<td>Estimated Output SINR for a TN jammer at $\phi = 0^\circ$, $R_j = 72$ Km, for the FTS adaptive filter.</td>
<td>98</td>
</tr>
<tr>
<td>5.30.</td>
<td>$P_d$, TN jammer at $\phi = 0^\circ$, $R_j = 132$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.1563$), for the FTS adaptive filter.</td>
<td>99</td>
</tr>
<tr>
<td>5.31.</td>
<td>$P_d$, TN jammer at $\phi = 0^\circ$, $R_j = 72$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.1563$), for the FTS adaptive filter.</td>
<td>100</td>
</tr>
<tr>
<td>5.32.</td>
<td>MF SINR Loss due to the TN jammer at $\phi = 0^\circ$. The RUT is 66 Km, the jammer is 72 to 132 Km from the radar.</td>
<td>102</td>
</tr>
<tr>
<td>5.33.</td>
<td>SINR Loss due to hot clutter, TN jammer at $\phi = 45^\circ$, 132 Km, for range cells close to the RUT.</td>
<td>103</td>
</tr>
<tr>
<td>5.34.</td>
<td>SINR Loss due to hot clutter, TN jammer at $\phi = 45^\circ$, 72 Km, for range cells close to the RUT.</td>
<td>104</td>
</tr>
<tr>
<td>5.35.</td>
<td>Output SINR using the estimated interference for a TN jammer at $\phi = 45^\circ$, 72 Km, for the JDL adaptive filter.</td>
<td>106</td>
</tr>
<tr>
<td>5.36.</td>
<td>$P_d$, TN jammer at $\phi = 45^\circ$, $R_j = 72$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = -0.07$), for the JDL adaptive filter.</td>
<td>107</td>
</tr>
<tr>
<td>5.37.</td>
<td>$P_d$, TN jammer at $\phi = 45^\circ$, $R_j = 132$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.10$), for the JDL adaptive filter.</td>
<td>108</td>
</tr>
<tr>
<td>5.38.</td>
<td>Output SINR using the estimated FTS filter for a TN jammer at $\phi = 45^\circ$, 72 Km.</td>
<td>109</td>
</tr>
<tr>
<td>5.39.</td>
<td>$P_d$, TN jammer $\phi = 45^\circ$, $R_j = 72$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = -0.07$), for the FTS adaptive filter.</td>
<td>110</td>
</tr>
<tr>
<td>5.40.</td>
<td>$P_d$, TN jammer $\phi = 45^\circ$, $R_j = 132$ Km, target at ($\phi = 0^\circ$, $\bar{\omega} = 0.10$), for the FTS adaptive filter.</td>
<td>111</td>
</tr>
<tr>
<td>6.1.</td>
<td>OC jamming scenario.</td>
<td>114</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>6.2</td>
<td>Non-adaptive Range-Doppler output of interference with an OC jammer at $\phi = 0^\circ$, $R_j = 72$ Km, for range cells 60 to 72 Km.</td>
<td>115</td>
</tr>
<tr>
<td>6.3</td>
<td>Non-adaptive Output SINR for an OC jammer at $\phi = 0^\circ$, 72 and 132 Km from the radar.</td>
<td>116</td>
</tr>
<tr>
<td>6.4</td>
<td>Non-adaptive Output SINR for an OC jammer at $\phi = 45^\circ$, 72 and 132 Km from the radar.</td>
<td>118</td>
</tr>
<tr>
<td>6.5</td>
<td>MF Output SINR for an OC jammer at $\phi = 0^\circ$, 72 and 132 Km from the radar.</td>
<td>120</td>
</tr>
<tr>
<td>6.6</td>
<td>MF Output SINR for an OC jammer at $\phi = 45^\circ$, 72 and 132 Km from the radar.</td>
<td>121</td>
</tr>
<tr>
<td>6.7</td>
<td>Output SINR for the FTS adaptive filter, OC jammer at $\phi = 0^\circ$, 132 Km from the radar.</td>
<td>123</td>
</tr>
<tr>
<td>6.8</td>
<td>Output SINR for the FTS adaptive filter, OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>124</td>
</tr>
<tr>
<td>6.9</td>
<td>Output SINR for the FTS adaptive filter, OC jammer at $\phi = 45^\circ$, 132 Km from the radar.</td>
<td>125</td>
</tr>
<tr>
<td>6.10</td>
<td>Output SINR for the FTS adaptive filter, OC jammer at $\phi = 45^\circ$, 72 Km from the radar.</td>
<td>126</td>
</tr>
<tr>
<td>6.11</td>
<td>Output SINR using the JDL adaptive filter, OC jammer at $\phi = 0^\circ$, 132 Km from the radar.</td>
<td>128</td>
</tr>
<tr>
<td>6.12</td>
<td>Output SINR using the JDL adaptive filter, OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>129</td>
</tr>
<tr>
<td>6.13</td>
<td>Output SINR using the JDL adaptive filter, OC jammer at $\phi = 45^\circ$, 132 Km from the radar.</td>
<td>130</td>
</tr>
<tr>
<td>6.14</td>
<td>Output SINR using the JDL adaptive filter, OC jammer at $\phi = 45^\circ$, 72 Km from the radar.</td>
<td>131</td>
</tr>
<tr>
<td>6.15</td>
<td>SINR Loss for the MF, OC jammer at $\phi = 0^\circ$, RUT= 66 Km, jammer ranges from 72 to 132 Km.</td>
<td>133</td>
</tr>
<tr>
<td>6.16</td>
<td>SINR Loss for adaptive and non-adaptive processing in the range cell sample support, OC jammer at $\phi = 0^\circ$, 132 Km from the radar.</td>
<td>134</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>6.17</td>
<td>SINR Loss for adaptive and non-adaptive processing in the range cell sample support, OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>136</td>
</tr>
<tr>
<td>6.18</td>
<td>Output SINR using estimated interference for JDL construction, OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>137</td>
</tr>
<tr>
<td>6.19</td>
<td>$P_d$, OC jammer $\phi = 0^\circ$, $R_j = 72$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.30)$, for the JDL adaptive filter.</td>
<td>139</td>
</tr>
<tr>
<td>6.20</td>
<td>$P_d$, OC jammer $\phi = 0^\circ$, $R_j = 132$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.10)$, for the JDL adaptive filter.</td>
<td>140</td>
</tr>
<tr>
<td>6.21</td>
<td>Output SINR using estimated interference for FTS construction, OC jammer at $\phi = 0^\circ$, 72 Km from the radar.</td>
<td>142</td>
</tr>
<tr>
<td>6.22</td>
<td>$P_d$, OC jammer at $\phi = 0^\circ$, $R_j = 72$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.30)$, for the FTS adaptive filter.</td>
<td>143</td>
</tr>
<tr>
<td>6.23</td>
<td>$P_d$, OC jammer at $\phi = 0^\circ$, $R_j = 132$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.10)$, for the FTS adaptive filter.</td>
<td>144</td>
</tr>
<tr>
<td>6.24</td>
<td>SINR Loss in the range cell sample support, OC jammer at $\phi = 45^\circ$, 72 Km from the radar.</td>
<td>145</td>
</tr>
<tr>
<td>6.25</td>
<td>SINR Loss in the range cell sample support, OC jammer at $\phi = 45^\circ$, 132 Km from the radar.</td>
<td>146</td>
</tr>
<tr>
<td>6.26</td>
<td>$P_d$, OC jammer at $\phi = 45^\circ$, $R_j = 72$ Km, target at $(\phi = 0^\circ, \bar{\omega} = 0.48)$, for the JDL adaptive filter.</td>
<td>148</td>
</tr>
<tr>
<td>6.27</td>
<td>$P_d$, OC jammer at $\phi = 45^\circ$, $R_j = 132$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.45)$, for the JDL adaptive filter.</td>
<td>149</td>
</tr>
<tr>
<td>6.28</td>
<td>$P_d$, OC at jammer $\phi = 45^\circ$, $R_j = 72$ Km, target at $(\phi = 0^\circ, \bar{\omega} = 0.48)$, for the FTS adaptive filter.</td>
<td>150</td>
</tr>
<tr>
<td>6.29</td>
<td>$P_d$, OC at jammer $\phi = 45^\circ$, $R_j = 132$ Km, target at $(\phi = 0^\circ, \bar{\omega} = -0.45)$, for the FTS adaptive filter.</td>
<td>151</td>
</tr>
</tbody>
</table>
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Thesis Notation</td>
<td>2</td>
</tr>
<tr>
<td>3.1</td>
<td>Jammer Model Parameters</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Radar Model Parameters</td>
<td>29</td>
</tr>
</tbody>
</table>
List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Azimuthal Elements</td>
</tr>
<tr>
<td>$P$</td>
<td>Elevation Elements</td>
</tr>
<tr>
<td>$d_x$</td>
<td>Azimuthal Inter-Element Spacing</td>
</tr>
<tr>
<td>$d_z$</td>
<td>Elevation Inter-Element Spacing</td>
</tr>
<tr>
<td>$R$</td>
<td>Range</td>
</tr>
<tr>
<td>$\hat{k}$</td>
<td>Unit Vector to any Location in the Radar Environment</td>
</tr>
<tr>
<td>$M$</td>
<td>Pulses</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Pulse Repetition Interval</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Pulse Width</td>
</tr>
<tr>
<td>$\alpha_l$</td>
<td>Signal Complex Amplitude of Range Cell $l$</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Range to $i^{th}$ Radar Clutter Ring</td>
</tr>
<tr>
<td>$h_a$</td>
<td>Radar Platform Altitude</td>
</tr>
<tr>
<td>$a_e$</td>
<td>Earth’s Effective Radius</td>
</tr>
<tr>
<td>$\phi_k$</td>
<td>$k^{th}$ Radar Ground Clutter Patch Azimuthal Location</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Grazing Angle</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Constant Reflectivity Model Parameter</td>
</tr>
<tr>
<td>$\Delta\phi$</td>
<td>Clutter Patch Angular Extent</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>Range Resolution</td>
</tr>
<tr>
<td>$\tilde{\omega}_{ik}^{cc}$</td>
<td>$ik^{th}$ Radar Clutter Patch Normalized Doppler Frequency</td>
</tr>
<tr>
<td>$\tilde{\vartheta}_{ik}^x$</td>
<td>$ik^{th}$ Radar Clutter Patch Spatial Frequency</td>
</tr>
<tr>
<td>$v_a$</td>
<td>Radar Platform Velocity</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Pulse Repetition Frequency</td>
</tr>
<tr>
<td>$\eta_a$</td>
<td>Azimuthal Bins in LPR</td>
</tr>
<tr>
<td>$\eta_b$</td>
<td>Temporal Bins in LPR</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$T$</td>
<td>JDL Transformation Matrix</td>
</tr>
<tr>
<td>$b$</td>
<td>Temporal Steering Vector</td>
</tr>
<tr>
<td>$a$</td>
<td>Azimuthal Steering Vector</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Space-Time Snapshot</td>
</tr>
<tr>
<td>$w_{jdl}$</td>
<td>Joint Domain Localized Adaptive Filter</td>
</tr>
<tr>
<td>$w_{fts}$</td>
<td>Factored Time Space Adaptive Filter</td>
</tr>
<tr>
<td>$f_m$</td>
<td>FTS Temporal Steering Vector for $m^{th}$ Doppler Filter</td>
</tr>
<tr>
<td>$t_b$</td>
<td>$Mx1$ Window Function</td>
</tr>
<tr>
<td>$B$</td>
<td>FTS Temporal Steering Matrix</td>
</tr>
<tr>
<td>$\hat{R}$</td>
<td>Estimated Interference Covariance Matrix</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Radar Transmit Power</td>
</tr>
<tr>
<td>$G_t$</td>
<td>Array Transmit Pattern</td>
</tr>
<tr>
<td>$g$</td>
<td>Element Transmit and Receive Pattern</td>
</tr>
<tr>
<td>$\sigma_{ik}$</td>
<td>Radar Cross Section for $ik^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Noise Power Spectral Density</td>
</tr>
<tr>
<td>$B$</td>
<td>Radar Receiver Bandwidth</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Receiver System Losses</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Received One-Way Power at a Specific Clutter Patch</td>
</tr>
<tr>
<td>$G_j$</td>
<td>Jammer Array Transmit Pattern</td>
</tr>
<tr>
<td>$P_j$</td>
<td>Jammer Transmit Power</td>
</tr>
<tr>
<td>$\sigma_{ik}^j$</td>
<td>$ik^{th}$ Clutter Patch RCS due to the Jamming Platform</td>
</tr>
<tr>
<td>$R_{ik}^j$</td>
<td>Range from the Jammer to $ik^{th}$ Radar Clutter Patch</td>
</tr>
<tr>
<td>$\phi_{jk}$</td>
<td>Jammer Reference Angle to $k^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$\phi_j$</td>
<td>Angle from Jammer Boresight to Radar Boresight</td>
</tr>
<tr>
<td>$\phi_k$</td>
<td>Azimuth Angle from Radar Boresight to $k^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$h_j$</td>
<td>Jammer Elevation</td>
</tr>
<tr>
<td>$\theta_{ik}^j$</td>
<td>Jammer Elevation Angle to $ik^{th}$ Radar Clutter Patch</td>
</tr>
<tr>
<td>$\phi_{ik}^j$</td>
<td>Jammer Azimuth Angle to $ik^{th}$ Radar Clutter Patch</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Clutter-to-Noise Ratio</td>
</tr>
<tr>
<td>$\xi_{\text{hc}}^{ik}$</td>
<td>Hot Clutter CNR for $ik^{th}$ Radar Clutter Patch</td>
</tr>
<tr>
<td>$\xi_{\text{cc}}^{ik}$</td>
<td>Cold Clutter CNR for $ik^{th}$ Radar Clutter Patch</td>
</tr>
<tr>
<td>$f_p$</td>
<td>Doppler Shift due to Radar Velocity in Jammer Direction</td>
</tr>
<tr>
<td>$v_p$</td>
<td>Radar Platform Velocity Component in Jammer Direction</td>
</tr>
<tr>
<td>$f_j$</td>
<td>Doppler Shift due to Jammer Velocity in the Radar Direction</td>
</tr>
<tr>
<td>$v_{jp}$</td>
<td>Jammer Platform Velocity Component in Radar Direction</td>
</tr>
<tr>
<td>$f_{ik}'$</td>
<td>Doppler Shift due to Jammer Velocity in Direction of $ik^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$v_j$</td>
<td>Jammer Platform Velocity</td>
</tr>
<tr>
<td>$f_{ik}$</td>
<td>Doppler Shift due to Radar Velocity in Direction of $ik^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$f_{ik}'$</td>
<td>Hot Clutter Doppler Shift Received by Radar</td>
</tr>
<tr>
<td>$\bar{\omega}_{\text{hc}}^{ik}$</td>
<td>Hot Clutter Normalized Doppler for $ik^{th}$ Clutter Patch</td>
</tr>
<tr>
<td>$v$</td>
<td>Non-Adaptive Steering Vector</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>Noise power per element per pulse</td>
</tr>
<tr>
<td>$\zeta_t$</td>
<td>SNR per element per pulse</td>
</tr>
<tr>
<td>$w$</td>
<td>Space-time Weighting Vector</td>
</tr>
<tr>
<td>$N_{\text{trials}}$</td>
<td>Number of Trials</td>
</tr>
<tr>
<td>$P_{fa}$</td>
<td>Probability of False Alarm</td>
</tr>
<tr>
<td>$w_{\text{mf}}$</td>
<td>Matched Filter Weight Vector</td>
</tr>
<tr>
<td>$P_d$</td>
<td>Probability of Detection</td>
</tr>
</tbody>
</table>
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>iid</td>
<td>Independently and Identically Distributed</td>
<td>iv</td>
</tr>
<tr>
<td>SL</td>
<td>Side-Looking</td>
<td>4</td>
</tr>
<tr>
<td>RCS</td>
<td>Radar Cross Section</td>
<td>11</td>
</tr>
<tr>
<td>JDL</td>
<td>Joint Domain Localized</td>
<td>14</td>
</tr>
<tr>
<td>LPR</td>
<td>Localized Processing Region</td>
<td>14</td>
</tr>
<tr>
<td>FTS</td>
<td>Factored Time Space</td>
<td>16</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
<td>16</td>
</tr>
<tr>
<td>RUT</td>
<td>Range Cell Under Test</td>
<td>17</td>
</tr>
<tr>
<td>CPI</td>
<td>Coherent Processing Interval</td>
<td>17</td>
</tr>
<tr>
<td>SCATS</td>
<td>Spatter, Clutter, and Target Signal Model</td>
<td>17</td>
</tr>
<tr>
<td>CNR</td>
<td>Clutter-to-Noise Ratio</td>
<td>18</td>
</tr>
<tr>
<td>NHD</td>
<td>Non-Homogeneity Detection</td>
<td>28</td>
</tr>
<tr>
<td>GIP</td>
<td>Generalized Inner Product</td>
<td>28</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
<td>34</td>
</tr>
<tr>
<td>MVE</td>
<td>Minimum Variance Estimator</td>
<td>34</td>
</tr>
<tr>
<td>SM</td>
<td>Signal Match</td>
<td>36</td>
</tr>
<tr>
<td>TN</td>
<td>Tangential</td>
<td>61</td>
</tr>
<tr>
<td>NA</td>
<td>Non-Adaptive</td>
<td>61</td>
</tr>
<tr>
<td>MF</td>
<td>Matched Filter</td>
<td>61</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference Plus Noise Ratio</td>
<td>61</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
<td>61</td>
</tr>
<tr>
<td>OC</td>
<td>Oncoming</td>
<td>112</td>
</tr>
</tbody>
</table>
I. Introduction

1.1 Objective

Interference in the radar environment degrades airborne radar performance. In conventional airborne radar, the scattered ground returns reflecting from the earth’s surface back to the radar degrade radar performance at a radar azimuth and Doppler frequency. This research examines hot clutter for side-looking airborne radar operation. Hot clutter occurs when an airborne jammer illuminates the ground, flying at some azimuth, elevation, velocity, and range from the radar platform. When the airborne jammer waveform scattered returns are perfectly coherent with the radar waveform, the radar cannot distinguish between the returns transmitted by the jammer and returns transmitted by the radar. In effect, hot clutter degrades radar performance for different locations in azimuth and Doppler depending on the jammer velocity and location in the radar environment. Hot clutter also creates heterogeneities within the radar environment. If the radar uses adaptive filters, these filters are created based on interference around the range cell under test (RUT). If this interference estimate does not match the RUT, adaptive radar performance degrades.

1.2 Purpose

This research characterizes hot clutter effects on side-looking adaptive airborne radar operation. The research effort introduces a hot clutter jammer into the Ward radar data model [12]. Once the modifications are made to the radar data model to include a hot clutter jammer, this research characterizes hot clutter as a function of velocity, azimuth, elevation, and range from the radar platform. Based on these
variables, the radar interference environment changes and radar performance using both adaptive and non-adaptive processing is affected.

1.3 Notation

In Table 1.1, one can see the mathematical notation used in this thesis. Unit vectors are described as \( \hat{x} \). This notation is similar to the estimated value notation. Surrounding text explains whether the variable is an estimated value or unit vector.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>Expected Value</td>
</tr>
<tr>
<td>( x )</td>
<td>Scalar</td>
</tr>
<tr>
<td>( \hat{x} )</td>
<td>Estimated Value</td>
</tr>
<tr>
<td>( x )</td>
<td>Vector</td>
</tr>
<tr>
<td>( x^H )</td>
<td>Hermetian Transpose</td>
</tr>
<tr>
<td>( X )</td>
<td>Matrix</td>
</tr>
<tr>
<td>( X_{ik} )</td>
<td>Matrix with Subscripts</td>
</tr>
</tbody>
</table>

1.4 Materials and Resources

All simulations were created and executed using MATLAB\textsuperscript{®} version 7.0.4. The computers used in research are Dell computers obtained by the Air Force Institute of Technology.

1.5 Organization

Chapter II offers a literature review describing the foundation of a radar data model based on [12] and extended into the planer array by [5]. The fully adaptive Matched Filter (MF), as well as Joint Domain Localized (JDL), and Factored Time Space (FTS) partially adaptive filters used in this research are reviewed. The discussion of previous research in hot clutter, and the necessity of this research is presented.

Chapter III develops the hot clutter model and introduces hot clutter into the radar data model. The hot clutter model development is discussed, as well as pre-
liminary model validation using Non-Heterogeneity Detection (NHD) and hot/cold clutter covariance matrix rank.

Chapter IV provides the discussion and results detailing the hot clutter interference environment created by the radar data model. This chapter describes the new interference created by the hot clutter for an oncoming jammer flying directly towards the radar, and a jammer flying tangential to the radar location. The interference is examined using the Minimum Variance Estimator (MVE) and Signal Match (SM) power spectral densities (PSD). This chapter examines the range and azimuth dependencies on the location of hot clutter for tangential and oncoming jammers.

Chapter V provides the discussion and results characterizing the impact a hot clutter jammer flying tangential to the radar has on radar performance. The impact hot clutter has on non-adaptive and adaptive processing is discussed using both known and estimated interference using Range-Doppler outputs, probability of detection, SINR (Signal to Interference plus Noise Ratio) Loss, and Output SINR metrics.

Chapter VI provides the discussion and results characterizing the impact an oncoming hot clutter jammer flying directly towards the radar has on radar performance. Similarly, the impact of hot clutter on non-adaptive and adaptive processing is discussed using both known and estimated interference using Range-Doppler outputs, probability of detection, SINR Loss, and Output SINR metrics.

Chapter VII is the conclusions chapter. The effect of hot clutter is reviewed. The effect on radar performance is summarized based on the jammer velocity vector and the jammer location in azimuth and range. Future research in hot clutter is discussed, along with suggested modifications to the hot clutter model.
II. Literature Review

The examination of hot clutter on airborne radar performance is performed using the radar data model [12], [5]. The basic radar data model framework is reviewed in this Chapter to understand the modifications made in Chapter III to include hot clutter. The radar data model framework is powerful because it allows isolating specific phenomena in the radar environment under analysis.

The radar data model is a phased array pulse Doppler radar. This radar has advantages over other radar types as it distinguishes a target in up to four dimensions: elevation, azimuth, Doppler frequency (velocity), and range.

2.1 Geometry

The following framework is an encapsulation of a radar data model developed by Ward [12] and extended into a planar array by Hale [5]. In a phased array radar, the array is constructed into N azimuthal elements and P elevation elements. The inter-element spacings \( d_x \) and \( d_z \) are the spacings between the elements. The reference element is defined as the first element to receive an incoming return from a positive azimuth and elevation. Figure 2.1 illustrates the array geometry for a side-looking (SL) radar. The element location is expressed as a vector

\[
d_{np} = \begin{bmatrix} -nd_x \\ -pd_z \end{bmatrix},
\]

where \( n = 0, 1, \ldots, N - 1 \) and \( p = 0, 1, \ldots, P - 1 \).

The next step in developing the radar data model is defining a coordinate system using azimuth, elevation, and range. The antenna array is in the \( x-z \) plane. Azimuth is defined from radar boresight with positive azimuth locations \( \phi \) in positive \( x \) and negative azimuth locations \( \phi \) in the direction of negative \( x \). The velocity vector for a side-looking (SL) radar is defined as

\[
v^\text{SL}_a = v_a \hat{x},
\]
Figure 2.1: SL radar planar array geometry with $N$ azimuth elements spaced $d_x$ apart and $P$ elevation elements spaced $d_z$ apart. The antenna array is located in the $x-z$ plane. The reference element is defined as the first element to receive a return from positive azimuth and elevation. As the radar velocity vector is along the positive $x$ axis, the reference element is in the top right-hand corner in this illustration.
where the aircraft is flying in the positive \( x \) direction. Elevation is defined as positive \( \theta \) above the radar and negative \( \theta \) below the radar. The range \( R \) to any point in space is defined as a direct line from the reference element to the location of interest. The radar platform geometry for a SL radar is illustrated in Figure 2.2. The aircraft is travelling along \( \hat{x} \) in a positive direction. The antenna array is located in the \( x - z \) plane. The reference element is the first element to receive a return from positive \( \phi \) and positive \( \theta \), thus making the reference element in this illustration the element in the top right-hand corner in the \( x - z \) plane of Figure 2.2. The unit vector \( \hat{k} \) to any location in the radar environment is expressed as

\[
\hat{k}(\theta, \phi) = \cos \theta \sin \phi \hat{x} + \cos \theta \cos \phi \hat{y} + \sin \theta \hat{z}. \tag{2.3}
\]

### 2.2 Data Format

The radar receives all returns for all azimuthal and elevation elements, pulses \( M \), and range cells. For a planar array, the radar has \( MNPL \) returns. The following development is for a linear array, where \( P = 1 \). Therefore, the returns are formatted into a radar data cube as shown in Figure 2.3. The radar receives \( MN \) samples for \( L \) range cells, where \( L \) generally is defined as

\[
L = \frac{T_r}{\tau}, \tag{2.4}
\]

where \( T_r \) is the pulse repetition interval and \( \tau \) is the pulse width. Note, this expression is true only when no pulse compression is used. Figure 2.4 illustrates fast-time sampling.

For each range cell, the radar \( MN \) returns are denoted as [5]

\[
\chi_{mn} = a_l e^{j2\pi n\phi x} e^{j2\pi m\bar{\omega}}, \tag{2.5}
\]
Figure 2.2:  The radar platform geometry. The aircraft is a side-looking radar, travelling along the positive $x$ axis at velocity $v_a$, at an altitude $h_a$. The array is located in the $x-z$ plane in the radar data model. Azimuth is defined from radar boresight with positive azimuth locations $\phi$ in positive $x$ and negative azimuth locations $\phi$ in the direction of negative $x$. Elevation is defined as positive $\theta$ above the radar and negative $\theta$ below the radar.
Figure 2.3: The radar data cube for $P = 1$. In a radar with a linear array there is only one elevation channel. Therefore, when $P = 1$, the radar has $MNL$ returns available for data processing.

Figure 2.4: Each $MNP$ return for a particular range cell $l$ in the radar environment corresponds to a range delay from $0 - T_r$ seconds.
where $\alpha_l$ is the signal complex amplitude of range cell $l$, and $\vartheta_x$ is the azimuthal spatial frequency defined as

$$\vartheta_x = \frac{nd_x \cos \theta \sin \phi}{\lambda_0}. \quad (2.6)$$

$\bar{\omega}$ is the normalized Doppler frequency defined as

$$\bar{\omega} = \frac{2v_a \cos \theta \sin \phi}{\lambda_0 f_r}, \quad (2.7)$$

where $\lambda_0$ is the wavelength, and $f_r$ is the pulse repetition frequency. The 2D space-time snapshot for a particular range cell for all spatial and temporal returns is denoted as

$$\chi_l = \begin{bmatrix}
\chi_0(0) \\
\chi_1(0) \\
\vdots \\
\chi_{(N-1)}(0) \\
\chi_0(1) \\
\chi_1(1) \\
\vdots \\
\chi_{(N-1)}(1) \\
\vdots \\
\chi_0(M - 1) \\
\chi_1(M - 1) \\
\vdots \\
\chi_{(N-1)}(M - 1)
\end{bmatrix}. \quad (2.8)$$

The space-time snapshot is simplified [12], and expressed as

$$\chi_l = \alpha_l b(\bar{\omega}) \otimes a(\vartheta_x), \quad (2.9)$$
where the azimuthal steering vector is

\[
a(\vartheta_x) = \begin{bmatrix}
e^{j2\pi\vartheta_x(0)} \\
e^{j2\pi\vartheta_x(1)} \\
e^{j2\pi\vartheta_x(2)} \\
\vdots \\
e^{j2\pi\vartheta_x(N-1)}
\end{bmatrix},
\]

and the temporal steering vector is

\[
b(\bar{\omega}) = \begin{bmatrix}
e^{j2\pi\bar{\omega}(0)} \\
e^{j2\pi\bar{\omega}(1)} \\
e^{j2\pi\bar{\omega}(2)} \\
\vdots \\
e^{j2\pi\bar{\omega}(M-1)}
\end{bmatrix}.
\]

The non-adaptive space-time steering vector \( v \) containing the weights to coherently beamform the radar returns is similarly

\[
v(\bar{\omega}, \vartheta_x) = b(\bar{\omega}) \otimes a(\vartheta_x).
\]

When the radar output

\[
y = v^H \chi
\]

is computed by the inner product, the scalar output is beamformed to a location azimuth and Doppler.

### 2.3 Clutter Model Review

An in-depth clutter model review developed by [12] and extended to the planer array by [5] is important to review. It gives an understanding of how a hot clutter jammer is introduced into the radar data model. For each range cell, the clutter
is divided into $k$ azimuthal clutter patches for $i$ clutter rings. The range cells also include returns ambiguous range rings. In Figure 2.5, the elevation and grazing angle is defined for every radar clutter patch at a specific range from the radar, denoted $R_i$. The elevation to each clutter patch is defined as [12]

$$\theta_i = \sin^{-1}\left(\frac{R_i^2 + h_a(h_a + 2a_e)}{2R_i(a_e + h_a)}\right), \quad (2.14)$$

where $R_i$ is the range to the $i^{th}$ radar clutter ring, $h_a$ is the radar platform altitude, and $a_e$ is the earth’s effective radius. From the radar platform, all clutter patches at a specific range ring have the same elevation. In practice, subscripts $i$ and $k$ indicate the $i^{th}$ clutter ring at a range of $R_i$ and the $k^{th}$ clutter patch at an azimuth of $\phi_k$.

The grazing angle $\psi$ characterizes the clutter patch Radar Cross Section (RCS). This grazing angle is the angle between an imaginary line from the radar to a clutter...
patch and a line tangential to the earth’s surface and is expressed as [12]

\[ \psi_i = \sin^{-1} \left( \frac{R_i^2 - h_a(h_a + 2a_e)}{2R_ia_e} \right). \]  \hspace{1cm} (2.15)

There is now a framework to characterize clutter returns at any location in azimuth, elevation, and Doppler. The effective clutter patch RCS is defined as [12]

\[ \sigma_{ik} = \gamma \sin \psi_i R_i \Delta \phi \Delta R \sec \psi_i, \]  \hspace{1cm} (2.16)

where \( \gamma \) is the constant reflectivity model parameter converted from dB into a numerical value, \( \psi_i \) is the grazing angle, \( R \) is the range, \( \Delta \phi \) is the angular extent of a clutter patch, and \( \Delta R \) is the range extent of a clutter patch radar range resolution. The constant gamma model RCS represents the backscattered RCS of any \( ik \)-th clutter patch. For a linear array, the clutter covariance matrix is represented as

\[
\mathbf{R}_c = \sigma^2 \sum_{i=0}^{N_r-1} \sum_{i=0}^{N_c-1} \xi_{ik} \mathbf{b}(\bar{\omega}_{ik}^{cc}) \mathbf{b}(\bar{\omega}_{ik}^{cc})^H \otimes \mathbf{a}(\hat{\theta}_{ik}^x) \mathbf{a}(\hat{\theta}_{ik}^x)^H, \]  \hspace{1cm} (2.17)

where \( \bar{\omega}_{ik}^{cc} \) is the cold clutter patch normalized Doppler frequency due to the clutter patch velocity relative to the radar platform, \( \hat{\theta}_{ik}^x \) is the spatial frequency component of each clutter patch, and \( \xi_{ik}^{cc} \) is the cold clutter-to-noise ratio of each clutter patch. This clutter-to-noise ratio is discussed in Chapter III, as this is one component used to create a separate hot clutter covariance matrix.

For a SL radar, the normalized Doppler of a clutter patch is expressed as

\[ \bar{\omega}_{ik}^{cc} = \frac{2v_a \cos \theta_i \sin \phi_k}{\lambda_0 f_r}, \]  \hspace{1cm} (2.18)

where \( v_a \) is the radar platform velocity, \( \phi_k \) is any location in azimuth, \( \lambda_0 \) is the wavelength, and \( f_r \) is the pulse repetition frequency.
The azimuthal spatial frequency associated with clutter is expressed as

\[ \vartheta_{ik}^x = \frac{d_x \cos \theta_i \sin \phi_k}{\lambda_o}, \]

(2.19)

where \( \vartheta_{ik}^x \) is the spatial frequency for any \( ik^{\text{th}} \) clutter patch. The clutter in this radar data model is strictly ground clutter illuminated by the radar.

When thermal noise is added into the radar environment along with the clutter covariance matrix, there is now a interference covariance matrix containing cold clutter and thermal noise. Chapter III develops modifications to the radar data model to include hot clutter in the radar environment.

2.4 Adaptive Radar Detection

Adaptive filters improve radar performance as the filters are able to place nulls on sources of interference not in the radar look direction. Adaptive radar use interference from surrounding range cells to build an estimate of interference within the range cell under test. Using this interference estimate, the filters are able to place nulls, both spatially and/or temporally, at locations of interference. Ideally, the fully adaptive Matched Filter (MF) would be used to mitigate all sources of interference. The MF improves radar detection as it is able to mitigate all sources of interference not in the radar look direction. The MF is expressed as

\[ w_{mf} = R^{-1}v, \]

(2.20)

where \( R \) is the known interference covariance matrix, and \( v \) is the space-time steering vector. However, the adaptive filters are required to obtain twice the amount of sample support as degrees of freedom (DOF) the adaptive filters provide [7]. The MF would require \( 2MNP \) sample support. As the radar has limited range cells, most radar systems do not have enough sample support to create the adaptive MF. For this reason, partially adaptive filters are used as they require considerably less sample
Figure 2.6: The Localized Processing Region for JDL. The LPR is a beamspace of $\eta_a, \eta_b$ Doppler and azimuth bins.

support. The two partially adaptive filters used in this research are Joint Domain Localized (JDL), and Factored Time Space (FTS).

2.4.1 Joint Domain Localized. The Joint Domain Localized (JDL) [11] adaptive filter uses a beamspace approach to adaptively null sources of interference using Doppler and angle bins around the location of interest. The JDL adaptive filter overview is a summary taken from [5].

JDL premise is the transformation from element-time space, representing azimuth elements and Doppler bins, to angle-Doppler space. This transformation is performed within a Localized Processing Region (LPR) seen in Figure 2.6. For a two-dimensional LPR, the LPR size is denoted as $\eta_a \times \eta_b$, where $\eta_a$ is the number of azimuthal bins and $\eta_b$ is the number of Doppler bins used in the LPR. The transformation between element-time space and angle-Doppler space is represented by the
transformation matrix \( T \), given by

\[
T = \left[ b(\bar{\omega}_{-1/M})b(\bar{\omega}_0)b(\bar{\omega}_{+1/M}) \right] \otimes \left[ a(\phi_{-1/N})a(\phi_0)a(\phi_{+1/N}) \right],
\]

(2.21)

where \( b \) and \( a \) are the temporal and azimuthal steering vectors previously defined, and \( \bar{\omega}_0, \phi_0 \) is the LPR center. The temporal and azimuthal bins in the LPR are a single bin above and below the target bin of interest. The LPR represented by Figure 2.6 and Eqn. (2.21) is \( 3 \times 3 \). The LPR can encompass up to the entire beamspace, making \( \eta_a \times \eta_b = N \times M \). This situation when the LPR is \( N \times M \) is the fully adaptive MF. The transformation matrix \( T \) is applied to a space-time snapshot \( \chi \) in the range cell under test, where

\[
\tilde{\chi} = T^H \chi.
\]

(2.22)

The interference covariance matrix \( \tilde{\mathbf{R}} \) is also transformed using the transformation matrix, expressed as

\[
\tilde{\mathbf{R}} = T^H \mathbf{R} T,
\]

(2.23)

where \( \mathbf{R} \) is the interference covariance matrix. Similarly the space-time steering vector must also be transformed using the transformation matrix and is given by

\[
\tilde{\mathbf{v}} = T^H \mathbf{v}.
\]

(2.24)

If the JDL output is denoted as

\[
y_{\text{jdl}} = \tilde{\mathbf{w}}^H \tilde{\chi}
\]

(2.25)

and the adaptive JDL filter, in the \textit{transform} domain is denoted as

\[
\tilde{\mathbf{w}} = \tilde{\mathbf{R}}^{-1} \tilde{\mathbf{v}},
\]

(2.26)

then the full JDL adaptive filter \( \mathbf{w}_{\text{jdl}} \) in the space-time domain is expressed as

\[
\mathbf{w}_{\text{jdl}} = (T^H \mathbf{R} T)^{-1} T^H \mathbf{v}.
\]

(2.27)
2.4.2 Factored Time Space. The Factored Time Space (FTS) adaptive filter is a reduced dimension algorithm able to spatially adapt to the environment. It is a reduced dimensionality algorithm because it sacrifices all temporal Degrees of Freedom (DOF). The FTS algorithm development follows the development by [5]. The FTS adaptive filter $w_{\text{fts}}$ is defined as

$$w_{\text{fts}} = f_m \otimes [(B^H R B)^{-1} a], \quad (2.28)$$

where $f_m$ is the temporal steering vector $b$ for the $m^{th}$ Doppler bin. This new temporal steering vector may or may not contain a window taper, and is expressed as

$$f_m = b \odot t_b, \quad (2.29)$$

where $t_b$ is a $M \times 1$ window function and $\odot$ is the Hadamard product. The matrix $B$ is defined as

$$B = f_m \otimes I_N, \quad (2.30)$$

where $I_N$ is a $N \times N$ identity matrix. Eqn. (2.28) is the expression under known covariance. In a real life scenario, adaptive steering vectors are calculated using an estimated interference covariance matrix $\hat{R}$. This estimated covariance is expressed as

$$\hat{R} = \frac{1}{2K} \sum_{k=1-K, k \neq l}^{l+K} \chi_k \chi_k^H, \quad (2.31)$$

where $l$ is the RUT, and $K$ is the number of DOF required to create the adaptive filter. The interference estimate is created using space-time snapshots around the range cell under test. The number of space-time snapshots required is twice the DOF. Because the FTS filter adapts only in azimuth, there is $N$ degrees of freedom. Therefore, the required sample support is $2N$. The estimated interference covariance matrix for the
FTS adaptive filter is expressed as

\[
\hat{\mathbf{R}} = \frac{1}{2N} \sum_{k=l-N, k \neq l}^{l+N} \mathbf{x}_k\mathbf{x}_k^H, \tag{2.32}
\]

where \( l \) is the range cell under test (RUT).

### 2.5 Previous Hot Clutter Research.

This thesis models and characterizes hot clutter through the eyes of a side-looking airborne radar. Previous research in the area of hot clutter focuses on mitigation. In [3], the radar transmits polyphase coded waveforms to distinguish between the jamming waveform and the transmitted waveform. In [6], [4], the authors present techniques for the mitigation of hot clutter using various adaptive algorithms. Others have created techniques to mitigate hot clutter using an auxiliary beam, or dead times between the coherent processing interval (CPI) to distinguish between the radar clutter returns and the returns from the hot clutter jammer.

Hot clutter modelling is a contentious task. This hot clutter research is performed under an assumption where the hot clutter RCS statistics reflecting from the \( ik \)th clutter patch to the radar are identical to the monostatic backscattered RCS statistics reflecting back to the jammer platform. The monostatic backscattered RCS is modelled using the constant gamma model [8]. In reality, the scattered jammer waveform received by the radar from the \( ik \)th clutter patch will be due to forward or diffuse scattering, whose statistics are not equivalent to backscattered monostatic clutter returns statistics. If the model is to be more realistic, scattering models such the Spatter, Clutter, and Target Signal Model (SCATS) used extensively in [9] and [10] should be employed in this hot clutter model to accurately define the bistatic hot clutter RCS characteristics received by the radar.
III. Hot Clutter Model

3.1 Introduction

Hot clutter degrades airborne radar performance and is the interference created by a jammer purposely illuminating the ground with its transmitter. If the jammer waveform scattered returns is received perfectly coherent with the radar waveform, the radar cannot distinguish between returns from its own transmitter and scattered returns from the jammer. One assumption in the model development is the jammer and radar travel with an associated velocity; however, they are at constant locations in the radar environment and are stationary throughout the coherent processing interval (CPI).

3.2 Model Development

A coherent jammer is included in the radar data model defined at a specific transmit power, azimuth, elevation, and stand-off range from the radar platform. The jammer transmit pattern is identical to the radar transmit pattern. In addition, the jammer waveform scattered returns is assumed to be perfectly coherent with the radar waveform. The jammer illuminates the ground, creating heterogeneities within the range cells by elevating the clutter power.

The traditional clutter-to-noise ratio (CNR) at a single element for the $ik^{th}$ radar clutter patch is defined in [5] as

$$
\xi_{ik} = \frac{P_t G_t(\theta_i, \phi_k) g(\theta_i, \phi_k) \lambda_0^2 \sigma_{ik}}{(4\pi)^3 N_0 B L_s R_i^4},
$$

(3.1)

where $P_t$ is the transmit power, $G_t$ is the radar array pattern on transmit, $g$ is the radar element pattern on receive, $\lambda_0$ is the wavelength, $\sigma_{ik}$ is the clutter patch radar cross section (RCS), $N_0$ is the noise power spectral density, $B$ is the radar receiver bandwidth, $L_s$ is the receiver system losses, and $R_i$ is the range to the clutter ring. This CNR expression in Eqn. (3.1) is modified to include hot clutter created by
Figure 3.1: This figure illustrates the one-way radar equation. As the clutter patch location changes in azimuth and elevation, the amount of reflected power $P_r$ at each clutter patch changes due to the radar array pattern $G_t$, the clutter patch radar cross section $\sigma_{ik}$, and range $R_{ik}$ to the $ik^{th}$ clutter patch.

The coherent jammer. The basic one-way radar equation sets a foundation for the development of a hot clutter jammer.

The one-way radar equation is expressed as [8]

$$P_r = \frac{P_t G_t \sigma}{4\pi R^2},$$  \hspace{1cm} (3.2)

where $P_r$ is the one-way clutter power of a specific clutter patch illuminated by the radar. The power reflected from this clutter patch depends on the RCS scattering characteristics (forward, back, or diffuse) to any location in the radar environment. The one-way radar equation is illustrated in Figure 3.1. The backscattered radar cross section $\sigma$ using the constant gamma model [8] is the defined by the platform grazing angle to a specific clutter patch, $\psi$, defined as

$$\psi = \sin^{-1} \left[ \frac{R^2 - h_a(h_a + 2a_e)}{2Ra_e} \right],$$  \hspace{1cm} (3.3)
where $h_a$ is the radar platform’s elevation, $a_e$ is the Earth’s effective radius, and $R$ is the range to the clutter patch. The backscattered RCS of any clutter patch can now be found at any range and grazing angle from the radar. This RCS is expressed as

$$\sigma = \gamma \sin \psi R \Delta \phi \Delta R \sec \psi,$$  \hspace{1cm} (3.4)

where $\gamma$ is the constant reflectivity model parameter [8] converted from dB into a numerical value, $\psi$ is the grazing angle, $R$ is the range, $\Delta \phi$ is the angular extent of a clutter patch, and $\Delta R$ is the radar range resolution. Therefore, the backscattered power at the $ik^{th}$ ground patch from the jammer is

$$P_r = \frac{P_j G_j \sigma_{ik}^j}{4\pi R_{ik}^j},$$ \hspace{1cm} (3.5)

where $G_j$ is the gain on transmit based on the jammer array pattern, $P_j$ is the jammer transmit power, $\sigma_{ik}^j$ is the clutter patch RCS with respect to the jammer platform, and $R_{ik}^j$ is the range from the jammer to any radar clutter patch.

There is now a foundation to compute the power of any clutter patch due to the hot clutter jammer. The next step is to calculate the range from the jammer to any radar clutter patch. The relationship between the radar and jammer’s azimuth angle and range is seen in Figure 3.2. The jammer reference angle $\phi_{jk}$ is defined as

$$\phi_{jk} = \phi_k - \phi_j,$$  \hspace{1cm} (3.6)

where $\phi_j$ is the angle from jammer boresight to radar boresight and $\phi_k$ is the azimuth angle from radar boresight to the $k^{th}$ clutter patch. Using the law of cosines, the range from the jammer to any $ik^{th}$ radar clutter patch is now

$$R_{ik}^j = \sqrt{R_i^2 + R_j^2 - 2R_i R_j \cos \phi_{jk}}.$$  \hspace{1cm} (3.7)
Figure 3.2: Figure describing the relationship between jammer range $R_j$ and the range to a radar clutter patch $R_{ik}$, radar azimuthal look direction $\phi_k$, and the jammer stand-off azimuth $\phi_j$ with respect to the radar platform.
One can see from Figure 3.3, the range from the jammer to a specific clutter patch is defined by the azimuthal angle with respect to the radar platform and the current range cell. The angle between the radar platform and the jammer in Figure 3.3 is $\phi = 20^\circ$. Using this range, and the jammer height $h_j$, the elevation to any radar clutter patch from the jammer $\theta_{ik}^j$ is defined as

$$\theta_{ik}^j = -\sin^{-1}\left(\frac{R_{ik}^j + h_j(h_j + 2a_e)}{2R_{ik}^j(a_e + h_j)}\right).$$ \hspace{1cm} (3.8)$$

Due to the azimuthal dependence of $R_{ik}^j$, the elevation to each clutter patch is different for every location in azimuth and every range cell.

Defining the azimuthal angle from the jammer to any radar clutter patch platform is a bit more daunting. Current modelling has only been developed for range rings between the jammer and the radar. The power radiating from the jammer backlobes has minimal effect on the environment. The jammer backlobes are negligible and expressed as $-\infty$ dB. Assuming the jammer mainbeam illuminates the radar platform, as seen in Figure 3.2, the angle with respect to jammer boresight is calculated using the law of sines. This angle $\phi_{ik}^j$ is expressed as

$$\phi_{ik}^j = \sin^{-1}\left(\frac{R_i \sin \phi_{jk}}{R_{ik}^j}\right).$$ \hspace{1cm} (3.9)$$

The angle $\phi_{jk}$ is defined as an angle less than $180^\circ$ as the jammer is always assumed to be outside the range ring. Therefore, the angle $\phi_{jk}$ is further defined as

$$\phi_{jk} = \begin{cases} 
\phi_k - \phi_j & \phi_k > \phi_j, \phi_k < 180^\circ - \phi_j \\
360^\circ - \phi_k - \phi_j & \phi_k < \phi_j, \phi_k > 180^\circ - \phi_j
\end{cases},$$ \hspace{1cm} (3.10)$$

where $\phi_k$ is defined from $-180^\circ < \phi_k < 180^\circ$. When the jammer is at a particular stand off azimuth, the angle to each radar clutter patch varies for each range ring.
Figure 3.3: The range from the jammer to any radar range ring clutter patch depends on the current range cell, the jammer range, and the azimuthal angle with respect to the radar platform. The range rings are 24, 36, and 48 Km from the radar. The jammer is 69 Km from the radar at $\phi = 20^\circ$. The range from the jammer to every radar clutter patch for every radar range ring varies with respect to the jammer location. Because the jammer is at an azimuth of $\phi = 20^\circ$, the range to the radar clutter patches are closest at this location. As the range ring at 48 Km is closest to the jammer at 69 Km, the azimuth location of $\phi = 20^\circ$ is closest at this location.
Figure 3.4: Radar azimuth values compared to jammer azimuth for different jammer locations; 72 Km, 108 Km, and 132 Km from the radar platform. The range cell under test is 66 Km. The jammer is located at $\phi = 45^\circ$; thus, when the jammer mainbeam is at $\phi_j = 0$, the corresponding radar azimuths at this location is $\phi_k = 45^\circ$ and in the radar backlobes at $\phi_k = -135^\circ$. The farther the jammer is from the RUT, the more radar clutter patches occupy the jammer mainbeam.
In Figure 3.4, the jammer azimuth angle to any radar range patch is no longer constant for every range cell. The jammer antenna pattern illuminates the range cells differently for every location in azimuth, elevation, and range. The jammer coordinate system is constructed with respect to the radar in order to find the jammer power illuminating onto the respective radar clutter patches. If the jammer model is constructed in this fashion, the jammer interference covariance matrix is simply added to the radar clutter covariance matrix.

The framework is now set to incorporate the jammer into the radar data model. The received clutter power due to the radar is extracted from the CNR expression $\xi$. The power transmitted and received by the radar due to clutter is expressed as

$$P_c^r = \frac{P_t G_t(\theta_i, \phi_k) G_r(\theta_i, \phi_k) \lambda^2 \sigma_{ik}}{(4\pi)^3 R_i^4}.$$  

(3.11)

The clutter power from the coherent jammer received by the radar is similarly

$$P_c^j = \frac{P_j G_j^j(\theta_i^j, \phi_k^j) G_r(\theta_i, \phi_k) \lambda^2 \sigma_{ik}^j}{(4\pi)^3 R_{ik}^j R_i^2 R_i^2}.$$  

(3.12)

The variable $G_r$ is the radar array pattern on receive. In phased array radars, the array pattern on receive is the radar element pattern $g$. The framework is now in place to calculate a new CNR only including the hot clutter is $\xi_{ik}^{hc}$, expressed as

$$\xi_{ik}^{hc} = \frac{P_c^j}{\sigma_{no}BL_s}.$$  

(3.13)

The $ik^{th}$ clutter patch RCS characteristics from the scattered jammer waveform reflecting to the radar platform $\sigma_{ik}^j$ are assumed to be identical to the backscattered RCS reflecting back to the jammer platform. The backscattered RCS is calculated using the constant gamma model [8]. In reality, the scattered jammer waveform received by the radar from the $ik^{th}$ clutter patch will be due to forward or diffuse scattering, whose statistics are not equivalent to backscattered monostatic clutter returns statistics. To make the hot clutter model more realistic, a diffuse scattering RCS model as in [9, 10] needs to
be incorporated into the radar data model. Forward and/or diffuse scattering changes the RCS statistics of each \( k \)th clutter patch.

The CNR resulting from cold clutter, \( \xi_{ik}^{cc} \), is similarly expressed as

\[
\xi_{ik}^{cc} = \frac{P_r}{N_o B L_s}, \tag{3.14}
\]

Due to the independence between the hot clutter power and cold clutter power, two separate covariance matrices are created. The conventional cold clutter, or the ground clutter created from the radar, covariance matrix is expressed as

\[
R_{cc} = \sigma^2 \sum_{i=0}^{N_r-1} \sum_{k=0}^{N_c-1} \xi_{ik}^{cc} b(\omega_{ik}^{cc})b(\omega_{ik}^{cc})^H \otimes a(\vartheta_{ik}^x)a(\vartheta_{ik}^x)^H. \tag{3.15}
\]

The hot clutter has a new associated Doppler frequency due to the jammer platform velocity and location in the radar environment. The radar transmits at the carrier frequency plus an associated Doppler shift in relation to the radar platform velocity component in the jammer direction. This Doppler frequency shift \( f_p \) is expressed as

\[
f_p = \frac{2v_p}{\lambda_0}, \tag{3.16}
\]

where \( v_p \) is the radar platform velocity component in the jammer direction. The jammer now receives the waveform from the radar, with another Doppler shift associated with the jammer velocity component in the radar direction. This Doppler frequency shift \( f_j \) is expressed as

\[
f_j = \frac{2v_{jp}}{\lambda_0}, \tag{3.17}
\]

where \( v_{jp} \) is the jammer velocity component in the radar direction. The total Doppler frequency shift at this time is

\[
\frac{2v_p}{\lambda_0} + \frac{2v_{jp}}{\lambda_0}. \tag{3.18}
\]

The jammer transmit waveform at this velocity then hits the ground and reflects to the radar. At the ground, the jammer transmit waveform also experiences another
Doppler shift due to the jammer velocity component in the direction of ground clutter. The waveform experiences a subsequent Doppler frequency shift $f_{jk}'$ expressed as

$$f_{jk}' = \frac{2v_j \cos \theta_{ik} \sin \phi_{ik}}{\lambda_0},$$  \hspace{1cm} (3.19)$$

where $v_j$ is the jammer platform velocity, and $\theta_{ik}$ and $\phi_{ik}$ are the jammer clutter patch locations in azimuth and elevation from the jammer platform. The radar platform receives the waveform with yet another Doppler shift $f_{ik}$ due to the radar platform velocity component in direction of ground clutter defined as

$$f_{ik} = \frac{2v_a \cos \theta_i \sin \phi_k}{\lambda_0}.$$  \hspace{1cm} (3.20)$$

All Doppler frequency shifts are added together to find the received waveform Doppler frequency shift. This Doppler frequency shift received by the radar as a result of hot clutter is $f_{jk}^i$ expressed as

$$f_{jk}^i = f_p + f_j + f_{jk}' + f_{ik},$$  \hspace{1cm} (3.21)$$

or

$$f_{jk}^i = \frac{2v_p}{\lambda_0} + \frac{2v_{jp}}{\lambda_0} + \frac{2v_j \cos \theta_{ik} \sin \phi_{ik}}{\lambda_0} + \frac{2v_a \cos \theta_i \sin \phi_k}{\lambda_0}.$$  \hspace{1cm} (3.22)$$

This Doppler frequency is normalized by the PRF and expressed as

$$\bar{\omega}_{ik}^c = \frac{f_{jk}^i}{f_r}.$$  \hspace{1cm} (3.23)$$

This new normalized Doppler $\bar{\omega}_{ik}^c$ along with the new hot clutter CNR are used to create the hot clutter covariance matrix, expressed as

$$\mathbf{R}_{hc} = \sigma^2 \sum_{i=0}^{N_r-1} \sum_{k=0}^{N_c-1} \mathbf{J}_{ik} \mathbf{B}(\bar{\omega}_{ik}^c) \mathbf{B}(\bar{\omega}_{ik}^c)^H \otimes \mathbf{a}(\theta_{ik}^x) \mathbf{a}(\theta_{ik}^x)^H.$$  \hspace{1cm} (3.24)$$

The hot clutter jammer parameters can be seen in Table 3.1. The parameters are identical to the radar model parameters in Table 3.2, except the jammer element
backlobe level is now $-\infty$ dB. This assumption has no effect other than eliminate the hot clutter ambiguous range ring returns at ranges farther than the jammer.

### 3.3 Non-Homogeneity Detection

Non-Homogeneity Detection (NHD) is a technique used to find non-homogeneous sample support vectors. This technique is used to find the space-time snapshots containing heterogeneous interference making them different from the other sample support vectors. Hot clutter creates heterogeneities within the range cell sample support. The hot clutter very heterogeneous when the jammer is close to the RUT. This NHD metric shows the heterogeneity of hot clutter. The homogeneity between the range cells is important in order to construct an accurate estimate of $\hat{R}$ when used to create adaptive filters. The NHD finds range cell sample support vectors containing an unusual amount of interference not similar to the range cell under test. According to [13], [2], the Generalized Inner Product (GIP) is a metric used to select the sample
Table 3.2: Radar Model Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>32</td>
</tr>
<tr>
<td>$N$</td>
<td>11</td>
</tr>
<tr>
<td>$P$</td>
<td>1</td>
</tr>
<tr>
<td>$f_o$</td>
<td>1240 MHz</td>
</tr>
<tr>
<td>$f_r$</td>
<td>1984 Hz</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.8 $\mu$s</td>
</tr>
<tr>
<td>$P_t$</td>
<td>200 kW</td>
</tr>
<tr>
<td>$B$</td>
<td>800 kHz</td>
</tr>
<tr>
<td>$F_n$ (Noise Figure)</td>
<td>3 dB</td>
</tr>
<tr>
<td>$N_c$</td>
<td>$MNP$</td>
</tr>
<tr>
<td>$h_a$ (Aircraft Altitude)</td>
<td>3000 m</td>
</tr>
<tr>
<td>$v_a$ (Aircraft Velocity)</td>
<td>$\frac{d_x}{f}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-3 dB</td>
</tr>
<tr>
<td>Array Transmit Gain</td>
<td>22 dB</td>
</tr>
<tr>
<td>Element Pattern</td>
<td>Cosine</td>
</tr>
<tr>
<td>Element Gain</td>
<td>4 dB</td>
</tr>
<tr>
<td>Element Backlobe Level</td>
<td>-30 dB</td>
</tr>
<tr>
<td>$d_x$</td>
<td>0.10922 m</td>
</tr>
<tr>
<td>$d_z$</td>
<td>0.1407 m</td>
</tr>
<tr>
<td>System Losses $L_s$</td>
<td>3 dB</td>
</tr>
<tr>
<td>Target $\phi$</td>
<td>0°</td>
</tr>
<tr>
<td>Target $\theta$</td>
<td>0°</td>
</tr>
<tr>
<td>Range Cell Under Test</td>
<td>66 Km</td>
</tr>
</tbody>
</table>
support vectors most like the others, expressed as

\[ y = \chi^H R^{-1} \chi, \]  

(3.25)

where the GIP uses the known interference in the RUT. The GIP distinguishes between the selected sample support vector and the covariance matrix by both amplitude and phase. If the GIP output is ranked from smallest to largest magnitude, the sample support vectors chosen should be closest to the GIP expected value. It is shown if the sample support vectors have a similar covariance to the covariance matrix \( R \), then for a linear array

\[ \varepsilon[y] = MN, \]  

(3.26)

where \( y \) is a vector containing the GIP for all range cells under test.

In Figure 3.5, one can see the differences between the hot clutter and the homogeneous sample support. If the space-time snapshots are similar to the known covariance \( R \), the GIP output should be equal to \( MN \). The output deviates from this value when \( \chi \) is non-homogeneous in covariance structure to the RUT. The GIP is computed comparing the space-time snapshots to the known interference in range cell 549, or 66 Km. The jammer is located at range cell 600. The range cells close to the jammer are more heterogeneous than the range cells far from the jammer. The interference within the environment increases at range cells far from the RUT; however, they are more homogeneous than the range cells close to the jammer.

### 3.4 Interference Covariance Matrix Rank

The interference covariance matrix rank [12] gives some insight on the amount of clutter within the environment and the required degrees of freedom needed to suppress the clutter. The increase in the interference covariance matrix rank is illustrated in Figure 3.6. The interference rank increases anywhere from 25 to 30 % depending on different jamming locations; therefore, the interference within the environment is significantly more severe than the interference containing only cold clutter.
Figure 3.5: Generalized Inner Product for all range cells computed with known covariance matrix $\mathbf{R}$ at the RUT = 66 Km, with the jammer located at range cell 600. Due to the jammer altitude, the jammer mainbeam at $\phi = 0^\circ$ will not illuminate the ground range cell 575. The GIP is calculated for a jammer flying directly towards the radar at $\phi = 0^\circ$. 
The clutter interference rank increases due to the hot clutter. The covariance matrix rank increases some 30% from the interference containing only cold clutter, indicating an increase in clutter in the presence of an oncoming hot clutter jammer at $\phi = 0^\circ$, 72 Km from the radar. The required number of degrees of freedom to sufficiently suppress the clutter is greater when the interference includes a hot clutter jammer as the interference covariance rank increases. The eigenvalue magnitude also increases up to 120 dB, indicating an increase in interference power.
3.5 Summary

The perfectly coherent hot clutter model is introduced in Chapter III. A new hot clutter covariance matrix is added to the radar data model. Model assumptions are summarized below:

1. The $i^k$th clutter patch RCS characteristics from the jammer reflecting to the radar are assumed to be identical the backscattered RCS reflecting back to the jammer. The RCS is actually either forward or diffuse scattering depending on the angle to the radar platform.

2. The direct path jammer signal is ignored. This research focuses only on interference reflecting from ground clutter.

3. The jammer backlobes are assumed to be $-\infty$ dB. Range rings at a greater range than $R_j$ will not include hot clutter.

4. The jammer and radar are moving with a associated velocity, but are stationary throughout the CPI. As the CPI only contains $M = 32$ pulses, the jammer and radar do not travel a significant distance and their movement throughout the CPI is neglected.

The construction of this covariance matrix depends on the jamming location, array transmit pattern, and velocity direction. As the jammer is now included into the radar data model, the interference in the radar environment changes. The hot clutter increases the clutter rank up to 30%, and increases the clutter eigenvalue magnitude greater than 120 dB. The interference is now harder to suppress than the original cold clutter and thermal noise interference. In Chapter IV, the hot clutter interference is examined for an oncoming jammer and a jammer flying tangential to the radar for different location in the radar environment.
IV. Hot Clutter Radar Interference Environment

This chapter discusses the effect hot clutter jamming has on the radar interference environment. The effect of hot clutter depends on many factors, including the jammer velocity vector, range, elevation, azimuth, array pattern, and transmit power. The hot clutter jammer effectively creates new ground clutter at different locations in azimuth and normalized Doppler. The location depends on the jammer velocity vector, range, and relative azimuth from the radar platform. When the jammer array pattern, transmit power, and elevation are constant, the jammer range and azimuthal dependence is examined for both a tangential (TN) jammer and an oncoming (OC) jammer. The TN jammer is a scenario where the jammer does not have a velocity component in the radar direction. The OC jammer is a scenario when the jammer is flying directly towards the radar thus the velocity component in the radar direction is at a maximum.

4.1 Interference From a TN Jammer

The interference from a TN jammer is examined by evaluating the interference power spectral densities (PSD). The Minimum Variance Estimator (MVE) provides an radar environment interference estimate. The Minimum Variance Estimator provides a high resolution spectral estimate to estimate the interference location within the radar interference environment. The MVE provides interference location within the environment; however, the relative amplitude information is useless. The output power in the MVE is

\[ P_{\text{mve}} = (v^H R^{-1} v)^{-1}, \]  

(4.1)

where \( R \) is the known interference covariance matrix. The MVE interference containing only cold clutter and noise is illustrated in Figure 4.1. Using the radar parameters in Table 3.2, the cold clutter increases interference around one location in azimuth for every location in normalized Doppler. The linear array transmits and receives at \( \phi = 0^\circ \). Hence, the region of most interest in this figure is the cut along \( \phi = 0^\circ \) as the radar does not search for targets in a direction other than the transmit direction.
Figure 4.1: MVE interference containing cold clutter and thermal noise. For a SL radar, the main source of interference is at $\phi = 0^\circ$, $\bar{\omega} = 0$ when the radar receives at $\phi = 0^\circ$. 
The Signal Match (SM) interference is the actual interference in the environment received by non-adaptive beamforming. Due to spectral leakage and poor resolution, the SM PSD does not give truly accurate interference location. However, it does accurately portray how the radar sees the interference. The Signal Match interference is expressed as

$$P_{\text{sm}} = \frac{v^H R v}{v^H v},$$

(4.2)

where $v$ is the non-adaptive steering vector and $R$ is the known interference covariance matrix. In Figure 4.2, one sees the SM interference across normalized Doppler and azimuth for interference containing cold clutter and thermal noise. SM calculates the interference power received by the non-adaptive steering vector $v$. However, the MVE provides better resolution and better displays the hot and cold clutter ridges in azimuth and Doppler.

4.1.1 Range Dependence. The relative Doppler location of hot clutter depends on the jammer range from the radar. The radar interference environment can be computed at any range from the radar platform. In this development, the range cell under test (RUT) is always 66 Km. As the jammer changes its location in range, the elevation angles from the jamming platform to the radar clutter patches in the RUT also change, forcing a Doppler change. The Doppler shift is expressed as

$$\bar{\omega}_{hc}^{ik} = \frac{2v_j \cos \theta_{ik}^j \sin \phi_{ik}^j}{\lambda_0 f_r},$$

(4.3)

where $v_j$ is the jammer platform velocity, $\theta_{ik}^j$ is the elevation to the $ik^{th}$ clutter patch, $\phi_{ik}^j$ is the azimuthal angle to the $ik^{th}$ clutter patch, $\lambda_0$ is the wavelength, and $f_r$ is the pulse repetition frequency. If the jammer platform range changes, the waveform transmitted by the jamming platform reflects off each clutter patch at a different angle, changing the Doppler frequency received by the radar. In addition, as the jammer gets closer to the RUT clutter patches, the azimuthal angle to each clutter patch also changes, further changing the Doppler frequency. As the jammer get closer to the
Figure 4.2: SM interference containing only cold clutter and thermal noise. It is difficult to discern the clutter ridge, as SM interference is a low resolution spectral estimator. The range cell under test is 66 Km.
RUT, the jammer sidelobes are able to radiate more power onto the radar clutter patches, creating more power at different Doppler frequencies. The jammer range dependence is examined for a TN jammer at \( \phi = 0^\circ \) and \( \phi = 45^\circ \).

### 4.1.1.1 TN Jammer at Boresight

In a scenario when the jammer is TN to the radar direction, the radar is SL, and the jammer is at an azimuth of \( \phi = 0^\circ \), the relative Doppler between the jammer and the radar is \( \bar{\omega} = 0 \). In addition, the jammer mainbeam clutter and the radar mainbeam clutter are at \( \bar{\omega} = 0 \). As stated in Chapter III, the hot clutter Doppler shift is due to the relative velocity between the platforms, the relative ground velocity with respect to the the jammer, and the relative ground velocity with respect to the radar. The hot clutter Doppler frequency shift is illustrated in Figure 4.3, where \( f_p \) and \( f_j \) are the Doppler frequency shifts due to the relative velocities between the radar and jamming platforms, \( f_j'_{ik} \) is the Doppler frequency from the jammer to the \( ik^{th} \) ground clutter patch, and \( f_j_{ik} \) is the Doppler frequency from the radar platform to the \( ik^{th} \) ground clutter patch. Therefore, when the jammer is TN to the radar, the radar is SL, and the jammer is at \( \phi = 0^\circ \), the normalized Doppler location of mainbeam jammer clutter is at the same location as the radar mainbeam clutter at \( \bar{\omega} = 0 \).

In Figure 4.4, the MVE interference is computed for various jammer ranges. The ranges vary from 132 Km to 72 Km from the radar. As the jammer gets closer to the RUT, the clutter occupies more locations in normalized Doppler at \( \phi = 0^\circ \), as the jammer sidelobes are able to radiate more power onto the clutter patches at different Doppler frequencies. Without examining any radar performance metrics, one can hypothesize as the jammer gets closer to the RUT, the radar performance decreases when the jammer is at \( \phi = 0^\circ \) as more Doppler frequencies around \( \phi = 0^\circ \) contain interference from hot clutter.

The increase in interference power can be seen by examining SM interference. When examining SM interference, the clutter ridge is difficult to discern. However, the SM PSD does give reliable amplitude information about the clutter power and also
Figure 4.3: The hot clutter created from the jammer has an associated Doppler shift due to the velocity between the platforms $f_p + f_j$, the ground velocity at the $ik^{th}$ clutter patch with respect to the jammer $f_{ik}'$, and the ground velocity at the $ik^{th}$ clutter patch in with respect to the radar $f_{ik}$. The jammer and radar are both flying into the paper.

shows the jammer mainbeam location in azimuth and normalized Doppler. When examining Figures 4.5 4.6, one can see the interference in the radar mainbeam at $\phi = 0^\circ$, $\bar{\omega} = 0$ increases approximately 3 dB when the jammer is at 132 Km, and 15 dB when the jammer is at 72 Km.

4.1.1.2 TN Jammer at 45 Degrees Azimuth. The jammer range dependence has a greater effect on the normalized Doppler location of mainbeam interference at $\phi = 0^\circ$ when the jammer is not located at boresight. In a TN jammer, the jammer interference at $\phi = 0^\circ$ is independent of range, as the mainbeam interference is $\bar{\omega} = 0$. When the jammer is at an off-boresight azimuthal location, the jammer mainbeam remains at the same location in normalized Doppler as the jammer does not have a velocity component in the radar direction in this scenario. Though the jammer mainbeam is range independent, the jammer sidelobes are not. As the jammer gets closer in range to the RUT, the angle of reflection to the clutter patches
Figure 4.4: MVE interference for a TN jammer illuminating the ground at $\phi = 0^\circ$ for different locations in range from 132 Km to 72 Km from the radar. As the jammer gets closer to the RUT, the jammer clutter ridge occupies more locations in Doppler around $\phi = 0^\circ$. 
Figure 4.5: SM interference for a TN jammer at $\phi = 0^\circ$. The jammer is at 132 Km. The jammer increases interference power in the radar mainbeam at $\phi = 0^\circ$, $\bar{\omega} = 0$ approximately 3 dB.
SM interference for a TN jammer at $\phi = 0^\circ$. The jammer is at 72 Km. The interference is increased approximately 15 dB at $\phi = 0^\circ$, $\bar{\omega} = 0$. The jammer increases interference power in the radar environment as the jammer gets closer to the range cell under test.
change. The jammer is TN to the radar direction, but no longer at $\phi = 0^\circ$. The jammer is now at $\phi = 45^\circ$.

In Figure 4.7, one can see the normalized Doppler shift of jammer interference as the jammer is 72 to 132 Km from the radar. At $\phi = 0^\circ$, the jammer creates interference at approximately $\bar{\omega} = 0.1$ when the jammer is 132 Km from the radar. As the jammer gets closer to the RUT, the jammer interference at $\phi = 0^\circ$ changes in normalize Doppler to approximately $\bar{\omega} = -0.07$ when the jammer is 72 Km from the radar. At $\phi = 45^\circ$, the jammer corrupts more Doppler frequencies at this azimuth location as it gets closer to the RUT. The increase in interference of Doppler frequencies at the mainbeam jamming location at $\phi = 45^\circ$ is similar to when the jammer increases interference at multiple locations in Doppler at $\phi = 0^\circ$ when the jammer is also at $\phi = 0^\circ$. Because the radar is transmitting and receiving at $\phi = 0^\circ$, the jammer does not degrade radar performance as serious as when the jammer is at boresight. The radar receives the jammer mainbeam at $\phi = 45^\circ$ through a sidelobe; therefore, the received interference is not as severe in the radar look direction. The SM interference when the jammer is at $\phi = 45^\circ$, 72 Km from the radar can be seen in Figure 4.8. The interference created from the jammer at $\phi = 0^\circ$ is around $\bar{\omega} = -0.07$. The jammer mainbeam is located $\phi = 45^\circ$, $\bar{\omega} = -0.36$. The interference power at $\phi = 0^\circ$ is less than when the jammer is at $\phi = 0^\circ$. The jammer mainbeam radiates through a radar sidelobe instead of directly into the radar mainbeam.

4.1.2 Azimuthal Dependence. Hot clutter also depends on the azimuth jamming location from the radar. The jammer and radar have a relative Doppler frequency between one another for any azimuthal location and the jammer and radar velocity vectors. When the TN jammer is at $\phi = 0^\circ$, the relative velocity between the jammer and radar platforms is zero. Therefore, the relative Doppler shift between the platforms is $\bar{\omega} = 0$. When the jammer platform changes location in azimuth, the relative velocity changes based on the jammer location. As the jammer changes in azimuth, the relative velocity between each radar clutter patch and the jammer
Figure 4.7: The MVE interference for a TN jammer at $\phi = 45^\circ$. The interference when looking at $\phi = 0^\circ$ experiences a Doppler shift as the jammer gets closer to the RUT. The interference at $\phi = 45^\circ$ is the mainbeam jammer location. As the jammer is TN and does not have a velocity component in the radar direction, the jammer mainbeam location in Doppler does not change. However, the jammer sidelobes are shown to change across normalized Doppler.
Figure 4.8: The SM interference for a TN jammer at $\phi = 45^\circ$. When the radar is receiving at $\phi = 0^\circ$, the hot clutter jammer mainbeam is at $\phi = 45^\circ$, $\bar{\omega} = -0.36$. 
platform also changes. The azimuthal angle to each clutter patch changes depending on the jammer azimuthal location. The azimuthal dependence is examined for two jammer locations at ranges of 132 and 72 Km. The jammer model is constructed to define the relative velocities between the two platforms as seen in Figure 4.9. The jammer mainbeam always illuminates the radar platform in this development. For a TN jammer velocity towards the radar platform, the jammer is perpendicular to the radar location. As the model is constructed in this manner, the jammer velocity component in the radar direction is zero.

4.1.2.1 TN Jammer at 132 Km. When the TN jammer is at 132 Km from the radar, one can see the effect of a change in jammer azimuth location in Figure 4.10. The jammer at various azimuth locations changes the the location of hot clutter in the radar environment. When the jammer is at $\phi = 0^\circ$, the mainbeam jammer interference is at $\bar{\omega} = 0$. When the jammer is at 45 degrees, the hot clutter increases interference at approximately $\bar{\omega} = 0.1$ at $\phi = 0^\circ$. Similarly, the hot clutter increases interference at $\phi = 0^\circ$, $\bar{\omega} = -0.07$ when the jammer is at $\phi = -45^\circ$.

4.1.2.2 TN Jammer at 72 Km. The jammer is now close to the RUT at 72 Km from the radar. When the jammer location varies in azimuth, the TN jammer normalized Doppler location range and azimuth dependence is apparent. As the jammer is closer to the RUT, the jammer sidelobes illuminate ground with more power, thereby increasing the interference at $\phi = 0^\circ$ at multiple locations in Doppler. The interference estimate is illustrated in Figure 4.11. In addition, the hot clutter normalized Doppler changes at $\phi = 0^\circ$ with respect to the jammer azimuth. For example, when the jammer mainbeam transmits at $\phi = 0^\circ$ at 132 Km from the radar, the jammer mainbeam is at $\bar{\omega} = 0$. Now, when the jammer is at $\phi = 10^\circ$ and a range of 72 Km, the interference at $\phi = 0^\circ$ is approximately $\bar{\omega} = 0.3$. However, this interference at $\bar{\omega} = 0.3$ is the interference radiated through a jammer sidelobe. When the jammer is at 132 Km from the radar and the same azimuth location at $\phi = 10^\circ$, the interference at $\phi = 0^\circ$ is now at $\bar{\omega} = 0.05$. The jammer range and azimuth affect
Figure 4.9: The TN jammer scenario. The jammer mainbeam illuminates the radar platform. When the jammer is TN, the jammer has no relative velocity component to the radar platform as the jammer velocity is perpendicular to the radar direction, therefore $f_j = 0$. The jammer is at a range $R_j$ and azimuth $\phi_j$ from the radar platform.
Figure 4.10: MVE interference for different jamming azimuth locations when the jammer is at 132 Km. The jammer location in azimuth creates a clutter ridge at some location in Doppler at $\phi = 0^\circ$. The jammer mainbeam is located at different locations in radar azimuth from $\phi = -45^\circ$ to $\phi = 45^\circ$. 
Figure 4.11: MVE interference for various jammer azimuth locations when the jammer is at 72 Km. In comparing azimuthal and range differences between Figures 4.10, 4.7, and 4.4, it is shown both azimuth and range have an effect on the location of hot clutter for a TN jammer.
the hot clutter location. In addition to range and azimuth dependence, the jammer velocity component also has an impact on the location of hot clutter. This velocity dependence is examined when the hot clutter jammer is an OC radar.

4.2 **Interference From an OC Jammer**

The jammer velocity direction has a significant impact on the effect of hot clutter. In the first scenario, the jammer located in the environment tangential to the radar direction where the jammer does not have a velocity component towards the radar. If the radar environment is slightly modified to include an OC jammer, the hot clutter location in azimuth and elevation change. The radar is still SL, and the only variable modified in the environment is the jammer velocity vector, as the jammer is now flying directly towards the radar platform. This jamming scenario is illustrated in Figure 4.12. The OC jammer antenna pattern and transmit power is identical to the TN jammer antenna pattern. The relative velocities between the jammer and radar are now different. In addition, the Doppler shift of ground clutter produced by the OC jammer will also be different, due to the change in the jammer velocity direction. The jammer velocity component in the direction of ground clutter changes. The Doppler frequency shift is now expressed as

\[ f_{ik} = \frac{2v_j \cos \theta_{ik} \sin (\phi_{ik} + 90^\circ)}{\lambda_0}, \]  

(4.4)

where \( v_j \) is the jammer velocity, and \( \theta_{ik} \) and \( \phi_{ik} \) are the radar clutter patches locations in azimuth and elevation. The ground velocity relative to the OC jamming platform is modified to include a 90\(^\circ\) crab angle in azimuth. The jammer velocity vector is now entirely in the radar platform direction.

4.2.1 **Range Dependence.** The normalized Doppler location range dependence for an OC jammer is similar to the normalized Doppler range dependence for a TN jammer except for one key difference. The OC jammer mainbeam Doppler location is now range dependent. The OC jammer range dependence is examined at
Figure 4.12: OC jamming scenario. The jammer is flying directly towards the radar platform. Therefore, the jammer velocity component in the radar direction is simply the jammer velocity $v_j$. The radar velocity in the jammer direction is unchanged, as is the jammer array pattern and transmit power. The jammer is at a range $R_j$ from the radar platform at an azimuth angle $\phi_j$. The relative velocities between the jammer and radar platform create a Doppler shift between the two platforms $f_p + f_j$. 
azimuthal locations of \( \phi = 0^\circ \) and \( \phi = 45^\circ \) to examine the effect changing the jammer velocity direction has on the radar interference environment.

4.2.1.1 OC Jammer at Boresight. The OC jammer illuminates the environment at \( \phi = 0^\circ \). The jammer range from the RUT affects the jammer main-beam location in normalized Doppler. As an example, if the jammer is at a velocity of 108 meters per second travelling directly towards the radar platform, the Doppler shift corresponding to the velocity component in the radar direction is

\[
\bar{\omega}_j = \frac{2v_j}{\lambda_0 f_r},
\]

or \( \bar{\omega}_j = 0.45 \). The clutter patch at \( \phi = 0^\circ \) velocity component from the radar is \( \bar{\omega} = 0 \), and the OC jammer clutter patch normalized Doppler at \( \phi = 0^\circ \) is expressed as

\[
\bar{\omega}_{hc}^{ik} = \frac{2v_j \cos \theta_{ik} \sin (0^\circ + 90^\circ)}{\lambda_0 f_r},
\]

where \( \theta_{ik} \) is the elevation angle from the jammer to the RUT clutter patch. When the clutter patch of interest is \( \phi = 0^\circ \), the normalized Doppler component is \( \bar{\omega} = 0.45 \) when the jammer is at 132 Km from the radar. As the OC jammer is at boresight, this clutter patch at \( \phi = 0^\circ \) is exactly equidistant from the jammer and radar platforms. The mainbeam hot clutter location in normalized Doppler is approximately \( \bar{\omega} = -0.10 \). When the jammer is at 72 Km, the elevation angle to the clutter patch is larger, thus the normalized Doppler frequency from the jammer to the clutter patch is \( \bar{\omega} = 0.39 \). The clutter patch is at jammer boresight exactly 6 Km from the jammer. The mainbeam jamming location in normalized Doppler when at the clutter patch of interest is \( \phi = 0^\circ \), RUT= 66 Km is now \( \bar{\omega} = -0.16 \). The normalized Doppler value for the jammer mainbeam when at ranges between these values are also between \( \bar{\omega} - 0.10 \) and \( \bar{\omega} = -0.16 \). The shift in normalized Doppler at \( \phi = 0^\circ \) for the jammer mainbeam can be seen in Figure 4.13.
Figure 4.13: MVE interference for an OC jammer illuminating the ground at $\phi = 0^\circ$. The radar is still SL. The jammer is changes in range from 72 to 132 Km. As the jammer location from the RUT changes, the mainbeam jammer location in normalized Doppler changes from approximately $\bar{\omega} = -0.10$ when the jammer is 132 Km from the radar to $\bar{\omega} = -0.16$ when the jammer is 72 Km from the radar.
Figure 4.14: SM interference for an OC jammer at $\phi = 0^\circ$. The jammer is at 132 Km. The jammer increases interference power in the radar mainbeam at $\phi = 0^\circ$, $\bar{\omega} = -0.10$. The clutter patch at $\phi = 0^\circ$ is equidistant from the jammer and radar platforms. Therefore, the interference power is approximately the same for both the hot clutter mainbeam and the cold clutter mainbeam.

The interference power increases as the jammer range is closer to the RUT. The interference power increases at all locations in jammer azimuth. The increase in interference power and the shift in jammer mainbeam normalized Doppler location can be seen in Figures 4.14 and 4.15.

4.2.1.2 OC Jammer at 45 Degrees. As illustrated in Figure 4.16, one can see the effect of jammer range when the OC jammer is at $\phi = 45^\circ$. The hot clutter interference created at $\phi = 0^\circ$ radiates through a jammer sidelobe. When the jammer is at 132 Km, the hot clutter creates interference at approximately $\bar{\omega} = 0.17$ at $\phi = 0^\circ$. The mainbeam jammer interference is located at $\phi = 45^\circ$, $\bar{\omega} = -0.45$. However, as
Figure 4.15: SM interference for an OC jammer at $\phi = 0^\circ$. The jammer is at 72 Km. The jammer increases interference power in the environment as the jammer is closer to the range cell under test, with the jammer mainbeam now at $\phi = 0^\circ$, $\bar{\omega} = -0.16$. 
Figure 4.16: MVE interference for an OC jammer at 45 degrees for different jammer locations in range. The mainbeam jammer is always at $\phi = 45^\circ$; however, the jammer mainbeam location in normalized Doppler changes as the jammer range from the radar changes.
the radar receives at $\phi = 0^\circ$, the radar will not receive a significant amount of hot clutter as it is received by the radar in a sidelobe. When the jammer is close to the RUT at 72 Km, the jammer interference at $\phi = 0^\circ$ is located approximately at $\bar{\omega} = -0.01$. The jammer mainbeam interference is now located at $\bar{\omega} = 0.48$. The OC jammer mainbeam Doppler location is range dependent, as the relative velocity of jammer mainbeam clutter is no longer zero.

4.2.2 Azimuthal Dependence. The OC jammer azimuthal dependence is different than the TN jammer azimuthal dependence. In a TN jammer scenario, the TN jammer does not have a velocity component in the radar direction. When the jammer is OC, the jammer velocity is always in the radar direction, inducing a positive Doppler shift to all returns in azimuth collected by the radar. Therefore, the location of hot clutter occurs at different locations in azimuth and elevation.

4.2.2.1 OC Jammer at 132 Km. In Figure 4.17, the MVE interference is computed for an OC jammer at 132 Km from the radar at different positions in azimuth. The jammer velocity component in the radar direction always induces a positive Doppler shift on the waveform for both positive and negative azimuth locations. When the jammer is at negative 45 degrees, the hot clutter normalized Doppler at radar boresight is close to $\bar{\omega} = -0.5$. However, when the jammer is at an azimuth location of positive 45 degrees, the hot clutter normalized Doppler at radar boresight is at $\bar{\omega} = 0.17$. As the jammer changes location in azimuth from $\phi = -45^\circ$ to $\phi = 45^\circ$, the normalized Doppler at the $\phi = 0^\circ$ shifts from approximately $\bar{\omega} = -0.5$ to $\bar{\omega} = 0.17$.

4.2.2.2 OC Jammer at 72 Km. When the jammer is 72 Km from the radar, one can see the difference in hot clutter location for different jammer locations in azimuth. The jammer range, azimuth, and velocity are all responsible for changing the interference power and location in azimuth and normalized Doppler of hot clutter. The interference when the jammer is at 72 Km from the RUT for different azimuth
Figure 4.17: MVE interference for an OC jammer at 132 Km for different azimuthal locations. The change in the jammer velocity direction results in hot clutter at different locations in azimuth and elevation.
Figure 4.18: MVE interference for an OC jammer at 72 Km for different locations in azimuth. The range, azimuth, and jammer velocity vector have an effect on the normalized Doppler location of hot clutter.

locations is illustrated in Figure 4.18. The interference power increases within the environment. The elevation and azimuth to each clutter patch changes, and thereby creates a change in the location of hot clutter in normalized Doppler. The radar mainbeam normalized Doppler location containing hot clutter is now in a totally new location.

4.3 Radar Interference Summary

Hot clutter interference is created for both TN and OC jammers at 72 and 132 Km, and for azimuthal locations of -45, -10, 0, 10, 20, and 45 degrees. One can calculate the Doppler frequency location of hot clutter at any range, azimuth,
and aircraft velocity. Hot clutter effectively increases the interference power within the environment by creating a second clutter ridge in azimuth and Doppler based on the jammer location and velocity. Hot clutter has a number of effects on the radar environment:

- The interference power within the scenario depends on the jammer range to the RUT clutter patches. Based on the range to the RUT, the location of radar clutter patches in jammer azimuth and elevation change. As the clutter patch locations change, the relative velocity and thus the normalized Doppler frequency shift to the jammer also changes.

- The location in jammer azimuth is also responsible for changing the interference environment. As the location in azimuth changes, the jammer mainbeam is also changes depending on the jammer velocity vector. In the unique situation when the TN jammer does not have a velocity component in the radar direction, the jammer mainbeam normalized Doppler location is independent of range. When the jammer is not in the radar mainbeam, the interference at $\phi = 0^\circ$ is not as severe as the hot clutter radiates the clutter patch at $\phi = 0^\circ$ is transmitted through a jammer sidelobe.

- The jammer velocity vector also changes the interference environment. When the jammer is TN in this scenario, the jammer mainbeam is independent of range. When the jammer is OC, the jammer mainbeam is now range dependent. However, if the only variable changing is the aircraft velocity direction, the hot clutter interference power at each $ik^{th}$ clutter patch is the same.

There is now enough information about the hot clutter radar interference environment to discuss adaptive and non-adaptive radar processing in the presence of hot clutter.
V. Tangential Hot Clutter Jammer Impact on Side-Looking Radar Performance

The addition of hot clutter into the radar interference environment is shown in Chapter IV to increase clutter power at locations in azimuth and Doppler based on the jammer velocity vector, and locations in elevation and azimuth from the radar. The impact added interference from hot clutter has on radar performance is examined for a tangential (TN) hot clutter jammer. In this scenario the jammer is flying in a direction tangential to the radar direction. The impact on radar performance using non-adaptive (NA) processing and the Matched Filter (MF), Factored Time Space (FTS), and Joint Domain Localized (JDL) adaptive filters is examined under known and estimated interference.

The performance metrics used to examine radar performance in this research are Range-Doppler outputs, Output SINR (Signal to Noise plus Interference), SINR Loss, and probability of detection analysis. The Output SINR for a given weight vector is expressed as

\[
\text{SINR} = \frac{\sigma^2 \zeta_t |w^Hv|^2}{w^H Rw}, \quad (5.1)
\]

where \(\sigma^2\) is the per element per pulse noise power, \(\zeta_t\) is the per element per pulse Signal to Noise Ratio (SNR), \(w\) is a space-time weighting vector, \(v\) is the non-adaptive space-time steering vector, and \(R\) is the known interference covariance matrix of a particular range cell. The numerator of Eqn. (5.1) is the output signal power and the denominator is the interference created from thermal noise and ground clutter, either containing hot or cold clutter. This scalar output is for some location in elevation, azimuth, and Doppler. One caveat in this analysis is the radar has the same transmit and look direction. Because the radar transmits at boresight, \((\phi = 0^\circ, \theta = 0^\circ)\), all performance metrics are evaluated at this look direction across all normalized Doppler \(\bar{\omega}\).
The SINR Loss metric [12] is the loss in SINR referenced to the maximum output SNR, defined as

$$\text{SINR}_{\text{loss}} = \frac{\text{SINR}}{\zeta_t MN P},$$

where $\zeta_t$ is the per element per pulse SNR, $M$ is the number of pulses within a coherent processing interval (CPI), $N$ is the number of azimuthal elements, and $P$ is the number of elevation elements. The SINR Loss is calculated for the interference covariance matrix $R$ only containing hot clutter and noise in this analysis. This SINR Loss metric is the loss in SINR resulting from the interference created by the hot clutter jammer. The SL radar range cells are approximately homogeneous when only containing cold clutter and thermal noise. The SINR Loss due to hot clutter is calculated to see the heterogeneities the hot clutter creates in the range cell sample support.

### 5.1 Non-Adaptive Radar Performance

The non-adaptive radar steering vector $\mathbf{v}$ for a linear array is expressed as

$$\mathbf{v}(\bar{\omega}, \vartheta_x) = \mathbf{b}(\bar{\omega}) \otimes \mathbf{a}(\vartheta_x),$$

where $\mathbf{b}$ and $\mathbf{a}$ are the temporal and azimuthal steering vectors. The non-adaptive steering vector is unable to place nulls on sources of interference and generally performs worse than FTS and JDL adaptive filters. The non-adaptive radar performance degradation from a TN hot clutter jammer is characterized using Range-Doppler output, Output SINR, SINR Loss, and probability of detection analysis for a TN jammer at 72 and 132 Km from the radar, and located in azimuth at $\phi = 0^\circ$ and $\phi = 45^\circ$.

#### 5.1.1 TN Jammer at Radar Boresight

In Chapter IV, hot clutter is shown to have both a range and azimuth dependence. Range-Doppler outputs are calculated using non-adaptive processing for various jamming locations. The non-adaptive
Figure 5.1: Range-Doppler output for non-adaptive processing. The homogeneous interference contains thermal noise and cold clutter. The ground clutter from the radar mainbeam results in a strong output at $\bar{\omega} = 0$. The range cells evaluated are 60 to 72 Km from the radar output is denoted as

$$y = v^H \chi.$$  \hspace{1cm} (5.4)

The non-adaptive output across range and normalized Doppler for interference containing thermal noise and cold clutter is illustrated in Figure 5.1. This output is the complex scalar received when the radar transmits and receives at $\phi = 0^\circ$. The main source of interference is located at $\bar{\omega} = 0$ due to the clutter returns from the SL radar mainbeam. The radar antenna pattern sidelobes creates interference at other locations in normalized Doppler. When a TN jammer is placed at $\phi = 0^\circ$, the interference increases across all normalized Doppler, as seen in Figure 5.2. The range cells evaluated are 60 Km to 72 Km and the jammer is at 132 Km. As the radar
Figure 5.2: Range-Doppler output for non adaptive processing with a TN jammer at $\phi = 0^\circ$ at a range of 132 Km. The range cells evaluated are 60 to 72 Km from the radar. The interference increases for all locations in normalized Doppler and Azimuth. The jammer is at 132 Km. As the jammer is far from the range cells, the output is homogeneous for all range cells.
Figure 5.3: Range-Doppler output for non-adaptive processing with a TN jammer at $\phi = 0^\circ$ at a range of 72 Km. The range cells evaluated are from 60 to 72 Km. The interference increases up to 15 dB at $\bar{\omega} = 0$. The jammer mainbeam does not begin to illuminate the ground until 69 Km as the jammer altitude is 3 Km. The Range-Doppler output is inhomogeneous for all evaluated range cells.

and the jammer are both far from the range cells; in this scenario at least 60 Km from the radar clutter patches, the Range-Doppler output is homogeneous across the evaluated range cells. When the TN jammer is at a range of 72 Km, one can see the non-adaptive range-Doppler output in Figure 5.3. The interference in the mainbeam increases up to 15 dB as the jammer is now extremely close to the range cell under test. The interference in other locations in Doppler also increases as the jammer antenna pattern sidelobes are radiating the clutter patches with more power, increasing the power for various normalized Doppler locations. The jammer is close to the evaluated range cells. The output is inhomogeneous for the evaluated range cells. The
Figure 5.4: Output SINR using non-adaptive processing. The TN jammer is at \( \bar{\omega} = 0 \) at 72 and 132 Km from the radar. The interference increases across all normalized Doppler. The interference power increases as the jammer is closer to the RUT, resulting in a degradation in Output SINR.

Output SINR is examined using non-adaptive processing when the jammer at \( \phi = 0^\circ \) at 72 and 132 Km in Figure 5.4. The Output SINR degrades more as the jammer is closer to the RUT, the interference power increases. The Output SINR degrades anywhere from 2 dB to approximately 10 dB when the jammer is at 132 Km, whereas the Output SINR degrades up to 20 dB at approximately \( \bar{\omega} = 0.15 \) when the jammer is at 72 Km.

As interference increases across all normalized Doppler when the TN jammer is at boresight, the probability of detection is simulated by a Monte Carlo analysis for an arbitrary location in the environment at \( \phi = 0^\circ, \bar{\omega} = 0.25 \). Monte Carlo analysis is
Figure 5.5: Probability of detection versus input SINR per element per pulse using non-adaptive processing in the presence of hot clutter at $\phi = 0^\circ$ at ranges of 132 and 72 Km. The radar is looking for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.25$. The hot clutter has more of an effect on radar performance as the jammer is closer to the RUT. The Monte Carlo analysis is computed for $N_{\text{trials}} = 1000$, with a $P_{fa} = 0.01$.

computing the probability of detection for a target at this location using 1000 trials with a probability of false alarm of $P_{fa} = 0.01$. The probability of detection versus per element per pulse input SINR is illustrated in Figure 5.5. The required input SINR per element per pulse to achieve the same probability of detection without hot clutter is approximately 1 to 2 dB more for when the jammer is at $\phi = 0^\circ$, 132 Km from the radar, and approximately 10 dB more when the jammer is at $\phi = 0^\circ$, 72 Km from the radar.
Figure 5.6: Range-Doppler output using non-adaptive processing with a TN jammer at $\phi = 45^\circ$ at a range of 132 Km. Though the jammer is far from the range cells, the radar output increases at $\bar{\omega} = -0.36$ resulting from the jammer mainbeam at $\phi = 45^\circ$, $\bar{\omega} = -0.36$.

5.1.2 TN Jammer at 45 Degrees Azimuth. The radar performance is evaluated using non-adaptive processing when the TN jammer is at $\phi = 45^\circ$. The Range-Doppler output using the non-adaptive steering vector for the jammer at $\phi = 45^\circ$ at 72 and 132 Km can be seen in Figure 5.6 and Figure 5.7. In Figure 5.6, the hot clutter at $\phi = 45^\circ$, $R_j = 132$ Km from the radar does not seriously increase the non-adaptive output. The TN jammer mainbeam is independent of range. At $\phi = 45^\circ$, the jammer mainbeam is located at $\bar{\omega} = -0.36$. As the jammer is far from the range cells under test, the jammer mainbeam only increases the non-adaptive output a few dB at $\bar{\omega} = -0.36$. In Figure 5.7, the jammer is much closer to the range cells. Therefore, the jammer mainbeam location in Doppler significantly increases the output power. It
Figure 5.7: Range-Doppler output using non-adaptive processing with a TN jammer at $\phi = 45^\circ$ at a range of 72 Km. The range cells evaluated are from 60 to 72 Km. The jammer is closer to the range cells at 72 Km. The jammer mainbeam at $\phi = 45^\circ$, $\bar{\omega} = -0.36$ increases the non-adaptive output at $\bar{\omega} = -0.36$. Though the radar is looking at $\phi = 0^\circ$, the jammer mainbeam normalized Doppler location degrades.
is difficult to draw much physical insight by only looking at the non-adaptive Range-Doppler output. The Output SINR is calculated to further build the physical picture. In Figure 5.8, one can see the Output SINR illustrating the degradation of a TN jammer at $\phi = 45^\circ$. The interference resulting from the jammer mainbeam located at $\phi = 45^\circ$, $\bar{\omega} = -0.36$ is responsible for the increase in interference around this location in Doppler as the the radar receives jammer mainbeam interference through one of its sidelobes. Because the jammer is tangential to the radar direction, the jammer does not have a velocity component in the radar direction, and thus the jammer mainbeam location will only be dependent on its azimuth location from the radar. As the jammer
is closer to the RUT, the interference increases and non-adaptive radar performance degrades.

A Monte Carlo analysis performing 1000 trials ($N_{\text{trials}}$) with a probability of false alarm ($P_{fa}$) of 0.01 is performed to simulate the probability of detection of a target at $\phi = 0^\circ$, $\bar{\omega} = -0.36$. The degradation in performance can be seen in Figure 5.9. The required per element per pulse input SINR to achieve the same probability of detection degrades approximately 5 dB more when the jammer is at 132 Km, and more than 20 dB when the jammer is at 72 Km.

5.2 Adaptive Radar Performance

To improve radar performance, adaptive filters place nulls on sources of interference in the radar environment. The effect of hot clutter on these adaptive filters will be examined for a TN jammer. The radar performance using known interference and estimated interference is examined. When the radar is using known interference, the radar performance is examined using the adaptive Matched Filter as well as the Factored Time Space and Joint Domain Localized partially adaptive filters. When the radar operates under estimated interference, only the radar performance using FTS and JDL partially adaptive filters are examined with a focus given to interference estimation corruption due to heterogeneities hot clutter introduces into the radar interference environment.

5.2.1 Radar Performance Using Known Interference. When the adaptive filters are constructed using known interference in the RUT, the radar performance operates under the optimum condition. These adaptive filters are either partially or fully adaptive. When the adaptive filter is fully adaptive, the filter is able to place nulls at locations of interference in azimuth and normalized Doppler. Some adaptive filters are only partially adaptive in azimuth and/or Doppler. The radar performance using the fully adaptive MF and the JDL and FTS partially adaptive filters are examined using known interference in the RUT.
Figure 5.9: Probability of detection versus input SINR per element per pulse using non-adaptive processing in the presence of hot clutter at 45 degrees at ranges of 132 and 72 Km. The radar is looking for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.36$, the mainbeam jammer normalized Doppler location. Hot clutter has more effect on radar performance as the jammer is closer to the RUT. The Monte Carlo analysis is computed for $N_{\text{trials}} = 1000$, with a $P_{fa} = 0.01$. 
5.2.1.1 Matched Filter. The MF is the ideal adaptive filter to null sources of interference. The MF weight vector $w_{mf}$ is expressed as [5]

$$w_{mf} = R^{-1}v,$$  \hspace{1cm} (5.5)

where $R$ is the known interference covariance matrix in the RUT. The MF is the optimum adaptive filter, and is the upper bound on adaptive radar performance. The MF only degrades at sources of interference in the radar look direction in azimuth, elevation, and Doppler.

The degradation in Output SINR for a TN jammer at $\phi = 0^\circ$ at 132 Km and 72 Km is seen in Figures 5.10 and 5.11. When the jammer is at boresight, the MF is unable to suppress the interference from the coherent jammer as the interference is the radar look direction. The hot clutter degrades more locations in normalized Doppler as the jammer is closer to the RUT as the range cell under test contains more interference from the hot clutter jammer at different Doppler frequencies.

When the jammer is at $\phi = 45^\circ$, the MF is able to filter out the jammer mainbeam located at $\phi = 45^\circ$. The MF is only unable to suppress hot clutter located in the radar look direction. As the location of hot clutter at $\phi = 0^\circ$ is dependent on the jammer range when $\phi_j \neq 0^\circ$, the location of hot clutter in normalized Doppler changes with range. When the jammer is at 132 Km, the MF suppresses all sources of interference except where the hot clutter exists at $\phi = 0^\circ$ at $\bar{\omega} = 0.10$, seen in Figure 5.12. The hot clutter at $\phi = 0^\circ$ is at $\bar{\omega} = -0.07$ when the jammer is at 72 Km. The degradation in Output SINR using the adaptive MF is seen at this location in Figure 5.13.

5.2.1.2 Factored Time Space. The FTS partially adaptive filter is only adaptive in azimuth. The Output SINR for the interference with a TN jammer located at $\phi = 0^\circ$, 132 Km from the radar, is seen Figure 5.14. When a Blackman-Harris (BH) taper is applied across the Doppler bins, performance is improved as the
Figure 5.10: MF Output SINR for a TN jammer at boresight, 132 Km from the radar. The jammer mainbeam and radar mainbeam are both located at $\bar{\omega} = 0$. The radar performance with a MF degrades at this jamming location as the fully adaptive filter is not able to place a null in the radar look direction, as the filter would suppress the target.
Figure 5.11: MF Output SINR for a TN jammer at boresight, 72 Km from the radar. The jammer is extremely close to the RUT, and the jammer sidelobes are responsible for a degradation in MF performance as they are responsible for increasing interference at locations across normalized Doppler.
Figure 5.12: MF Output SINR for a TN jammer at $\phi = 45^\circ$ at a range of 132 Km. The MF is able to suppress all the hot clutter except at the normalized Doppler location at $\phi = 0^\circ$, located at $\bar{\omega} = 0.10$. The MF offers some 30 dB improvement at the jammer mainbeam Doppler location.
Figure 5.13: MF Output SINR for a TN jammer at $\phi = 45^\circ$, at a range of 72 Km. The Doppler location of hot clutter at $\phi = 0^\circ$ is now $\bar{\omega} = -0.07$, as the adaptive filter is unable to suppress sources of interference in the radar look direction. The hot clutter at $\phi = 0^\circ$ is at $\bar{\omega} = -0.7$. The jammer mainbeam is completely suppressed using the MF even when the jammer is extremely close to the RUT. The increase in output SINR from the MF at $\bar{\omega} = -0.36$ is approximately 40 dB.
window provides some sidelobe attenuation and is able to mitigate unwanted sources of interference in Doppler. When the TN jammer is at \( \phi = 0^\circ \), the performance around the mainbeam clutter ridge degrades around \( \bar{\omega} = 0 \) as the jammer is directly in the radar mainbeam. As the FTS adaptive filter is only adaptive in azimuth, the filter performs about as well as the non-adaptive steering vector. When a BH window is applied in Doppler, the Output SINR improves. The Output SINR using both FTS adaptive filters degrades for more locations in Doppler than the MF as the FTS filters are not able to suppress interference in surrounding Doppler locations in the radar look direction.

When the jammer is at \( \phi = 0^\circ \), 72 Km from the radar, the FTS filter performs significantly worse than when the jammer is far away from the RUT. The Output SINR is seen in Figure 5.15. The inability to adapt in Doppler creates a large degradation in Output SINR even when a Blackman-Harris window is applied.

When the jammer is at \( \phi = 45^\circ \), the FTS filter to places a nulls in azimuth and is able to suppress hot clutter not located at \( \phi = 0^\circ \). When the jammer is at 132 Km, the hot clutter interference normalized Doppler location is \( \bar{\omega} = 0.10 \). The FTS adaptive filter without a taper only degrades 1 to 2 dB due to hot clutter at this location in normalized Doppler, and the BH FTS adaptive filter degrades around 15 dB at \( \bar{\omega} = 0.10 \). The FTS filter without a Doppler taper is not seriously affected by hot clutter because the performance of this filter is already lacking at the hot clutter Doppler location at \( \bar{\omega} = 0.10 \).

When the jammer is at 72 Km, at \( \phi = 45^\circ \), the FTS adaptive filter is able to mitigate the interference created from the jammer mainbeam at \( \bar{\omega} = -0.36 \). The degradation in the FTS adaptive filters occurs around the hot clutter at \( \phi = 0^\circ \), located at \( \bar{\omega} = -0.07 \). Performance in this normalized Doppler location degrades around 7 dB for the BH FTS adaptive filter. The degradation using FTS filters from hot and cold clutter occurs at more normalized Doppler locations than the degradation in Output SINR for the fully adaptive MF as the FTS filters only adapts in azimuth.
Figure 5.14: Output SINR for the FTS adaptive filter. The interference includes a TN jammer at $\phi = 0^\circ$, 132 Km from the radar. As the FTS adaptive filter is unable to suppress sources of interference in Doppler at the same look direction, the hot clutter effectively degrades more locations in Doppler for the FTS adaptive filters. When no taper is applied in Doppler, the FTS adaptive filter degrades in Output SINR for all Doppler locations.
Figure 5.15: Output SINR for a TN jammer at $\phi = 0^\circ$, 72 Km from the radar for the FTS adaptive filter. The hot clutter is very close the the RUT; therefore, the jammer sidelobes corrupts Output SINR at all Doppler values.
Figure 5.16: Output SINR for a TN jammer at $\phi = 45^\circ$, 132 Km from the radar for the FTS adaptive filter. As the jammer is in a radar sidelobe, the FTS adaptive is able to suppress the hot clutter not located around $\phi = 0^\circ$. The hot clutter is located at $\phi = 0^\circ$, $\bar{\omega} = 0.10$. As the FTS filter is unable to place a null in Doppler, the surrounding Doppler values also degrade in Output SINR.
Figure 5.17: Output SINR for a TN jammer at $\phi = 45^\circ$, 72 Km from the radar for the FTS adaptive filter. The hot clutter is very close the the RUT, however the impact on radar performance using the FTS adaptive filter is not seriously affected. The hot clutter is located at $\phi = 0^\circ$, $\bar{\omega} = -0.07$. The FTS adaptive filter is able fully suppress the jammer mainbeam at $\bar{\omega} = -0.36$. 
5.2.1.3 Joint Domain Localized. The Joint Domain Localized partially adaptive filter is able to adapt in both azimuth and Doppler. One expects the radar performance using JDL to perform better than the radar performance using FTS in hot clutter as the JDL filter can adapt to the interference in Doppler. Figures 5.18, 5.19, 5.20, and 5.21 can be examined to see the effect a TN hot clutter jammer has on JDL adaptive filtering. The JDL filters are only partially adaptive. However, they are given both temporal and azimuthal DOF to suppress the clutter. As the JDL filter is able to suppress the hot clutter in Doppler, the degradation in Output SINR for the JDL filter will occur for less locations in normalized Doppler. The JDL filters are still unable to suppress the clutter located at $\phi = 0^\circ$. The Output SINR using the JDL adaptive filters performs better than the FTS adaptive filters, and are closer to fully adaptive MF performance.

The Output SINR performance metrics computed are under known interference. The interference is changing from range cell to range cell. The actual radar performance under hot clutter conditions differs based on the amount of heterogeneities within the sample support.

5.2.2 Radar Performance Using Estimated Interference. In a real-world scenario, the interference in the environment is never known. The radar interference environment is estimated from the sample support vectors $\mathbf{x}$ at range cells near the range cell under test. From these sample support vectors, covariance matrix interference estimate is computed as

$$\hat{\mathbf{R}} = \frac{1}{2K} \sum_{k=l-K, k \neq l}^{l+K} \mathbf{x}_k \mathbf{x}_k^H,$$  \hspace{1cm} (5.6)

Where $K$ is the number of sample support vectors used in the covariance matrix estimation, and $l$ is the RUT. The number of sample support vectors required depends on the number of degrees of freedom needed for each partially adaptive filter. The adaptive radar performance is evaluated under estimated interference by examining
Figure 5.18: Output SINR for a TN jammer at $\phi = 0^\circ$, 132 Km from the radar for the JDL adaptive filter. As the JDL filter is able to adapt both in Doppler and azimuth, the degradation in Output SINR is reduced when compared to the FTS adaptive filters and non-adaptive performance. The JDL filters using $3 \times 3$ and $3 \times 7$ LPRs perform approximately the same.
Figure 5.19: Output SINR for a TN jammer at $\phi = 0^\circ$, 72 Km from the radar for the JDL adaptive filter. The hot clutter is very close the the RUT. The jammer sidelobes have an impact on radar performance as they create hot clutter at multiple Doppler locations. As the $3 \times 7$ JDL has more temporal DOF, this JDL adaptive filter performs better than the $3 \times 3$ JDL filter.
Figure 5.20: Output SINR for a TN jammer at $\phi = 45^\circ$, 132 Km from the radar for the JDL adaptive filter. As the jammer mainbeam is in a radar sidelobe, the JDL adaptive filter is able to suppress the hot clutter not located around $\phi = 0^\circ$. The interference at $\phi = 0^\circ$ is located at $\bar{\omega} = 0.10$. As the JDL filter is adaptive in Doppler, one can see the significant improvement in Output SINR around $\bar{\omega} = 0.10$ as compared to the FTS adaptive filters in the same conditions in Figure 5.16.
Figure 5.21: Output SINR for a TN jammer at $\phi = 45^\circ$, 72 Km from the radar for the JDL adaptive filter. As the jammer is in a radar sidelobe, the JDL filter is able to suppress the jammer mainbeam. The Output SINR degrades around $\tilde{\omega} = -0.07$, as this Doppler location is to location of hot clutter at $\phi = 0^\circ$. The Output SINR using the JDL adaptive filters perform closer to the Output SINR using the MF as the JDL adaptive filter uses both azimuthal and temporal DOF.
the heterogeneities the hot clutter jammer introduces in range by examining the known SINR Loss at different range cells. The SINR Loss is useful as it shows the SINR Loss related to interference in the radar look direction. The SINR Loss is computed using known interference throughout the sample support for JDL and FTS. The adaptive MF and NA processing SINR Loss is computed to further build the physical picture of heterogeneities within the sample support. as well as the MF and NA processing. In addition, the Output SINR using the estimated interference covariance to construct the adaptive filters, as well as probability of detection analysis. These performance metrics are evaluated for a TN jammer at \( \phi = 0^\circ \) and \( \phi = 45^\circ \) at a range of 72 and 132 Km from the RUT.

5.2.2.1 TN Jammer at Boresight. The RUT is chosen to be 66 Km as when the RUT is at a significant distance from the radar, the range cells around the RUT can approximated to be homogeneous. The closer the jammer is from the range cell under test, the larger the interference in the RUT becomes, and also the interference at other locations in normalized Doppler increases. The SINR Loss is the loss associated with added interference within the environment. Similar techniques were used in [1] to illustrate in inhomogeneities within the samples support. The SINR Loss is calculated using the known interference containing only hot clutter and thermal noise. Therefore, if the SINR Loss metric is 0, the interference at the particular location in azimuth and Doppler only contains thermal noise, and the loss will represent the SINR Loss from the hot clutter. The MF SINR Loss is calculated for the RUT at 66 Km for a jammer at \( \phi = 0^\circ \), at locations in range from 72 to 132 Km. The SINR Loss is illustrated in Figure 5.22. Though the MF SINR Loss metric is not the interference within the environment, this metric does show how ideal adaptive filters processes the interference in the range cells. The MF SINR Loss shows the residual interference occurring in all adaptive filters as the MF is the optimum bound on adaptive performance. The MF SINR Loss only occurs as a result of hot clutter. When the jammer is far from the RUT, the MF SINR Loss
Figure 5.22: MF SINR Loss for a TN jammer at $\phi = 0^\circ$. The MF SINR Loss is evaluated for RUT= 66 Km as the jammer is placed from 72 Km to 132 Km from the radar. The MF SINR Loss is the loss in SINR only associated with the interference from hot clutter. As the jammer is closer to the RUT, the residual interference not able to mitigated by any adaptive filter at $\phi = 0^\circ$ changes in normalized Doppler.

is similar. One could equate the similarity in SINR Loss for the range cells to infer the sample support vectors $\chi$ are much like the interference in the RUT, and are approximately homogeneous. However, when the jammer is very close the radar, the location of interference changes from range cell to range cell. The range cell snapshots are heterogeneous with one another, and the interference estimate is corrupted.

The range cells very close to the jammer are heterogeneous from one another. The MF SINR Loss associated for range cells close the the TN jammer at $\phi = 0^\circ$ is seen in Figure 5.23. The range cells evaluated are from 58 to 72 Km, with the jammer located at 72 Km. The jammer mainbeam does not illuminate the ground at $\phi = 0^\circ$.
Figure 5.23: MF SINR Loss associated with the interference created from the TN jammer at $\phi = 0^\circ$. The jammer is located at 72 Km, and the range cells evaluated are from 54 to 72 Km. The jammer platform is 3 Km, therefore the jammer mainbeam will not illuminate the ground until 69 Km. When the jammer range is close to the range cells under test, the interference in the range cells become heterogeneous with the surrounding range cells.

until the range cell at 69 Km as the jammer altitude is 3 Km. The MF is able to adapt to all the interference in the RUT not in the radar look direction. The range cells are heterogeneous with one another as the MF SINR Loss is changing from range cell to range cell close to the TN jammer. In Figure 5.23, the MF SINR Loss in computed for range cells from 54 to 72 Km, with the jammer located at 72 Km at $\phi = 0^\circ$. Even though the jammer mainbeam at $\phi = 0^\circ$, the sidelobes are corrupting locations at $\phi = 0^\circ$ at different normalized Doppler frequencies, and change for different range cells. The interference in the sample support is no longer similar to the RUT. The
estimated interference does not reflect the interference in the RUT, and adaptive performance degrades.

**Sample Support Corruption.** The adaptive filters create an interference environment covariance matrix estimation by selecting twice the amount of sample support vectors as the number of degrees of freedom the adaptive filters provide. The JDL adaptive filters used in this analysis have 9 or 21 degrees of freedom, and the FTS adaptive filter uses $N$ or 11 degrees of freedom. Therefore, the maximum amount of range cell sample support vectors needed for covariance matrix estimation is 42. In examining the SINR Loss across for the range cell sample support around the RUT with the jammer at 72 Km, one can see the sidelobe normalized Doppler location changes depending on the adaptive filter used, as seen in Figure 5.25. When the jammer is at 132 Km, the SINR Loss is homogeneous, therefore it is inferred the sample support vectors are homogeneous as seen in Figure 5.24.

When the jammer is at 132 Km, and the range cell under test is 66 Km, the SINR Loss from the jammer is calculated for the corresponding sample support vectors around the range cell under test. This SINR Loss is seen in Figure 5.24. The SINR Loss for NA processing and the MF, $3 \times 3$ JDL, $3 \times 7$ JDL, FTS, and BH FTS weighting vectors is approximately the same for all range cells. When the jammer is at 132 Km, it is assumed the sample support for all filters are homogeneous.

The sample support SINR Loss differs with range as the jammer is now at 72 Km in Figure 5.25. The jammer sidelobe interference changes Doppler frequency depending on the range to the jammer. If the sample support is small, as in the FTS and $3 \times 3$ JDL adaptive filters, the Doppler frequency of jammer sidelobes will not experience a significant shift. As more sample support vectors are used in interference estimation, as in the $3 \times 7$ JDL adaptive filter, the worse the estimate can potentially become. However, it is a double edged sword as the more range cells used for interference estimation, the more DOF the adaptive filter has to adapt to the interference. As less sample support vectors are used to create the estimated interference, the adaptive
Figure 5.24: SINR Loss from the TN jammer at $\phi = 0^\circ$, 132 Km from the radar. NA processing and the MF, $3 \times 3$ JDL, $3 \times 7$ JDL, FTS, and BH FTS adaptive filters are used to calculated the SINR Loss for the corresponding sample support vectors. The SINR Loss is calculated for the range cell sample support around the RUT at 66 Km. As the jammer is far from the RUT, the sample support is approximately homogeneous for all weighting vectors.
Figure 5.25: SINR Loss from the TN jammer at $\phi = 0^\circ$, 72 Km from the radar using non-adaptive and adaptive processing. The SINR Loss is no longer the same for the range cell sample support; therefore, the sample support is no longer homogeneous. The $3 \times 7$ JDL sample support is most heterogeneous as it uses the most range cells. The SINR Loss is calculated for range cells around the RUT at 66 Km.

filters will have less DOF. However, in a heterogeneous environment the interference estimate is closer to the RUT. The effect of estimated interference is evaluated for JDL and FTS adaptive filtering.

*Joint Domain Localized.* When the jammer is at $\phi = 0^\circ$, the effect of estimated interference is examined for the JDL adaptive filter. In Figure 5.26, the Output SINR is calculated using the estimated interference covariance matrix to construct the JDL adaptive filter. The jammer in this scenario is at 72 Km. As the MF SINR Loss for the TN jammer at 132 Km is the same for all range cell sample support vectors, the Output SINR under estimated interference is approximately 3

93
dB less for all locations in normalized Doppler than the Output SINR using known covariance [7].

The Output SINR under known covariance for JDL filtering is seen in Figure 5.19. If the estimated covariance matrix interference uses iid sample support, the difference between known and estimated Output SINR should be approximately 3 dB less when the estimated interference is close to the known interference in the RUT, according to [7]. As the estimate becomes increasingly unlike the interference in the RUT, the difference between known and estimated Output SINR will increase. The estimated interference requires twice the sample support as the DOF needed for the JDL adaptive filter. When only 18 sample support vectors are used in covariance matrix estimation for the $3 \times 3$ JDL adaptive filter, the sample support vectors are heterogeneous. As these sample support vectors are in a small range extent, the sample support are not extremely heterogeneous from one-another. When 42 sample support vectors are used in covariance matrix estimation, as in the $3 \times 7$ JDL adaptive filter, the sample support begins to significantly differ from one-another, and interference estimate is corrupted. The poor estimation is displayed by the degradation of Output SINR in Figure 5.26. The $3 \times 7$ JDL adaptive filter is degraded in some locations in normalized Doppler up to 20 dB in comparison to the $3 \times 7$ JDL adaptive filter constructed using known interference in Figure 5.19.

When the TN jammer is at $\phi = 0^\circ$, all locations across normalized Doppler will suffer degradation in radar performance. A Monte Carlo analysis is performed to simulate probability of detection analysis for a TN jammer at $\phi = 0^\circ$, at ranges of 72 and 132 Km. The Monte Carlo analysis is performing detection probability for $\phi = 0^\circ$, at specific velocities, or locations in normalized Doppler. The probability of detection for the jammer at 132 Km is seen in Figure 5.27. The Monte Carlo analysis is for the radar looking at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. Both the JDL adaptive filters with 9 and 21 DOF require approximately an increase of 6 dB input SINR per element per pulse. The non-adaptive radar performance requires approximately an increase of 3 dB input SINR per element per pulse.
Figure 5.26: The Output SINR using estimated interference to construct the JDL adaptive filter. The TN jammer is at $\phi = 0^\circ$, 72 Km from the radar. The $3 \times 7$ JDL adaptive filter degrades in performance from known to estimated interference, as the sample support over 42 range cells can no longer assumed to be homogeneous. As the $3 \times 3$ JDL filter uses a small number of sample support vectors, the Output SINR is not drastically different from the $3 \times 3$ JDL Output SINR using known covariance.
Figure 5.27: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. The TN jammer is at $\phi = 0^\circ$, 132 Km from the radar. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
When the jammer is at 72 Km, the probability of detection is worse than when the jammer is at 132 Km, and is seen in Figure 5.28. The input SINR per element per pulse is required to be approximately 22 dB more to achieve the same probability of detection using the non-adaptive steering vector. As the interference estimate is poorer for the $3 \times 7$ JDL, the performance degradation is around 16 dB input SINR as compared to around 14 or 15 dB input SINR performance degradation for the $3 \times 3$ JDL. As the $3 \times 7$ JDL adaptive filter has more DOF, the radar performance is better than the $3 \times 3$ JDL adaptive filter even though the $3 \times 7$ adaptive filter contains a more inaccurate interference estimate.

Figure 5.28: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. The TN jammer is at $\phi = 0^\circ$, 72 Km from the radar. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
Figure 5.29: Output SINR using the FTS adaptive filter created from the estimated interference. The TN jammer is at $\phi = 0^\circ$, at 72 Km from the radar. As the sample support is small, the interference estimate is similar to the range cell under test and the FTS adaptive filter does not seriously degrade due to the heterogeneities within the interference environment.

Factored Time Space. The Factored Time Space adaptive filter uses $2N$, or 22 range cell sample support for estimated covariance interference creation. As sample support is low, the estimated interference is similar to the interference in the RUT. The Output SINR using the estimated FTS adaptive filter created using estimated interference is seen in Figure 5.29. The Output SINR when the FTS adaptive filter is created under known covariance is similar to the Output SINR using estimated covariance. Hot clutter creates heterogeneities within the range cells close to the radar; however, the heterogeneities are not significant when using a low number of sample support vectors.
Figure 5.30: Probability of Detection using Monte Carlo analysis for the FTS adaptive filter detecting at target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. The TN jammer is at $\phi = 0^\circ$, 132 Km from the radar. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$.

A probability of detection analysis is simulated for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$ for the TN jammer at $\phi = 0^\circ$ at 72 and 132 Km using the FTS adaptive filter. When the jammer is at 132 Km, the probability of detection is seen in Figure 5.30. The BH FTS adaptive filter degrades approximately 6 dB in input SINR, and the FTS adaptive filter degrades approximately 3 dB in input SINR. Both the FTS and BH FTS adaptive filter perform worse than the JDL adaptive filters at this location in normalized Doppler jamming location. The FTS filters are expected to perform worse at this location as the range cell sample support is homogeneous, as well as the JDL adaptive filters are able to adapt in Doppler.
Figure 5.31: Probability of Detection using Monte Carlo analysis for the FTS adaptive filter detecting a target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. The TN jammer is at $\phi = 0^\circ$, 72 Km from the radar. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$.

When the jammer is at $\phi = 0^\circ$ 72 Km from the radar, the FTS adaptive filter degrades significantly, as seen in Figure 5.31. The BH FTS adaptive filter now requires 20 dB more input SINR to achieve the same probability of detection in a radar environment with only cold clutter and thermal noise. The FTS filter without a Doppler taper requires 10 dB more input SINR to achieve the probability of detection in a cold clutter and thermal noise radar environment. As the FTS adaptive filters are only able to adapt in azimuth, the JDL adaptive filter typically performs better than the FTS adaptive filter, as is the case in this scenario for a TN jammer at $\phi = 0^\circ$.  

100
5.2.2.2 TN Jammer at 45 Degrees Azimuth. When the TN jammer is at an azimuth of $\phi = 45^\circ$, the jammer mainbeam is also at $\phi = 45^\circ$. Adaptive filters are able to place a null at locations in azimuth not in the radar look direction. Adaptive radar performance suffers most when the hot clutter jammer is at $\phi = 0^\circ$ as it is unable to adapt to the TN jammer mainbeam interference. When the jammer is not located in the mainbeam, the adaptive filters are able to place a null at sources of interference except at $\phi = 0^\circ$. Therefore, the hot clutter transmitting through a jammer sidelobe is the only location in normalized Doppler corrupted at $\phi = 0^\circ$. The normalized Doppler location of this hot clutter will change as the jammer range from the RUT changes, as seen in Figure 5.32.

When the jammer is at 72 Km, and the RUT is 66 Km, the jammer is illuminating the radar. At $\phi = 0^\circ$, RUT= 66 Km, the azimuth angle from jammer to the clutter patches change. When the jammer is at 72 Km, the jammer sidelobes at $\phi = -62^\circ$ illuminate the clutter patch at $\phi = 0^\circ$. When the jammer is at 132 Km, the jammer sidelobes at $\phi = -28^\circ$ illuminate the clutter patch at $\phi = 0^\circ$. The elevation angle to the clutter patches also changes. The hot clutter Doppler location at $\phi = 0^\circ$ occurs at $\bar{\omega} = 0.10$ for the jammer at 132 Km, and $\bar{\omega} = -0.07$ for the jammer at 72 Km. When the sample support is small, the hot clutter Doppler locations do not drastically change within a small range extent. The SINR Loss at $\phi = 0^\circ$ due to hot clutter varies little over the sample support vectors in Figures 5.33 and 5.34. The adaptive filters are able to mitigate the mainbeam jammer interference at $\bar{\omega} = -0.36$.

When the jammer is at $\phi = 0^\circ$, the range cells close to the jammer suffered serious performance degradation due to a large increase in interference. When the jammer is at $\phi = 45^\circ$, the jammer is illuminating the clutter patches at $\phi = 0^\circ$, 132 Km and 72 Km from the radar through a sidelobe. The adaptive filters are able to mitigate all interference except at $\phi = 0^\circ$, thus mitigating the interference from the jammer mainbeam at $\phi = 45^\circ$, $\bar{\omega} = -0.36$. The change in the jammer sidelobe normalized Doppler is less in the $3 \times 3$ JDL and the FTS and BH FTS adaptive filters.
Figure 5.32: MF SINR Loss due to a TN jammer at $\phi = 45^\circ$. The RUT is 66 Km. The Output SINR loss due to the jammer is calculated for jammer ranges from 72 to 132 Km. The hot clutter at $\phi = 0^\circ$ is dependent upon range, even if the jammer mainbeam is not. The maximum MF SINR loss changes with respect to the hot clutter Doppler location at $\phi = 0^\circ$ as the jammer is at different ranges from the radar.
Figure 5.33: SINR Loss for adaptive and non-adaptive processing due to hot clutter, for a TN jammer at $\phi = 45^\circ$ at 132 Km from the radar. As the jammer is far from the RUT, the hot clutter at $\phi = 0^\circ$ changes little over the sample support. The adaptive filters mitigate the jammer mainbeam normalized Doppler location at $\bar{\omega} = -0.36$. 
Figure 5.34: SINR Loss for adaptive and non-adaptive processing due to hot clutter, for a TN jammer at $\phi = 45^\circ$ at 72 Km from the radar. The hot clutter at $\phi = 0^\circ$ changes little over the sample support, even though the radar is extremely close to the sample support. The adaptive filters mitigate the jammer mainbeam at $\bar{\omega} = -0.36$. 
than the $3 \times 7$ JDL adaptive filter as they use less sample support to estimate the interference.

*Joint-Domain Localized.* The Output SINR using the estimated interference covariance matrix to construct the JDL adaptive filters is seen in Figure 5.35. The interference estimate is created from sample support vectors above and below the RUT at 66 Km. The mainbeam jammer interference is averaged to occur at the interference normalized Doppler location in the RUT. The interference estimate is similar to the RUT. Therefore, the performance degradation due to hot clutter is still approximately at $\bar{\omega} = -0.07$.

The jammer interference at $\phi = 0^\circ$ occurs at $\bar{\omega} = 0.10$ for a TN jammer at $\phi = 45^\circ$, 132 Km from the radar. Similarly, the jammer interference at $\phi = 0^\circ$ occurs at $\bar{\omega} = -0.07$ for a TN jammer at $\phi = 45^\circ$, 72 Km from the radar. Monte Carlo analysis to simulate probability of detection is performed at these two respective locations in normalized Doppler to examine the effect hot clutter has on the JDL adaptive filter. Both locations degrade JDL adaptive filtering performance. When the jammer is at 72 Km from the radar, the probability of detection for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.07$ is seen in Figure 5.36. The required input SINR per element per pulse is 20 dB more for both JDL adaptive filters to achieve the same probability of detection. As normalized Doppler location is already in a location where non-adaptive performance suffers, the probability of detection of non-adaptive radar at this location is relatively unaffected.

In Figure 5.37, the JDL adaptive radar performance is seen for a TN jammer at $\phi = 45^\circ$, 132 Km from the radar for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.10$. The probability of detection is performed at the hot clutter locations at $\phi = 0^\circ$ for each location in range. It is important to note the performance degradation is similar for both jammer locations in range. The adaptive filter is able to filter out the jammer mainbeam at $\phi = 45^\circ$, therefore the interference at $\phi = 0^\circ$ is radiated from jammer sidelobes. As the jammer sidelobe at 72 Km is at $\phi = -62^\circ$, and the jammer sidelobe at 132
Figure 5.35: Output SINR using the JDL adaptive filter created from estimated interference. The TN jammer is at $\phi = 45^\circ$, at 72 Km from the radar. As the sample support is small, the interference estimate is similar to the range cell under test. The JDL radar performance does not seriously degrade due to the heterogeneities within the environment.
Figure 5.36: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.07$. The TN jammer is at $\phi = 45^\circ$, 72 Km from the radar. The probability of detection is seriously degraded as this Doppler location is the location of hot clutter at $\phi = 0^\circ$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability of Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA w/o HC</td>
<td></td>
</tr>
<tr>
<td>NA w/ HC</td>
<td></td>
</tr>
<tr>
<td>JDL 3x3 w/o HC</td>
<td></td>
</tr>
<tr>
<td>JDL 3x3 w/ HC</td>
<td></td>
</tr>
<tr>
<td>JDL 3x7 w/o HC</td>
<td></td>
</tr>
<tr>
<td>JDL 3x7 w/ HC</td>
<td></td>
</tr>
</tbody>
</table>

Diagram: A graph showing the probability of detection against the input SINR per element per pulse [dB]. The x-axis represents the input SINR, while the y-axis represents the probability of detection. Different lines represent different scenarios, such as NA w/o HC, NA w/ HC, JDL 3x3 w/o HC, etc.
Figure 5.37: Probability of Detection for the JDL adaptive filter using Monte Carlo analysis for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.01$. The TN jammer is at $\phi = 45^\circ$, 132 Km from the radar. The probability of detection is seriously degraded as this Doppler location is the location of hot clutter at $\phi = 0^\circ$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$.

is at $\phi = -28^\circ$, the gain on the clutter patch is similar as the difference in range compensates for the difference in the jammer sidelobe power.

Factored Time Space. The radar performance using the FTS adaptive filter under estimated interference is examined by examining Output SINR across normalized Doppler for the TN jammer at $\phi = 45^\circ$, 72 Km from the RUT in Figure 5.38. The interference estimate requires a low number of sample support vectors; therefore, the Output SINR loss is not seriously affected due to the heterogeneities within the sample support and the interference does not drastically change...
Figure 5.38: Output SINR using the FTS adaptive filter created from estimated interference. The TN jammer is at $\phi = 45^\circ$, at 72 Km from the radar. As the sample support is small, the interference estimate is similar to the range cell under test, thus the FTS radar performance does not seriously degrade due to the heterogeneities within the environment.

over a small range extent. The Output SINR using estimated interference for FTS adaptive filtering creation is approximately 3 dB less than Output SINR using known interference for FTS adaptive filter in Figure 5.17.

The probability of detection of a target is simulated for the same locations in normalized Doppler as the JDL adaptive filter; $\phi = 0^\circ$, $\bar{\omega} = -0.07$ for a jammer at $\phi = 45^\circ$, 72 Km from the radar, and $\phi = 0^\circ$, $\bar{\omega} = 0.10$ for a jammer at $\phi = 45^\circ$, 132 Km from the radar. The probability of detection for the FTS adaptive filter is seen at these locations in normalized Doppler in Figures 5.40 and 5.39. The detection probability
for both FTS adaptive methods requires a larger input SINR than the non-adaptive steering vector at these locations in normalized Doppler. However, these locations in normalized Doppler are the worst case scenario. The FTS adaptive filter is able to significantly improve detection probability at the normalized Doppler location of jammer mainbeam at $\bar{\omega} = -0.36$, seen in the Output SINR for estimated interference in Figure 5.38.

### 5.3 TN Jammer Performance Impact Summary

The TN jammer is able to produce ground clutter at new locations in azimuth and normalized Doppler based on the jammer velocity direction and the jammer
Figure 5.40: Probability of Detection for the FTS adaptive filter using Monte Carlo analysis for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.1563$. The TN jammer is at $\phi = 45^\circ$, 132 Km from the radar. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.001$. 
azimuth from the radar. The location of hot clutter in azimuth and Doppler is dependent on the TN jammer range, and azimuth. In this development, the jammer velocity component in the radar direction is always zero. When the jammer is located at $\phi = 0^\circ$, the jammer mainbeam is always at $\bar{\omega} = 0$ regardlessly of jamming range to the radar platform. Similarly, if the jammer is at an azimuth other than $\phi = 0^\circ$, the jammer mainbeam will always be in at a particular Doppler location regardless of range. In the TN jamming scenario illustrated, the mainbeam jamming location is always in the same location in Doppler. The jammer model is slightly modified to only change the jammer velocity component in order to make the jammer fly directly towards the radar. The jammer mainbeam location in normalized Doppler will no longer be independent of range, and will no longer be at $\bar{\omega} = 0$ when the jammer is at $\phi = 0^\circ$. The impact on radar performance for a oncoming (OC) jammer flying directly towards the radar is discussed in Chapter VI.
VI. Oncoming Hot Clutter Jammer Impact on Side-Looking Radar Performance

In Chapter III, the hot clutter model is developed for a tangential (TN) jammer. In these simulations, the jammer is modified to be an oncoming (OC) jammer. The jammer is now flying directly towards the radar at a velocity \( v_j \). The new jamming scenario is illustrated in Figure 6.1. The largest degradation in radar performance occurs when the jammer is directly in the radar mainbeam at \( \phi = 0^\circ \). When the jammer is OC, the jammer mainbeam Doppler location changes due to the range from the radar, even when the jammer is at \( \phi = 0^\circ \). The heterogeneities within the sample support is greatest when the jammer is close to the range cell under test (RUT). The effect of changing the jammer velocity component to make the jammer OC is examined for the same locations as the TN jammer; at \( \phi = 0^\circ \) and \( \phi = 45^\circ \) in azimuth and 132 Km and 72 Km from the radar platform.

6.1 Non-Adaptive Radar Performance

Non-adaptive radar performance is similar to the non-adaptive radar performance for the TN jammer, except the jammer mainbeam location in Doppler is now different.

6.1.1 OC Jammer at Boresight. When the OC jammer is at boresight, the jammer mainbeam changes location in Doppler with respect to range. The range dependence in Doppler of an OC jammer can be seen in Figure 6.2. When range cells are extremely close to the jammer, the jammer mainbeam changes from range cell to range cell, as the elevation angle to the clutter patches are large. As the range cells are farther from the jammer, the more homogeneous the range cells become.

When the jammer is at \( \phi = 0^\circ \), one can see the non-adaptive Output SINR for the jammer 72 and 132 Km from the radar in Figure 6.3. When examining the Output SINR, one can see the jammer mainbeam change in normalized Doppler based on the jammer range.
Figure 6.1: The OC jamming scenario. The jammer velocity component in the radar direction is simply the jammer velocity $v_j$. The relative velocity of ground clutter from the OC jammer is different than the velocity of ground clutter from the TN jammer. The jammer velocity component to the $i_k^{th}$ radar clutter patch is changed.
Figure 6.2: Range-Doppler output for non-adaptive radar performance. The OC jammer is at $\phi = 0^\circ$, 72 Km from the radar. The jammer mainbeam range dependence can be seen from the large output resulting from the jammer mainbeam starting at 69 Km. The range cells are clearly heterogeneous from one-another in this jamming scenario. The range cells evaluated are from 60 to 72 Km from the radar.
Figure 6.3: Non-adaptive Output SINR for the OC jammer at $\phi = 0^\circ$ for jammer ranges of 72 and 132 Km from the radar. As the jammer is OC, the jammer mainbeam is no longer at $\bar{\omega} = 0$, as changes for different jammer locations in range. When the jammer is at 72 Km, the jammer mainbeam is at $\bar{\omega} = -0.16$. When the jammer is at 132 Km, the jammer mainbeam is now at $\bar{\omega} = -0.10$. The degradation in Output SINR becomes greater as the jammer is closer to the RUT.
6.1.2 OC Jammer at 45 Degrees Azimuth. For an OC jammer at $\phi = 45^\circ$, the Output SINR for this jamming location is seen in Figure 6.4 for ranges of 72 Km and 132 Km from the radar. When the jammer is at 132 Km, the largest interference occurs at the jammer mainbeam location in Doppler at $\bar{\omega} = -0.45$. This interference location enters the radar through a sidelobe as the radar is looking at $\phi = 0^\circ$. There is also a degradation in interference along $\bar{\omega} = 0.17$. This degradation is the location in normalized Doppler of jammer interference at $\phi = 0^\circ$. The interference at radar boresight is transmitted through a jammer sidelobe; therefore, the loss in Output SINR is less at this location than at $\bar{\omega} = -0.45$, the mainbeam jammer Doppler frequency.

When the jammer is at 72 Km, the jammer mainbeam interference is now at a normalized Doppler frequency of $\bar{\omega} = 0.48$. The radar is receiving the jammer through one of its sidelobes. As the jammer is closer to the RUT, the interference is much greater than when the jammer is at 132 Km. The jammer interference at $\phi = 0^\circ$ is at a normalized Doppler frequency of $\bar{\omega} = -0.01$. There is minimal impact in Output SINR at this location in normalized Doppler as a result of hot clutter as there is already a significant degradation in Output SINR for non-adaptive performance around $\bar{\omega} = 0$ resulting from the ground clutter illuminated by the radar mainbeam. In addition, when the jammer is at 72 Km, the jammer antenna pattern illuminates the clutter patch at $\phi = 0^\circ$ in a jammer sidelobe at $\phi = -62$ degrees. The jammer is not able to illuminate this clutter patch with significant power, and the degradation in Output SINR at $\bar{\omega} = -0.01$ is not significant due to the OC jammer at $\phi = 45^\circ$, 72 Km from the radar.

6.2 Adaptive Radar Performance

The impact of an OC hot clutter jammer on adaptive radar performance is examined under known and estimated interference. Using the same performance metrics as in Chapter V, the performance impact of an OC jammer on the Matched Filter (MF), Factored Time Space (FTS), and Joint Domain Localized (JDL) adaptive
Figure 6.4: Output SINR for non-adaptive processing. The interference contains an OC jammer at $\phi = 45^\circ$, 72 Km and 132 Km from the radar. When the jammer is at 132 Km, the hot clutter degrades Output SINR at the mainbeam jammer location in Doppler and the hot clutter at $\phi = 0^\circ$ at $\bar{\omega} = -0.45$, and $\bar{\omega} = 0.17$ respectively. When the jammer is at 72 Km, the interference primarily increases at the mainbeam jammer location in Doppler at $\bar{\omega} = 0.48$. The hot clutter at $\phi = 0^\circ$ for a jammer at $\phi = 45^\circ$, 72 Km from the radar is radiated through a jammer sidelobe, and degrades radar performance at $\bar{\omega} = -0.01$. As this Doppler location already suffers in performance, and the hot clutter power is not significant in this location, the non-adaptive performance in Output SINR is not affected.
filters are examined using Output SINR, SINR Loss, and probability of detection analysis. As the OC jammer mainbeam changes in normalized Doppler, an attention is given to the heterogeneities within the sample support when the OC jammer is close to the RUT. These range cells have the largest jammer mainbeam range dependence in Doppler frequency.

6.2.1 Radar Performance Using Known Interference. When adaptive filters are operating under known covariance, they are able to adapt to sources of interference within the environment. The effect of an OC jammer on radar performance is examined using the known interference in the RUT using the MF, FTS, and JDL adaptive filters.

6.2.1.1 Matched Filter. The MF is the fully adaptive filter able to perfectly adapt to interference within the RUT. The MF is able to place spatial and temporal nulls on interference not located in the radar look direction in azimuth and Doppler. The adaptive MF Output SINR for the OC jammer at \( \phi = 0^\circ \) is seen in Figure 6.5. When the jammer is at 132 Km, the OC jammer mainbeam is located at \( \bar{\omega} = -0.10 \). The maximum loss of 30 dB in Output SINR occurs at this location in normalized Doppler. When the jammer is at 72 Km, 6 Km from the RUT, the jammer mainbeam is now at \( \bar{\omega} = -0.16 \). As the jammer is closer to the RUT, the jammer sidelobes corrupt more Doppler frequencies and the maximum loss in Output SINR in the jammer mainbeam at \( \bar{\omega} = -0.16 \) is approximately 85 dB in Output SINR.

When the jammer is at \( \phi = 45^\circ \), the MF is able to null the mainbeam jammer interference in azimuth and Doppler as it is not in the radar look direction. The MF is able to mitigate all the hot clutter everywhere except the hot clutter present at \( \phi = 0^\circ \). The Output SINR for the fully adaptive MF is seen in Figure 6.6. At 132 Km, the OC jammer mainbeam is at \( \bar{\omega} = -0.45 \). The MF does not suffer a performance impact at this location in Doppler as the MF is able to suppress the jammer mainbeam. The OC hot clutter jammer degrades performance around \( \bar{\omega} = 0.17 \), the hot clutter location
Figure 6.5: Output SINR for the fully adaptive MF for an OC jammer at $\phi = 0^\circ$. The jammer is 72 and 132 Km from the radar. The jammer mainbeam changes in normalized Doppler as the jammer changes in range. In addition, the closer the jammer is to the RUT, the larger the degradation in Output SINR becomes.
Figure 6.6: Output SINR for the fully adaptive MF under known interference. The jammer is at $\phi = 45^\circ$, 72 and 132 Km from the radar. The MF is able to place nulls on interference everywhere except the hot clutter located in the radar look direction at $\phi = 0^\circ$, $\bar{\omega} = -0.01$ for the jammer 72 Km from the radar, and $\bar{\omega} = 0.17$ for the jammer 132 Km from the radar.
in Doppler at $\phi = 0^\circ$. Similarly, when the jammer is at $\phi = 45^\circ$, 72 Km from the radar, the only location corrupted in normalized Doppler is around $\bar{\omega} = -0.01$.

6.2.1.2 Factored Time Space. The Factored Time Space adaptive filter is only able to adapt in azimuth. The FTS filter performance in Output SINR is worse than the MF as the filter is unable to place nulls at Doppler frequencies containing hot clutter at $\phi = 0^\circ$. Therefore, the Output SINR around the Doppler frequencies containing hot clutter will degrade more for the FTS adaptive filter as it does not have the ability to adapt in Doppler.

When the jammer is at $\phi = 0^\circ$, 132 Km from the radar, the degradation in Output SINR for the FTS adaptive filter in seen in Figure 6.7. As the jammer mainbeam is located at $\bar{\omega} = -0.10$, the FTS filter is unable to suppress the hot clutter interference at locations around this location in Doppler. Similarly, when the jammer is at $\phi = 0^\circ$, 72 Km from the radar, the radar performance using the FTS adaptive filter degrades at the new jammer mainbeam location at $\bar{\omega} = -0.16$, seen in Figure 6.8. The performance impact in Output SINR is worse as the OC jammer at 72 Km is closer to the RUT, the illuminating power from the jammer to the clutter patches is greater. As seen in Figures 6.7 and 6.8, the FTS adaptive filter without a Doppler taper performs similar to the non-adaptive steering vector. Both the radar performance using the FTS filter non-adaptive processing are similar as the FTS in unable to adapt to the jammer mainbeam, as the jammer mainbeam is located in the radar look direction. When a Blackman-Harris (BH) taper is applied across normalized Doppler, the radar performance is better than the FTS without a Doppler Taper and non-adaptive radar performance.

When the jammer is at $\phi = 45^\circ$, one can see the radar performance using FTS adaptive filters for the jammer at 72 and 132 Km in Figures 6.9 and 6.10. The FTS adaptive filter is able to place a nulls in azimuth in the jammer mainbeam at $\phi = 45^\circ$. When the jammer is at 132 Km, the FTS performance improves Output SINR in the radar mainbeam Doppler frequency almost 30 dB. The radar performance using the
Figure 6.7: Output SINR for the FTS adaptive filter for an OC jammer at $\phi = 0^\circ$, 132 Km from the radar. As the jammer is at $\phi = 0^\circ$, the FTS filter is not able to suppress the mainbeam jammer interference.
Figure 6.8: Output SINR for the FTS adaptive filter for an OC jammer at $\phi = 0^\circ$, 72 Km from the radar. The jammer mainbeam is at $\phi = 0^\circ$, $\bar{\omega} = -0.16$. The FTS is unable to suppress the jammer mainbeam as it is in the radar look direction. The locations in Doppler around the mainbeam degrades more than MF Output SINR as the FTS filter is unable to suppress interference in Doppler.
Figure 6.9: Output SINR for the FTS adaptive filter for an OC jammer at $\phi = 45^\circ$, 132 Km from the radar. The FTS filter is unable to place a null in azimuth around the hot clutter at $\phi = 0^\circ$, $\bar{\omega} = 0.17$ as it is in the radar look direction. The jammer is able to place a null in the jammer mainbeam Doppler location at $\bar{\omega} = -0.45$, improving radar performance at this location in Doppler up to 30 dB.
Figure 6.10: Output SINR for the FTS adaptive filter for an OC jammer at $\phi = 45^\circ$, 72 Km from the radar. The FTS filter is able to suppress the jammer at $\phi = 45^\circ$, $\bar{\omega} = 0.48$. As the radar performance for the FTS filter around $\bar{\omega} = 0$ is already poor, the jammer sidelobe illuminating $\phi = 0^\circ$, $\bar{\omega} = -0.01$ has minimal effect on the FTS Output SINR.
FTS adaptive filter degrades around $\bar{\omega} = 0.17$ as it is unable to null the hot clutter located at $\phi = 0^\circ$.

The radar performance in Output SINR using the FTS adaptive filter suffers minimal degradation when the jammer is at $\phi = 45^\circ$, 72 Km from the radar. The FTS adaptive filter places nulls in the jammer mainbeam at $\phi = 45^\circ$, resulting in an improvement in the jammer mainbeam Doppler at $\bar{\omega} = 0.48$. The hot clutter at $\phi = 0^\circ$ is located in Doppler at $\bar{\omega} = -0.01$. This Doppler location is where the FTS filter already suffers performance loss resulting from the radar mainbeam; therefore, performance is relatively unaffected. The BH FTS filter improves performance up to approximately 40 dB at $\bar{\omega} = 0.48$, whereas the FTS filter without a Doppler taper improves performance more than 20 dB at this Doppler location.

6.2.1.3 Joint Domain Localized. The radar performance using JDL adaptive filters is better than radar performance using FTS adaptive filters under known covariance as the JDL filter is able to place nulls in Doppler as well as azimuth. The maximum degradation in Output SINR in the jammer mainbeam locations in Doppler are less when using the JDL filters than Output SINR using FTS filters. Under known covariance, the $3 \times 3$ and $3 \times 7$ JDL filters perform approximately the same. The degradation in Output SINR is only results from the hot clutter interference located at $\phi = 0^\circ$, resulting from either the jammer mainbeam or sidelobes depending on the jamming location in azimuth. The radar performance in Output SINR for the JDL adaptive filters is better than the FTS filter. Using known interference, the radar performance using the JDL filters in Output SINR is close to the radar performance when using the adaptive MF. The Output SINR for the OC jammer at $\phi = 0^\circ$ and $\phi = 45^\circ$, at ranges of 72 and 132 Km can be seen in Figures 6.11, 6.12, 6.13, and 6.14. The Output SINR calculated for FTS and JDL adaptive filters is when the filters is using the known interference within the RUT. The next section evaluates the radar performance using FTS and JDL partially adaptive filters under estimated interference.
Figure 6.11: Output SINR for the JDL adaptive filter for an OC jammer at $\phi = 0^\circ$, 132 Km from the radar. Both the $3 \times 3$ and $3 \times 7$ adaptive JDL filters perform approximately the same. The jammer mainbeam is at $\phi = 0^\circ$, $\bar{\omega} = 0.10$. The JDL filter is able to suppress locations of interference not in the jammer mainbeam or radar mainbeam. The JDL adaptive filter improves performances compared to the FTS adaptive filter at Doppler locations close to the jammer and radar mainbeam. For example, when the radar has a look direction of $\phi = 0^\circ$, $\bar{\omega} = -0.05$, the JDL filters improve in Output SINR about 40 dB over the Output SINR using the FTS filters seen in Figure 6.7.
Figure 6.12: Output SINR for the JDL adaptive filter for an OC jammer at $\phi = 0^\circ$, 72 Km from the radar. The JDL filter performs worse than when the jammer is at 132 Km as the jammer is now closer to the RUT. The jammer mainbeam is now located at $\bar{\omega} = -0.16$. The JDL filter is able to adapt in Doppler. The JDL adaptive filter offers significant improvement in Output SINR from the FTS filter and non-adaptive processing.
Figure 6.13: Output SINR for the JDL adaptive filter for an OC jammer at $\phi = 45^\circ$, 132 Km from the radar. As the JDL filter is able to adapt in azimuth and Doppler, the radar performance using the JDL filter is only corrupted around $\tilde{\omega} = 0.17$, the location of hot clutter at $\phi = 0^\circ$. 
Figure 6.14: Output SINR for the JDL adaptive filter for an OC jammer at $\phi = 45^\circ$, 72 Km from the radar. The location of hot clutter at $\phi = 0$ is at $\bar{\omega} = -0.01$. The JDL adaptive filter is already lacking at this location in normalized Doppler; therefore, hot clutter at $\phi = 45^\circ$, 72 Km from the RUT is largely unaffected when using both the $3 \times 3$ and $3 \times 7$ JDL adaptive filters. The JDL is able to mitigate the jammer mainbeam at $\bar{\omega} = 0.48$, improving Output SINR at this location in normalized Doppler approximately 40 dB.
6.2.2 Radar Performance Using Estimated Interference. The JDL and FTS adaptive filters are evaluated using estimated interference. The radar performance using these filters are evaluated using SINR Loss, Output SINR using estimated interference, and probability of detection using Monte Carlo analysis.

6.2.2.1 OC Jammer at Boresight. It is shown for a TN jammer very close to the RUT, the interference becomes different from range cell to range cell. However, the mainbeam interference for a TN jammer is always at $\omega = 0$ when the jammer is in the radar mainbeam at $\phi = 0^{\circ}$. The estimated interference is responsible for a degradation in performance, however as the mainbeam is always at $\omega = 0$, the interference estimate is not extremely corrupted. For an OC jammer, the heterogeneity within the range cells close to the RUT for a jammer at $\phi = 0^{\circ}$, 72 Km from the RUT is apparent in the non-adaptive output in Figure 6.2. In the case with an OC jammer, the mainbeam interference now changes. The SINR Loss using the MF under known interference for the RUT= 66 Km, as the jammer varies in range from 72 Km to 132 Km from the radar is illustrated in Figure 6.15. When the jammer is far from the range cell under test, the SINR Loss associated with the jammer mainbeam is approximately in the same location in normalized Doppler. As the jammer approaches the RUT, the mainbeam jammer interference noticeably changes in normalized Doppler as the jammer is closer to the RUT. The sample support is corrupted if the jammer is close to the RUT as the mainbeam jammer interference changes locations in normalized Doppler frequency.

When the jammer is at $\phi = 0^{\circ}$, 132 Km from the radar, thus 66 Km from the RUT clutter patch at $\phi = 0^{\circ}$, one can see the SINR Loss due to hot clutter in the sample support range cells around the RUT at 66 Km in Figure 6.16. The SINR Loss for the non-adaptive and adaptive radar performance as the hot clutter is approximately the same for all range cells around the RUT when the jammer is at 132 Km. The SINR Loss is approximately the same for all ranges cells; therefore, one
Figure 6.15: MF SINR Loss for an OC jammer at $\phi = 0^\circ$ for the RUT at 66 Km. The jammer range is calculated from 72 to 132 Km. When the jammer range is close to the RUT, the jammer mainbeam changes from range cell to range cell. When the jammer is far from the RUT, the mainbeam jammer interference location is approximately the same.
Figure 6.16: SINR Loss for adaptive and non-adaptive processing from hot clutter in the range cell sample support around the RUT at 66 Km. The jammer is OC, 132 Km from the radar. As the jammer is far from the RUT, the sample support vectors are approximately homogeneous with one another.
can infer the interference within the range cell sample support to be homogeneous and will create an accurate interference estimate.

The SINR Loss due to hot clutter using non-adaptive and adaptive processing when the jammer is at 72 Km can be seen in Figure 6.17. The jammer mainbeam changes 0.2 in normalized Doppler throughout the $3 \times 7$ JDL sample support. This change in the degradation in SINR Loss representing the jammer mainbeam will result in a poor interference estimate, and a loss in radar performance. The FTS, BH FTS, and $3 \times 3$ JDL sample support uses less range cells to create the estimate interference. The estimated interference is not as corrupted in these adaptive filters as the jammer mainbeam does not change as much in normalized Doppler as across the $3 \times 7$ JDL sample support.

*Joint Domain Localized.* The Joint Domain Localized adaptive filter is constructed using two different Localized Processing Regions. The first LPR is size $3 \times 3$, and the second is size $3 \times 7$. The corresponding sample support needed for interference covariance matrix estimation is, respectively, 18 and 42. When these JDL adaptive filters are created using estimated interference, the degradation due to the poor interference estimate in Output SINR is illustrated in Figure 6.18. The jammer mainbeam changes in normalized Doppler from approximately $\bar{\omega} = -0.10$ to $\bar{\omega} = -0.30$ over 42 range cells around the sample support. The jammer mainbeam in the RUT is at $\bar{\omega} = -0.16$. The $3 \times 7$ JDL adaptive filter using the interference estimate of all 42 range cells is corrupted, resulting in a degradation in Output SINR around $\bar{\omega} = -0.10$ to $\bar{\omega} = -0.30$. When the $3 \times 3$ JDL adaptive filter only uses 18 range cells for sample support, the degradation due to a poor estimate is still apparent. However, as the mainbeam is changing less in normalized Doppler across 18 range cells, the radar degradation in Output SINR for the $3 \times 3$ JDL adaptive filter is less than the $3 \times 7$ JDL adaptive filter.

When examining the probability of detection using Monte Carlo analysis, the impact of a poorly estimated interference covariance matrix for the $3 \times 7$ JDL con-
Figure 6.17: SINR Loss for adaptive and non-adaptive processing from hot clutter in the range cell sample support around of RUT at 66 Km. The jammer is OC, 72 Km from the radar. The SINR Loss associated with the jammer mainbeam changes approximately 0.2 in normalized Doppler throughout the $3 \times 7$ JDL sample support. As the FTS and $3 \times 3$ JDL filters use less sample support than the $3 \times 7$ JDL filter, the jammer mainbeam does not change as much in normalized Doppler. The interference estimate using these sample support vectors, especially for the $3 \times 7$ JDL filter poorly represents interference in the RUT.
Figure 6.18: Output SINR using estimated interference for JDL construction. The OC jammer is at $\phi = 0^\circ$, 72 Km from the RUT. The jammer mainbeam changes from range cell to range cell when the jammer is close to the sample support. The $3 \times 3$ JDL uses less sample support than the $3 \times 7$ JDL. As the jammer mainbeam changes less over a small range extent, the estimated interference is more like the interference in the RUT for the $3 \times 3$ JDL interference estimate than the $3 \times 7$ JDL interference estimate. The radar performance in Output SINR is better for the $3 \times 3$ JDL adaptive filter than the $3 \times 7$ JDL adaptive filter, even though it uses less degrees of freedom.
struction is apparent in Figure 6.19. The probability of detection is simulated when the radar is looking for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.30$. When the OC jammer is at $\phi = 0^\circ$, 72 Km from the jammer, the jammer mainbeam is at $\bar{\omega} = -0.16$ in the RUT. In Figure 6.19, one can see the $3 \times 7$ JDL adaptive filter suffer significant degradation in the presence of hot clutter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.30$, even though the mainbeam is at $\bar{\omega} = -0.16$. As the $3 \times 7$ JDL adaptive filter interference estimate is poor, the input SINR to achieve a reliable probability of detection of $P_d = 0.99$ is on the order of 24 dB in input SINR. This required input SINR is extremely large, and the likelihood of a radar ever detecting a target at this normalized Doppler is slim. The $3 \times 3$ JDL filter performs better than the $3 \times 7$ JDL filter as the interference estimate is more like the interference in the RUT.

When the jammer is at 132 Km, the probability of detection is again simulated for the JDL adaptive filter at $\bar{\omega} = -0.10$, seen in Figure 6.20. As this location in Doppler is the location of mainbeam jammer interference, the JDL filters are expected to degrade around this Doppler location. Though probability of detection degrades for the JDL adaptive filters, they still perform better than radar performance using non-adaptive processing. The interference estimate is more accurate as the jammer is far from the RUT, and the sample support is homogeneous.

**Factored Time Space.** The FTS adaptive filter uses $2N$, or 22 sample support vectors to create the estimated interference. As the number of sample support vectors is relatively small, the interference estimate is not seriously corrupted resulting from the shift in jammer mainbeam normalized Doppler. The Output SINR using estimated interference to create the FTS adaptive filter when the jammer is at $\phi = 0^\circ$, 72 Km is seen in Figure 6.21. When compared to the Output SINR for the FTS filter using known covariance in Figure 6.8, the Output SINR using estimated interference further degrades across more locations in normalized Doppler around the jammer mainbeam. This degradation occurs as the jammer mainbeam is changing in normalized Doppler at values slightly above and below $\bar{\omega} = -0.16$ throughout the
Figure 6.19: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.30$. The OC jammer is at $\phi = 0^\circ$, 72 Km from the radar. The corruption in the $3 \times 7$ JDL sample support results in a significant loss in radar performance for the $3 \times 7$ JDL filter. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 

\begin{align*}
\text{Probability of Detection} \\
\text{Input SINR per element per pulse [dB]}
\end{align*}
Figure 6.20: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.10$. The OC jammer is at $\phi = 0^\circ$, 132 Km from the radar. The jammer is far from the RUT; therefore, the interference estimate similar to the RUT. The hot clutter degrades the performance of both JDL filters and non-adaptive radar performance. As the sample support is homogeneous, the JDL filters perform better than non-adaptive processing in the radar mainbeam. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
sample support. However, as the sample support is small the interference estimate does not seriously corrupt radar performance.

The FTS adaptive filter performance is examined using Monte Carlo analysis for the probability of detection. The probability of detection is simulated for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.30$ when the jammer is at $\phi = 0^\circ$, 72 Km from the radar. The $3 \times 7$ JDL adaptive filter performance at this normalized Doppler location suffers due to an inaccurate interference estimate. The FTS adaptive filter performs better than the $3 \times 7$ JDL filter as the interference estimate is not seriously corrupted, as illustrated in Figure 6.22. The BH FTS adaptive filter performs approximately 35 dB better than the $3 \times 7$ JDL adaptive filter. However, the $3 \times 3$ JDL filter performs better than both FTS and BH FTS adaptive filters. The radar performance using the $3 \times 3$ JDL filter is able to provide adaptivity in Doppler, and uses less sample support for interference estimation than FTS adaptive filters.

The probability of detection for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.10$ for a jammer at 132 Km is seen in Figure 6.23. At $\bar{\omega} = -0.10$, the radar performance is lacking for the FTS adaptive filters, as this location in normalized Doppler is the location of mainbeam jammer interference. The FTS adaptive filters perform worse than the non-adaptive steering vector. The JDL adaptive filters are able to perform better than the FTS adaptive filters at this location as they are able to null location of interference in Doppler.

6.2.2.2 OC Jammer at 45 Degrees Azimuth. When the OC jammer is at $\phi = 45^\circ$, the adaptive radar performance is similar to the radar performance with a TN jammer at $\phi = 45^\circ$. The hot clutter Doppler location at $\phi = 0^\circ$ for TN and OC jammers is range dependent when they illuminate the radar mainbeam and the jammers are not located at $\phi = 0^\circ$. In Figure 6.24 and Figure 6.25, the location of jammer interference at $\phi = 0^\circ$ changes with respect to the jammer range; however, the Doppler shift of hot clutter at $\phi = 0^\circ$ is small. Therefore, the interference in the sample support is similar to the RUT for all adaptive filters. The location of jammer
Figure 6.21: Output SINR using estimated interference for FTS construction. The OC jammer is at $\phi = 0^\circ$, 72 Km from the RUT. As the sample support is small, the FTS adaptive filter constructed under estimated interference is similar to the FTS adaptive filter under known interference. Output SINR further degrades around locations in Doppler at $\bar{\omega} = -0.16$, as the jammer mainbeam interference in the sample support is slightly above and below this normalized Doppler value. As the sample support is small, the degradation in performance using estimated interference is not severe as the sample support is similar to the RUT.
Figure 6.22: Probability of Detection using Monte Carlo analysis for the FTS adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.30$. The OC jammer is at $\phi = 0^\circ$, 72 Km from the radar. The FTS adaptive filter uses less sample support than the $3 \times 7$ JDL filter. The degradation in radar performance at this location in normalized Doppler is not large as the $3 \times 7$ JDL adaptive filter. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
Figure 6.23: Probability of Detection using Monte Carlo analysis for the FTS adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.10$. The OC jammer is at $\phi = 0^\circ$, 132 Km from the radar. The sample support when the jammer is far from the RUT is approximately homogeneous. As the jammer mainbeam is located at $\phi = 0^\circ$, the FTS adaptive filter is unable to place nulls in Doppler; therefore, the FTS adaptive filter performs worse than the JDL adaptive filter and non-adaptive processing. This location in Doppler is corrupted most by hot clutter. The FTS adaptive filters expect to perform better to mitigate hot clutter at other Doppler locations. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
Figure 6.24: SINR Loss for non-adaptive and adaptive processing from hot clutter in the range cell sample support around the RUT at 66 Km. The OC jammer is 72 Km from the radar at $\phi = 45^\circ$. Even though the jammer is close to the RUT, the SINR Loss in the adaptive filters is approximately at the same location in normalized Doppler. The adaptive filters are able to mitigate the jammer mainbeam located around $\bar{\omega} = 0.48$. The interference in the range cell sample support is similar to the interference in the RUT.
Figure 6.25: SINR Loss for non-adaptive and adaptive processing from hot clutter in the range cell sample support around the RUT at 66 Km. The jammer is OC, 132 Km from the radar at $\phi = 45^\circ$. The SINR loss occurs approximately at $\bar{\omega} = 0.17$ for all range cell sample support using adaptive processing. The adaptive filters are able to mitigate the jammer mainbeam around $\bar{\omega} = -0.45$. 
normalized Doppler interference at $\phi = 0^\circ$ changes within the sample support more when the jammer is close to the RUT, than when the jammer is far from the RUT. The interference estimate is further from the known interference in the RUT when the jammer is at 72 Km, than when the jammer is at 132 Km. The mainbeam jammer interference is at $\phi = 45^\circ$, $\bar{\omega} = 0.48$ for the jammer at 72 Km. For the jammer at 132 Km, the jammer mainbeam is located at $\phi = 45^\circ$, $\bar{\omega} = -0.45$. As the estimated interference is not seriously corrupted for heterogeneous range cell sample support for the FTS and JDL adaptive filters for both 72 and 132 Km, the only difference between the interference in the TN and OC jamming scenarios at $\phi = 45^\circ$ is the Doppler location of hot clutter at $\phi = 0^\circ$. In Chapter V, the JDL and FTS adaptive filters are shown to degrade at the Doppler location of hot clutter at $\phi = 0^\circ$. Now, the JDL and FTS adaptive filters are examined at the jammer mainbeam Doppler locations. The adaptive filters improve performance at these locations in Doppler as they spatially adapt to jammer mainbeam interference when the jammer is not in the mainbeam.

*Joint Domain Localized.* When the jammer is at 72 Km, the probability of detection is simulated for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.48$ in Figure 6.26. Similarly, the probability of detection simulated for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.45$ when the jammer is at 132 Km. These Doppler values are the location of jammer mainbeam interference. At these normalized Doppler locations, the JDL adaptive filters are able to suppress the mainbeam jammer interference. The performance for the $3 \times 3$ and $3 \times 7$ adaptive JDL filters at 72 Km and 132 Km from the radar are approximately the same, with each only degrading in performance due to hot clutter about 1 or 2 dB in input SINR per element per pulse.

*Factored Time Space.* When the FTS adaptive filter is used to simulate the probability of detection in the jammer mainbeam normalized Doppler location, the results are similar to the JDL adaptive filter. As the jammer is not at $\phi = 0^\circ$, the FTS adaptive filter places spatial nulls in the jammer mainbeam, and
Figure 6.26: Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = 0.48$. The OC jammer is at $\phi = 45^\circ$, 72 Km from the radar. As the jammer is not at boresight, the JDL adaptive filter is able to suppress the mainbeam jammer interference at $\bar{\omega} = 0.48$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 

148
The OC jammer is at $\phi = 45^\circ$, 132 Km from the radar. As the jammer is not at boresight, the JDL adaptive filter is able to suppress the mainbeam jammer interference at $\bar{\omega} = -0.45$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 

---

**Figure 6.27:** Probability of Detection using Monte Carlo analysis for the JDL adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.45$. The OC jammer is at $\phi = 45^\circ$, 132 Km from the radar. As the jammer is not at boresight, the JDL adaptive filter is able to suppress the mainbeam jammer interference at $\bar{\omega} = -0.45$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 

---

149
The OC jammer is at $\phi = 45^\circ$, 72 Km from the radar. As the jammer is not at boresight, the FTS adaptive filter suppresses the mainbeam jammer interference at $\bar{\omega} = 0.48$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$.

suppresses jammer mainbeam interference. Though the JDL adaptive filters require less input SINR to achieve the same probability of detection than the FTS adaptive filters, the degradation in input SINR due to hot clutter is approximately the same for both JDL and FTS filters when the jammer is at $\phi = 45^\circ$, 72 Km and 132 Km from the RUT. The probability of detection at the jammer mainbeam normalized Doppler for the FTS adaptive filters can be seen in Figures 6.28 and 6.29.
Figure 6.29: Probability of Detection using Monte Carlo analysis for the FTS adaptive filter for a target at $\phi = 0^\circ$, $\bar{\omega} = -0.45$. The OC jammer is at $\phi = 45^\circ$, 132 Km from the radar. As the jammer is not at boresight, the FTS adaptive filter suppresses the mainbeam jammer interference at $\bar{\omega} = -0.45$. The probability of detection is for $N_{\text{trials}} = 1000$, and a $P_{fa} = 0.01$. 
6.3 OC Jammer Performance Impact Summary

In this chapter, the jammer velocity direction is changed to make the jammer an OC jammer. The OC jammer mainbeam illuminates the radar and travels directly towards the radar platform. Changing the jammer velocity vector effectively makes the jammer mainbeam Doppler location range dependent. The velocities between the radar and jamming platforms are different than the relative velocities for the TN jammer scenario where the jammer did not have a velocity in the radar direction. The relative ground velocity from the jammer is also different. The jammer velocity vector changes the location of hot clutter within the radar interference environment in azimuth and Doppler. When the jammer is extremely close to the RUT in the radar mainbeam, the range cell sample support is heterogeneous. When a large number of sample support vectors are used to create an interference estimate, this estimated interference is much different from the interference in the RUT, and adaptive radar performance degrades.
VII. Conclusions

7.1 Hot Clutter Results

In this research, it is shown hot clutter affects the radar environment differently depending on many variables. The jammer antenna pattern illuminates the ground clutter with different amounts of power in azimuth and Doppler. In addition, the hot clutter jammer velocity vector, azimuth, elevation, and range from the radar change hot clutter normalized Doppler frequency and power radiated to each $i_k$th clutter patch. The hot clutter creates new ground clutter at locations in azimuth and Doppler, and thereby degrades adaptive and non-adaptive radar performance. The probability of detecting a target at locations of hot clutter in the radar environment decreases. The hot clutter jammer is assumed to be a coherent jammer. This jammer has the same waveform and pulse repetition frequency as the radar. All hot clutter power received by the radar is the multi-path coherent scattering reflecting from $i_k$th clutter patch. All the scattered jammer returns reflected to the radar are assumed to be perfectly coherent with the radar waveform. The hot clutter model introduced into the radar data model [12] has four main assumptions:

1. The $i_k$th clutter patch RCS characteristics from the scattered jammer waveform reflecting to the radar platform are assumed to be identical to the backscattered RCS reflecting back to the jammer platform. The RCS is actually either forward or diffuse scattering depending on the angle to the radar platform.

2. The direct path jammer signal is ignored. This research focuses only on interference reflecting from the ground.

3. The jammer backlobes are assumed to be $-\infty$ dB. Range rings at a greater distance from the radar than the jammer platform do not contain hot clutter.

4. The jammer and radar are moving with a associated velocity, but are stationary throughout the CPI. As the CPI only contains $M = 32$ pulses, the jammer and radar movement do not have a significant impact.
In this research, hot clutter is shown to have four main effects on the radar interference environment.

1. The power to each radar clutter patch changes with respect to the jammer array pattern and jammer transmit power.

2. The jammer velocity vector dictates the hot clutter normalized Doppler locations. Whether the jammer is side-looking, forward-looking, or simply flying at a crab angle, the velocity vector is responsible for both the relative velocity between the jammer and radar platform, and the relative velocity between the ground clutter and the jammer.

3. The jammer azimuth location with respect to the radar changes the jammer mainbeam location in Doppler. The jammer location in azimuth also changes the range and thus received interfering power to the radar clutter patches.

4. Though not addressed in this research, the jammer altitude effects hot clutter as well. The jammer altitude changes the elevation angle to the clutter patches and the clutter patch power and radar cross section. The relative velocities between the jammer and radar platforms are different; therefore, the hot clutter Doppler location changes.

In this research, hot clutter has is shown to have different effects on non-adaptive and adaptive radar performance based on the jammer velocity, azimuth, and range to the radar platform.

1. When the jammer has a velocity in the radar direction, the jammer mainbeam normalized Doppler location received by the radar changes with range. The worst case scenario is when the jammer flying directly towards the radar (oncoming (OC) scenario) in the radar mainbeam. The jammer mainbeam has a large Doppler dependence in the range cells close to the jammer making these range cells heterogeneous with one another. When the jammer is tangential (TN) to the radar direction, the jammer mainbeam does not change in normalized Doppler as the jammer does not have a velocity component in the radar
direction. Range cells close to the jammer are heterogeneous but not as severe as in a radar environment with an OC jammer flying directly into the radar mainbeam.

2. When the hot clutter is in the radar mainbeam, the adaptive filters are unable to spatially suppress the mainbeam jammer interference. This hot clutter jamming location in azimuth provides the largest performance degradation.

3. When the hot clutter jammer is in a radar sidelobe, the adaptive filters are able to suppress mainbeam interference. The only interference not suppressed by adaptive filters is the hot clutter interference located at some location in normalized Doppler in the radar look direction in azimuth.

Hot clutter caused maximum degradation in radar performance when the jammer mainbeam is in the radar look direction at $\phi = 0^\circ$. If the jammer is close to the RUT, and the jammer mainbeam changes from range cell to range cell, as in the OC jamming scenario, adaptive radar performance seriously degrades. The adaptive filters are unable to mitigate the mainbeam interference at $\phi = 0^\circ$. In addition, the sample support does not reflect the interference in the RUT, further corrupting the adaptive filters and degrading radar performance.

Hot clutter caused minimum degradation in radar performance when the jammer is not located in the radar mainbeam. Hot clutter in the radar look direction at $\phi = 0^\circ$ at some location in normalized Doppler degrades adaptive radar performance, as the filters cannot place nulls in the radar look direction. Though adaptive filters degrade in this location in Doppler in the radar look direction, they mitigate interference in the jammer mainbeam Doppler location. The radar performance improves up to 32-36 dB input SINR per element per pulse to achieve the same probability of detection using FTS and JDL adaptive filters over non-adaptive processing. This improvement in radar performance is for the OC jamming scenario $\phi = 45^\circ$, 72 Km from the radar. The adaptive filters are able to place a spatial null on the jammer mainbeam Doppler location thus greatly improves radar performance.
7.2 Recommendations for Future Work

The hot clutter covariance matrix is constructed in Chapter III. Although only two adaptive filters are examined in this research, a hot clutter model is created in this research effort to examine airborne radar performance in hot clutter using any adaptive filter. The radar data model [12] is powerful as it is able to isolate hot clutter interference.

One assumption in this research is the jammer and radar are at the same location in the radar environment throughout the coherent processing interval. The jammer range and velocity are constant. For a long coherent processing interval, the assumption might not be valid. The hot clutter model can be modified on a pulse-to-pulse basis for different flight paths to make the model more robust. The hot clutter model could also be modified to include the direct path jamming signal. Future work could also include adaptive filters created to mitigate the hot clutter in the mainbeam. The current clutter model uses the 4/3 Earth model. A more robust model could be created to characterize different ground reflectivity characteristics. The current model examines the worst case hot clutter scenario where the radar is not able to distinguish the scattered jammer returns from the radar returns. The model could be modified to make the hot clutter returns non-coherent with the jamming waveform. Depending on the waveform and the jammer transmit characteristics, the matched filter response will vary for coherent and non-coherent returns.

A simplifying assumption used in this research is the $i^k_{\text{th}}$ clutter patch RCS characteristics from the scattered jammer waveform reflecting to the radar platform are identical to the backscattered RCS reflecting back to the jammer platform. The backscattered RCS is calculated using the constant gamma model [8]. In reality, the scattered jammer waveform received by the radar from the $i^k_{\text{th}}$ clutter patch will be due to forward or diffuse scattering, whose statistics are not equivalent to backscattered monostatic clutter returns statistics. To more accurately portray the
hot clutter interference environment, a ground scatter model such as SCATS (Spatter, Clutter, and Target Signal Model) used in [9] and [10] needs to be implemented.
Bibliography


This research effort examines the theory, application and results of side-looking airborne radar operation in hot clutter. Hot clutter is an electronic counter-measure used to degrade the performance of airborne radar. Hot clutter occurs by illuminating the ground with an airborne jammer at some velocity, azimuth, elevation, and range from the airborne radar. When the received RCS scattered hot clutter waveform is perfectly coherent with the radar waveform, the radar believes the returns created by the hot clutter jammer resulted from the transmitting radar. Hot clutter degrades radar performance at locations in azimuth and Doppler. The effect of hot clutter is examined for side-looking airborne radar using adaptive and non-adaptive processing. Factored Time Space and Joint Domain Localized adaptive filters are shown to improve radar performance 32 to 36 dB per element per pulse, respectively, over non-adaptive processing in the mainbeam jammer normalized Doppler location when the jammer is not in the radar look direction in azimuth.