Outline

• Fully polarimetric SAR ATR

• Superresolution SAR ATR
  – Lincoln Lab Template-based Classifier
    Lincoln Lab High Definition Imaging (HDI)
  – 10-target/20-target Classifier Performance
  – Model-based Target Recognition System
    Extended Operating Conditions
  – Other Superresolution Algorithms

• SAR Change Detection
Lincoln Laboratory Journal

"The Automatic Target-Recognition System in SAIP"
GLOBAL HAWK
Unmanned Air Vehicle

SAR Resolution: 1.0 m × 1.0 m (Stripmap mode)
Area Coverage: 140,000 Km² / Day
Loiter Altitude: 65,000 ft
Range: 3000 nm Radius from Landing Base
Global Hawk SAR Imagery*

* "Global Hawk Relays Images Via Commercial Satellite," Aviation Week and Space Technology, 15 Feb 1999
ATR Performance – TEL Targets*

- False Alarms per km²
- Probability of Detection

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Clutter: 74 km² of Stockbridge, NY and Ayer, MA HH Polarization

* L.M. Novak, et al., "ATR Performance Using Enhanced Resolution SAR Data"
SPIE Conf. on Algorithms for SAR III, Orlando FL, April 1996
Semi-Automated Image Processing

Concept of Operation

Global Hawk UAV

Complex SAR Imagery

SAIP Van

Analyst Workstation
End-to-End System Block Diagram

Image Data → CFAR Detection → Targets and False Alarms

- Terrain Delimitation
- Change Detection
- Feature Extraction
- Cultural Clutter ID
- Spatial Clustering

TARGETS AND FALSE ALARMS

Target - Likeness Characterizations

D/T

Priority - Ordered Candidates

Templates

Classification, Confidence, Image Chip & Templates

HDI/MSE Classification

FSA

Image Analyst Review → Target Reports
MSE Classifier Block Diagram

2-D FFT Image Processing
(35 dB Sidelobe Weighting)

- 10-target classifier
  - Template based

- Performance metrics
  - Classifier confusion matrix
  - Probability of correct classification ($P_{CC}$)
Tactical Target Array
Tactical Target Set

Independent Test Data

Confuser Vehicles

BMP2 #1
M2 #1
T72 #1
BTR60
BTR70
M548

BMP2 #2
M2 #2
T72 #2
M1
M109
M110

BMP2 #3
M2 #3
T72 #3
M113

M35
HMMWV
Template Matching Concept

Test Input

Reference Library

Compare (MSE)

Best Match

M1
## Classifier Performance Results

**HH-Data, 0.3 m $\times$ 0.3 m Resolution ($P_{cc} = 93.9\%$)**

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- **Red**: Independent Test Data
- **Blue**: Confuser Vehicles (Not in Training Set)
# Classifier Performance Results

**HH-Data, 1.0 m × 1.0 m Resolution (P_cc = 45.4%)**

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[Independent Test Data] [Confuser Vehicles (Not in Training Set)]
MSE Classifier Block Diagram

HDI Image Processing

- 10-target classifier
  - Template based
- Performance metrics
  - Classifier confusion matrix
  - Probability of correct classification ($P_{CC}$)
M35 Truck Images

Conventional image
1 m × 1 m resolution

After HDI Processing
## Classifier Performance Results

**HDI-Processed 1.0 m × 1.0 m Resolution Data (P_{cc} = 73.4%)**

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- **Independent Test Data**
- **Confuser Vehicles (Not in Training Set)**
ATR Performance vs Resolution
10-Target MSE Classifier*

![Bar Chart]

Probability of Correct Classification

1.0 m HDI
1.0 m HDI
0.5 m HDI
0.3 m HDI
0.3 m HDI

45
73
84
94
97

Tactical Target Array
Tactical Targets Used in Training Set

- BMP2
- M110
- M548
- M520
- M978
- BTR60
- M113
- T72
- M577
- T62
- BTR70
- M1
- M35
- M60
- ZIL
- M109
- M2
- 2S1
- M88
- ZSU
T72 Intraclass Variability

T72 Tank

Skirts, No Barrels

No Skirts, Barrels

T62 Tank

No Skirts, Barrels
T72 Intraclass Variability

T72 (S/NB)  T72 (NS/B)  T62 (NS/B)

20°

170°
MSE Classifier Performance*

0.3 m × 0.3 m Resolution, HH Data

Number of Test Inputs: 5,195

Percent of Targets Classified As

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</tr>
<tr>
<td>M2 (2)</td>
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<td></td>
<td></td>
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<td>0.25</td>
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<tr>
<td>T72 (9)</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>94.0</td>
<td>5.0</td>
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10-Target Classifier  Pcc = 95.8%

Percent of Targets Classified As

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<th>BMP2</th>
<th>BTR60</th>
<th>BTR70</th>
<th>M109</th>
<th>M110</th>
<th>M113</th>
<th>M1</th>
<th>M2</th>
<th>M548</th>
<th>T72</th>
<th>M35</th>
<th>2S1</th>
<th>M520</th>
<th>M577</th>
<th>M60</th>
<th>M88</th>
<th>M978</th>
<th>T62</th>
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<th>ZSU</th>
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<tr>
<td>BTR70 (3)</td>
<td></td>
<td></td>
<td>91.5</td>
<td></td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.5</td>
<td></td>
<td>3.0</td>
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<td>M109 (4)</td>
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<tr>
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<td>2.25</td>
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<td></td>
<td>0.8</td>
<td>2.25</td>
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<td></td>
</tr>
<tr>
<td>T72 (9)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>91.0</td>
<td>0.2</td>
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</tbody>
</table>

20-Target Classifier  Pcc = 92.6%

* With additional T72 templates
MSE Classifier Confuser Rejection

0.3 m × 0.3 m Resolution

*Additional T72 templates
Typical Model-based ATR System
“Predict, Extract, Match, Search”

- **Input Image**
- **Feature Extraction**
- **Target Hypothesis List**
- **Search Hypothesis Management**
  - Hypothesis 1
  - Hypothesis 2
  - Hypothesis 3
- **On-line Signature Prediction**
  - Grayscale Signature
  - Labeled Regions
  - Peaks
  - CAD Model

**ATR Output**
ATR Performance Against Reveted Targets
Model-Based System vs. Templates

- M109’s:
  - 2 & 5 Ft Depth
- T72’s:
  - 2 & 4 Ft Depth
  - 15° Depression
  - 240 Test Inputs

MODEL-BASED TEMPLATES

\[ P_D \times P_{ID} \]
Performance of Model-Based System
M109 Target with Articulated Turret

Label Matching with Articulation Reasoning

Ave Pid: 0.93

2460 images
ATR Performance Using Other Superresolution Algorithms

• Description of superresolution algorithms
  – SAR superresolution processing — some basics

• Classifier performance using other superresolution algorithms
  – MSE classifier with “mean matching” used as baseline

• Improving ATR performance by fusion of classifier outputs

• Summary/Observations
M109 SAR Images
X-Band Data, HH-Polarization

0.3 m × 0.3 m HDI EV

SVA Super-SVA Music
## Multiresolution Classifier Performance

10-Target Classifier, 1,170 Independent Test Inputs  
1.0 m × 1.0 m Resolution, HH Data

<table>
<thead>
<tr>
<th>Method</th>
<th>Pcc</th>
<th>*3,086 Independent Test Inputs from Fall ‘95 and Fall ‘96 MSTAR Collections</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 m × 0.3 m Up Sampling (UP3)</td>
<td>54.5%</td>
<td>—</td>
</tr>
<tr>
<td>Spatially Varying Apodization (SVA3)</td>
<td>46.8%</td>
<td>—</td>
</tr>
<tr>
<td>Super SVA (SSVA3)</td>
<td>21.8%</td>
<td>—</td>
</tr>
<tr>
<td>Super SVA/Median Filtering (SSVA3/MF)</td>
<td>46.2%</td>
<td>—</td>
</tr>
<tr>
<td>MUSIC (MU3)</td>
<td>46.8%</td>
<td>—</td>
</tr>
<tr>
<td>Eigenvector (EV3)</td>
<td>67.1%</td>
<td>71.2%*</td>
</tr>
<tr>
<td>High Definition Imaging (HDI3)</td>
<td>66.2%</td>
<td>71.5%*</td>
</tr>
<tr>
<td>Fused HDI3/EV3</td>
<td>72.9%</td>
<td>77.3%*</td>
</tr>
</tbody>
</table>

* 3,086 Independent Test Inputs from Fall ‘95 and Fall ‘96 MSTAR Collections
Confuser Vehicles Used in 10-Target Classifier Studies

- 2S1
- BRDM-2
- D7
- M520
- M577
- M60
- M88
- M978
- T62
- ZIL-131
- ZSU23
• 10-target classifier performance results were evaluated using 1.0 m x 1.0 m resolution SAR imagery

• Classifier performance was compared using different image enhancement techniques; algorithms were tested against:
  – 3086 independent test target images
  – 3398 independent confuser vehicle images

• Each classifier’s threshold was adjusted to give identical confuser rejection performance ($P_{REJ} = 56\%$)

• HDI/MSE classifier obtained $P_{CC} = 71.5\%$

• EV/MSE classifier obtained $P_{CC} = 71.2\%$

• Fusion of HDI and EV classifiers gave $P_{CC} = 77.3\%$
“HDI/PWF” Processing

• PWF processing of fully polarimetric SAR imagery has been shown to provide significantly improved ATR performance vs single-channel SAR

• Superresolution processing of single-channel SAR imagery has been shown to provide significantly improved ATR performance vs 2-D FFT processing

• The “best of all worlds”
  – Superresolution processing of fully polarimetric SAR data
  – “HDI/PWF” processing
Superresolution Processing of Fully Polarimetric SAR Imagery

Superresolution Algorithms:
- HDI
- MVM
- EV
- SVA
- SSVA
- MUSIC
- ...

\[ y = |HH|^2 + \frac{|HV|}{\sqrt{\epsilon}}^2 + \frac{|VV - \rho \star \sqrt{\gamma} HH|}{\sqrt{\gamma(1 - |\rho|^2)}}^2 \]
Lincoln North Building: HDI/PWF-Processed
Some Lessons Learned

• Good image quality is required for good ATR performance
  – We need to develop an image quality metric
  – Image quality should be reflected in the confidence of the ATR decision

• A theory of ATR must be developed!!
  – What are the ATR trade-offs between sensor resolution, polarization, image quality, ...
  – How well should an algorithm be doing?
  – Can we predict ATR performance versus the number of target classes?
Good Image Quality is Required for Good ATR Performance

M35 Truck

???
Target “Intrinsic Separability” Studies

- Actual performance of various 5-target classifiers depends on intrinsic separability of the targets
  - Easy target set: ZSU, M88, M9, M35, M109
  - Hard target set: T72, M60, M2, M113, M577

- Using available data of 14 targets, classifier performance for every possible combination of 5 targets was evaluated

\[
\binom{14}{5} = \frac{14!}{(14 - 5)! \cdot 5!} = 2002 \text{ unique 5-target classifiers}
\]

- Classifier training data: Turntable
- Classifier test data: Airborne
14 Targets used in “Intrinsic Separability” Studies

Hard Target Set:
- T72
- M60
- M2
- M113
- M577

Easy Target Set:
- ZSU-23
- M88
- M9
- M35
- M109

Additional Targets:
- 2S1
- 2S3
- SA-9
- SA-13
Intrinsic Target Separability
5-Target Classifiers

Average $P_{cc} = 51.3\%$

- Tank: T72
- Tank: M60
- APC: M2
- APC: M113
- APC: M577
- ZSU: AAG
- M88: Tank Wrecker
- M9: Bulldozer
- M35: Truck
- M109: SPG

Probability of Correct Classification (%)
Intrinsic Target Separability
5-Target vs 10-Target Classifiers

Ave $P_{CC} = 35.1\%$

Ave $P_{CC} = 51.3\%$
Summary – Intrinsic Target Separability Studies

• Classifier performance depends on:
  – The number of targets in classifier training set (5, 10, 20, ... targets)
  – The actual target types in classifier training set, e.g.,
    Easy target set: ZSU, M88, M9, M35, M109
    Hard target set: T72, M60, M2, M113, M577
  – Classifier training data (turntable data, models, ... )

• 5-target vs 10-target classifier performance summary:

<table>
<thead>
<tr>
<th></th>
<th>5-targets</th>
<th>10-targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Pcc</td>
<td>68.5%</td>
<td>42.3%</td>
</tr>
<tr>
<td>Ave Pcc</td>
<td>51.3%</td>
<td>35.1%</td>
</tr>
<tr>
<td>Min Pcc</td>
<td>35.2%</td>
<td>27.0%</td>
</tr>
</tbody>
</table>