Intelligence, Surveillance and Reconnaissance

From Physics to the Physical – A Systems Perspective

Eric R. Keydel, Chief Scientist
Science Applications International Corporation
3600 Green Ct., Suite 650
Ann Arbor, MI 48105
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Overview

• Synthetic aperture radar today
  • Sensing and imaging
  • Exploitation

• Relevant phenomenology
  • SAR imaging
  • Shape/structure

• Shape recovery
  • Inverse Path
  • History
  • Components
  • Gaps
  • Areas Needing More Research
Active
Don’t have to worry about the sun

All-Weather:
Don’t have to worry about weather/clouds

Many Applications
Environmental Monitoring
Crops/Land Cover Assessment
Sea Ice Monitoring
DTED Extraction

....

Vehicles, Objects

Examples
RADARSAT
SIR-C
SRTM
ERS
Global Hawk

....

Courtesy of the Environmental Research Institute of Michigan
SAR Sensing Is Mature

- Sensors are becoming small and lightweight (<30lb)
- Image formation can be done in near real time onboard
- Systems are deployed on both manned and unmanned platforms
- Image quality is becoming exquisite
- Advanced collection modes and diversity are emerging
Examples: Scenes Vehicles

Albuquerque Airport (Ka-band, 1m)

Isleta Lake (X-band, 1m)

National Guard Vehicle Lot (Ka-band, 4 in)

Maricopa Agricultural Center (Ku-band, 1m)
Examples: Real-time Onboard Image Formation
Sandia MINI-SAR: Ku-band, 27lb

C130: (4 inch)  
Vehicles: (12 inch)

DC-3, Helicopter Static Display (4 inch)  
Baseball Field KAFB (4 inch)

Imagery provided by Sandia National Laboratory (http://www.sandia.gov/RADAR/imagery.html)  
Used with permission
Examples: 360 Deg Continuous Collect
GOTCHA Radar
Even with spectacular quality, SAR imagery from SAR systems isn’t literal and must be “interpreted”
How We Exploit SAR Today

- Sensing Hardware
  - Antenna
  - Receiver
  - A/D
  - ...

- Imaging/Processing
  - Mocomp
  - Impulse Response
  - Image Plane
  - Projection
  - ...

- Display
  - Detection
  - Dynamic Range Mapping
  - ...

- We Model the Sensing Transformation
  - Analyst Training
  - Reference Data Collections
  - Signature Predictions from Models

- We infer what the unknown is (hypothesize and test)

- Object Exemplars

- EM Interactions

- They don’t look anything like each other

- Signature References

- Match and Score
  - Keys
  - Templates
  - Predictions

- MSTAR Public Data Set

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Comments On Today’s SAR Exploitation

• Using analysts
  • Extensive interpretation training
  • In-depth domain expertise
  • Reference signature keys

• Using measured reference data
  • Collections must be representative/inclusive
  • Confounded when unknown signature/reference data set

• Using computer-generated templates
  • Exemplar CAD models: labor intensive
  • Sensor prediction models: must have fidelity

• Match and score
  • Sophisticated reasoning logic
What If

Collected Radar Signals

EM Interactions

The sensing transformation

Shape recovery exploitation (SRE)

Direct analysis Interpretation

- Literal view
- Reduced need for deep SAR domain expertise

Excellent focused research has already provided key components for SRE
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Object Electromagnetic Interactions

Object signature determined by backscattered signal:
- Incident waveform
- Specific object geometry
- Background characteristics

Interactions

Multiple mechanisms contribute to backscattered signal

Elementary Structural Scattering Mechanisms

- TOP HAT
- DIHEDRAL
- FLAT PLATE
- CYLINDER
- ELLIPSOID

EPC: “Effective Phase Center”
**Signal Model**

- **Response from n\(^{th}\) elementary scatterer (ab\(^{th}\) polarization channel)**

\[
E_{n}^{ab} (f, \phi) = s_{n}^{ab} (f, \phi) e^{-j\psi(R_n, f)}
\]

- **Signal collected over the synthetic aperture (m\(^{th}\) aspect on object)**

\[
S_{m}^{ab} (f, \phi(t)) = w(f, t) K \sum_{n=1}^{N} E_{n}^{ab} (f, \phi(t), \theta_m)
\]

- **Function of:**
  - Size
  - Orientation
  - Shape
  - Material
  - Frequency
  - Polarization

- **Function of:**
  - Range
  - Frequency

- **Aperture weighting**
- **Radar constants**
- **Scatterer amplitude**
- **Scatterer phase**

\( \Delta \theta \): Angle subtended by synthetic aperture

\( \theta_m \): Aspect on object at aperture center
SAR Image Plane Projection

• SAR slant plane: contains line-of-sight and velocity vector

• Image pixels: coherent superposition of scatterer contributions along ambiguity contour slant plane

Effects of Depression Angle Variation

Simulator : Xpatcht
Object : M60 tank
Aspect : 135 dg
Squint : 90 deg
Resolution : 1 ft
Frequency : X-band
Background : Imperfect conductor random ripples

Impacts ambiguity of 3-D object geometry in slant SAR plane
Pixel Scintillation

Simulator: Xpatcht
Object: M60 tank
Squint: 90 deg
Resolution: 1 ft
Frequency: X-band
Background: Imperfect conductor with random ripples

Depression Angle (deg)
17
20
23

Range
-123 -120 -117

Object Pose (deg)

Scatterer Phasors

Coherent Sum Amplitude

Causes amplitude fluctuations in pixels containing the same scatterers

Object Representation with Primitive Scatterers

BRL-CAD Model

Radar Reflector Extractor (RAREX)

T72 Reflector Model

Color Coded Based on Reflector Type

Plates

Trihedrals

Dihedrals

Tophats

Cones

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Signature Synthesized from Primitive Scatterers

**Full Primitive Model**

- Aspect: -135
- Depr: 30
- Squint: -90

**WIDE APPLICATION SIGNATURE PREDICTOR (WASP)**

- Primitives capture most relevant phenomenology for *forward* predictions of complex objects
- Challenge for SRE is to recover primitives from collected radar data
Recovering Structure Parameters

• Given the original model (with aperture centered around at the $m^{th}$ aspect)

$$S_m^{ab}(f, \phi(t)) = w(f, t)K \sum_{n=1}^{N} E_n^{ab}(f, \phi(t), \theta_m)$$

- Aperture Weighting
- Radar Constants

$$t \in \left[ -\frac{T}{2}, \frac{T}{2} \right]$$
$$\phi \in \left[ \theta_m - \frac{\Delta\theta}{2}, \theta_m + \frac{\Delta\theta}{2} \right]$$
$$f \in \left[ f_a - \frac{BW}{2}, f_a + \frac{BW}{2} \right]$$

• Postulate this (at aspect $\theta_m$, $ab^{th}$ polarization (Tx a, Rx b))

$$E_n^{ab}(f, \phi, \theta_m) = S_n^{ab}(\theta_m) \left( j \frac{f}{f_c} \right)^{\alpha_n} A(f, \phi, \theta_m)e^{-\frac{j4\pi}{c}(x_n\cos\phi + y_n\sin\phi)}$$

- Polarization Dependence (Shape)
- Frequency Dependence (Curvature)
- Angular Dependence (Dimensions)
- Location Dependence

• Estimate these:

$$S_n^{ab}(\theta_m) \left( j \frac{f}{f_c} \right)^{\alpha_n} A(f, \phi, \theta_m)e^{-\frac{j4\pi}{c}(x_n\cos\phi + y_n\sin\phi)}$$

$m = 1, ..., M_{aspects}$
Angle and Frequency Response Interpretation

\[ E_n^{ab} (f, \phi, \theta_m) = S_n^{ab} (\theta_m) \left( j \frac{f}{f_c} \right)^{\alpha_n} A(f, \phi, \theta_m) e^{-j \frac{4\pi f}{c} (x_n \cos \phi + y_n \sin \phi)} \]

**FREQUENCY DEPENDENCE**
(Relates to Local Structure)

<table>
<thead>
<tr>
<th>FREQUENCY EXPONENT, (\alpha)</th>
<th>LOCAL SCATTERING GEOMETRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>Corner</td>
</tr>
<tr>
<td>-1/2</td>
<td>Edge</td>
</tr>
<tr>
<td>0</td>
<td>Point Scatterer, Doubly-Curved Surface</td>
</tr>
<tr>
<td>1/2</td>
<td>Singly-Curved Surface</td>
</tr>
<tr>
<td>1</td>
<td>Flat Surface</td>
</tr>
</tbody>
</table>

**AMPLITUDE DEPENDENCE**
(Relates to Dimensions, Area)

\[ \sigma = \frac{2\sqrt{\pi ab}}{\lambda} \cos(\theta) \begin{bmatrix} \sin(kas\cos \phi) \\ kas \cos \phi \end{bmatrix} \begin{bmatrix} \sin(kbs\sin \theta \sin \phi) \\ kbs \sin \theta \sin \phi \end{bmatrix} \]

Analogies hold for other structures

**ANGULAR DEPENDENCE**
(Relates to AzimuthExtent)

\[ \theta = 0.5 \frac{\lambda}{b} \]

\[ \phi = 0 \rightarrow \theta = 0.22 \frac{\lambda}{b} \]

\[ \theta = 0.5 \frac{\lambda}{b} \]
Polarimetric Response Interpretation: 
Huynen Decomposition*

Descriptors computed from complex polarimetric scattering matrix

$\varphi$: orientation angle $\ -90^\circ < \varphi < 90^\circ$

$\tau$: helicity angle $\ -45^\circ < \tau < 45^\circ$

$\nu$: skip angle $\ -45^\circ < \nu < 45^\circ$

$\gamma$: polarizability angle $\ -45^\circ < \gamma < 45^\circ$

$\varphi = 0^\circ$: symmetric

$\varphi = 45^\circ$: non-symmetric

$\nu = 0^\circ$: odd bounce

$\nu = 45^\circ$: even bounce

$\gamma = 0^\circ$: full polarizability

$\gamma = 45^\circ$: no polarizability

* One of several polarimetric decompositions derived from polarization scattering matrix $[ S^{aa}, S^{ab}, S^{ba}, S^{bb}]$
Polarimetric Response Interpretation:
Poincare Sphere Mapping

Descriptors computed from complex polarimetric scattering matrix

<table>
<thead>
<tr>
<th>$\Psi_c$</th>
<th>$\chi_c$</th>
<th>Scatterer Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0°</td>
<td>Plate / Trihedral</td>
</tr>
<tr>
<td>18°</td>
<td>0°</td>
<td>Cylinder</td>
</tr>
<tr>
<td>45°</td>
<td>0°</td>
<td>Dipole</td>
</tr>
<tr>
<td>90°</td>
<td>0°</td>
<td>Dihedral</td>
</tr>
<tr>
<td>Any</td>
<td>+/- 45°</td>
<td>Helix</td>
</tr>
</tbody>
</table>
One Taxonomy for Shape Recovery

Angular Response

Odd Bounce
\( \nu = 0^\circ \)
Even Bounce
\( \nu = 45^\circ \)

Skip Angle \( \nu \)

Poincare Sphere Coordinates \( (\psi_c, \chi_c) \)

Odd Bounce
\( \psi_c \approx 0^\circ \)
Even Bounce
\( \psi_c \approx 90^\circ \)

Odd Bounce
\( \psi_c \approx 0^\circ \)
Even Bounce
\( \psi_c \approx 90^\circ \)

Even Bounce
\( \psi_c \approx 45^\circ \)

Primitive Types

Flat Plate
\( \alpha = 1 \)
Horizontal Cylinder
\( \alpha = 1/2 \)
Horizontal Dihedral
\( \alpha = 1 \)
Trihedral
\( \alpha = 1 \)
Vertical Dihedral
\( \alpha = 1 \)
Vertical Cylinder
\( \alpha = 1/2 \)
Tophat
\( \alpha = 1/2 \)

Ambiguous Without Polarimetric Data

Huynen Parameters Computed from Polarimetric Response

\( \alpha = 1 \)
\( \alpha = 1/2 \)
\( \alpha = 1 \)
\( \alpha = 1/2 \)
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  • Inverse Path
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  • Gaps
  • Areas Needing More Research
## Inverse Path

### Mechanisms

\[
w(f, t)K \sum_{n=1}^{N} E^a_n(f, \phi(t), \theta_m) \sum_{n=1}^{N} E^b_n(f, \phi(t), \theta_m) S^b_n(\theta), a_n, A(f, \phi, \theta) \]

### Sensing

- Collect Mode
- Mocomp Acquisition
- Geometry Resolution
  
### Sensor Capabilities

- Calibration data
- Processing Design

### Collect Mode

- Calibrate
- Remove Weighting
- ... 

### Mocomp Acquisition

- Estimate Parameters
- Derive Mechanisms

### Geometry Resolution

- Resolve \( z \)
- Refine \((x, y, z)\)

### INFLUENCES/ENABLERS

- Trajectory Diversity
- Navigation Accuracy
- Exquisite Registration
- Navigation Accuracy

- Uncertainty Models in all Parameters
- Geometric reasoning under uncertainty

- Display
- Inferred surface display

### System Design

- Sensor Capabilities
- Frequency

- Polarimetry
- Bandwidth

- Aspects
- Altitudes

- Navigator Quality

### Frequency

- Trajectory Diversity

- Navigation Accuracy

### Polarimetry

- Exquisite Registration

### Bandwidth

- Navigation Accuracy

### Aspects

- Uncertainty Models in all Parameters

### Altitudes

- Geometric reasoning under uncertainty

### Navigator Quality

- Display

### Display

- Mensurate

### Mensurate

- Assess

### Transition:

- Ideal → Actual

### Infer Surfaces

### Display

- Mensurate

### Assess

### INFER SPOUTS

### ESTABLISH SPATIAL RELATIONS

### DEFINE CANDIDATE SHAPES

### SCULPT INTO MODEL

### ANALYST DISPLAY/DECISION AIDS
Early History*


Remaining discussion focuses on recent advances building on this foundation.

* Representative and a only subset of prior research
Polarimetric Analysis
Huynen Parameter Estimation: Slicey

Polarization Angle - $\gamma$
Symmetry Angle - $\tau$
Skip Angle - $\nu$

Data:
Polarimetric X-band SLICEY data
Nominal elevation: 20°
linear polarization basis
rotated 30 deg. W.r.t. horizontal

Blue - odd bounce
Red - even bounce

Created by N Subotic, J,W. Burns, Michigan Tech Research Institute,
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Impact of Elevation Angle:
Changing Angle Changes Scattering

Polarimetric X-band SLICEY data
linear polarization basis
rotated 30 deg. W.r.t. horizontal

Created by N Subotic, J.W. Burns, Michigan Tech Research Institute,
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Attributed Scatterers to Sort Out Layover

2D, 22cm, and 3cm res Synthetic Data

Kerry Dungan, Christian Austin, John Nehrbass, Lee C. Potter, “Civilian Vehicle Radar Data Domes, SPIE1-a Poster
Used with permission of authors

360 deg coverage Gotcha data

Gotcha public release data

8 passes, HH & VV

Odd bounce
Even bounce

Used with permission of authors
Julie Ann Jackson and Randolph L. Moses, “Feature Extraction Algorithm for 3D Scene Modeling and Visualization Using Monostatic SAR, Ohio State University, Dept of Electrical and Computer Engineering Used with permission of authors
Multi-dimensional Attribute Extraction
Interferometric Processing for 3-D

Julie Ann Jackson and Randolph L. Moses, “Feature Extraction Algorithm for 3D Scene Modeling and Visualization Using Monostatic SAR, Ohio State University, Dept of Electrical and Computer Engineering
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Shape Estimation

Example Results

Turntable Data

SAR Image
Complex Phase History

Wideband
Wide Angle
Polarimetric

Extracted Scattering Primitives
Re-Constructed Surface
Predicted

More Likely
Less Likely

COMPLEX PHASE HISTORY EXPLOITATION
AMBIGUITY MANAGEMENT
CAD RECONSTRUCTION

Elementary Primitives
Plausible Relationships

Original Object
Measured

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Surface Reconstruction

- Combine structures from multiple views
- Bootstrap surface boundary
- Refine surface boundary
  - Surface extension
  - “Shrink-Wrap”
  - Block sculpture
  - Surface draping

Local physical structures and 3-D locations

Object model
- Local physical surfaces
- Occlusion boundaries
- Uncertainties

Stage 1

Stage 2

Stage 3
Key elements that enable SRE are supported by a strong research base and demonstrated proof of concept:
- Theory and practice supporting mechanism extraction have been verified in the lab
- Prototype sensing systems (e.g., Gotcha) that support these techniques are flying
  - Initial SRE components have been demonstrated using them

Modern synthetic aperture radar sensing and imaging technology produces exquisite data and images:
- Manned and unmanned systems, onboard processing, smaller and smaller SWaP
- A major advance over early systems that were flying when SRE research began (~ 1995)

Significant advantages could accrue if SRE could become part of mainstream exploitation:
- Literal object-like outputs
- Revolutionized object recognition and high confidence declaration

SRE needs now to be thought about and developed in a system context:
- Fill in weak research areas
- Make demonstrated capabilities robust to real-world collection system issues
System-Level Considerations

**CONDITION SIGNAL**
- Collect Mode
- Mocomp
- Acquisition
- Geometry
- Resolution

**DECOMPOSE SIGNAL**
- Calibrate
- Remove Weighting
- Derive Mechanisms

**PUT INTO 3-D**
- Resolve z
- Refine (x,y,z)

**ESTABLISH SPATIAL RELATIONS**
- Register to Common Frame

**DEFINE CANDIDATE SHAPES**
- Manage Ambiguities

**SCULPT INTO MODEL**
- Transition: Ideal → Actual
- Infer Surfaces

**ANALYST DISPLAY/DECISION AIDS**
- Display Mensurate
- Assess

### SYSTEM-LEVEL DEPENDENCIES

**Mechanisms**
- Sensing Diversity
- Trajectory Diversity
- Navigation Accuracy
- Exquisite Registration
- Uncertainty Models in all Parameters
- Geometric reasoning under uncertainty

**Primitives**
- Sensor Capabilities
- System Design Info
- Calibration data
- Available Diversity
- Collection/Tasking Degrees of Freedom
- INS Accuracy/Sampling

**System Design Info**
- Sensing Diversity
- Trajectory Diversity
- Navigation Accuracy
- Exquisite Registration
- Uncertainty Models in all Parameters

**Available Diversity**
- System Design
- Collection/Tasking Degrees of Freedom

**Mechanism Uncertainties/Ambiguities**
- Bandwidth
- Polarization
- Altitudes

**Shape/geometry Uncertainty Representation**
- Shape/geometry uncertainty
- Representation

**Display Inferred surface display**

$$w(f,t)K \sum_{n=1}^{N} E_n^{ab}(f,\phi(t),\theta_m) \sum_{n=1}^{N} E_n^{ab}(f,\phi(t),\theta_m) S_n^{ab}(\theta_i), a_n, A(f,\phi,\theta_i)$$
## Areas Needing More Research

The diagram illustrates the system-level dependencies and the need for more research in various areas. The dependencies are outlined in a flowchart format, with each step leading to the next, highlighting the flow of information and processes involved. The steps include:

1. **Sensing**
   - Collect Mode Mocomp
   - Acquisition Geometry Resolution

2. **Condition Signal**
   - Calibrate Remove Weighting

3. **Decompose Signal**
   - Estimate Parameters Derive Mechanisms

4. **Put into 3-D**
   - Resolve z Refine (x,y,z)

5. **Establish Spatial Relations**
   - Register to Common Frame

6. **Define Candidate Shapes**
   - Manage Ambiguities
   - Transition: Ideal ➔ Actual Infer Surfaces

7. **Sculpt into Model**
   - Constrained surface definition under uncertainty

8. **Analyst Display/Decision Aids**
   - New user interface concepts

### System-Level Dependencies

The diagram includes a series of dependencies and factors that need further research:

- **Sensing Diversity in Operational Systems**
- **Increase Diversity in Operational Systems**
- **System Design Info**
- **Sensor Capabilities**
- **System Design Frequency Polarimetry Bandwidth Aspects Altitudes Navigator Quality**
- **Collection/Tasking Degrees of Freedom**
- **INS Accuracy/Sampling**
- **Mechanism Uncertainties/Ambiguities**
- **Performance within constrained diversity**
- **Performance w/o IFSAR and as function of INS**
- **Trajectory Diversity Navigation Accuracy**
- **Exquisite Registration Navigation Accuracy**
- **Uncertainty Models in all Parameters**
- **Shape/Gallery under mechanism uncertainty**
- **Shape/Gallery Representation under uncertainty**

The flowchart provides a visual representation of the dependencies and the need for further research in these areas.
Thoughts -1

Condition Signal

*Work within operational system information constraints*
Develop algorithms that in context of non-ideal assumptions about the data signal model

Decompose Signal

*Performance within constrained diversity*
Develop algorithms that claw back against diversity limitations that may be characteristic of current flying systems: meaningful uncertainty characterization

Put Into 3-D

*Work without IFSAR assumption and as function of INS quality*
Explore alternatives to getting 3-D; e.g. trajectory diversity/other, feedforward to how sensors collect

Establish Spatial Relationships

*Automated turnkey registration and refinement*
Tackle exquisite registration at scatterer level
Thoughts-2

Define Candidate Shapes

*Shape definition under mechanism uncertainty*
Develop calculus/framework for dealing with shape ambiguities resulting from uncertain or incomplete scattering mechanism definition (e.g. due to limited diversity, noise...)

Sculpt Into Model

*Constrained surface definition under uncertainty*
Develop rigorous framework for converting (possibly uncertain) elementary primitives into model conforming to real-object constraints (closure, connectedness....)

Analyst Display/Decision Aids

*New user interface options*
SRE would be a new way of presenting data for interpretation; what are the best ways to use it?