Intelligence, Surveillance and Reconnaissance

From Physics to the Physical – A Systems Perspective

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NATIONAL SECURITY • ENERGY & ENVIRONMENT • HEALTH • CYBERSECURITY

Overview

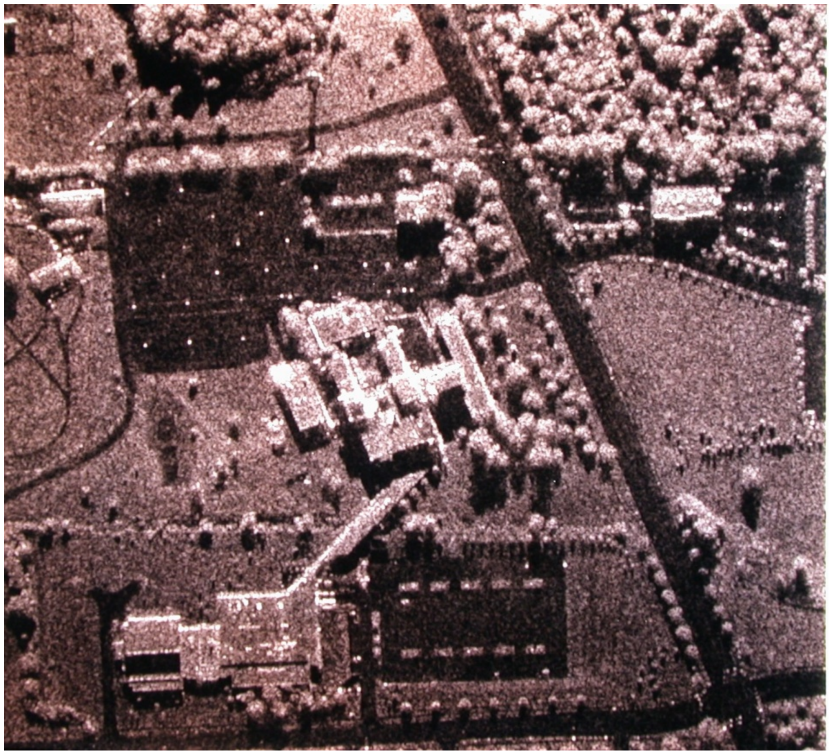
- **Synthetic aperture radar today**
  - **Sensing and imaging**
  - **Exploitation**

- Relevant phenomenology
  - SAR imaging
  - Shape/structure

- Shape recovery
  - Inverse Path
  - History
  - Components
  - Gaps
  - Areas Needing More Research

Synthetic Aperture Radar Today

EARLY EXAMPLE


Courtesy of the Environmental Research Institute of Michigan

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

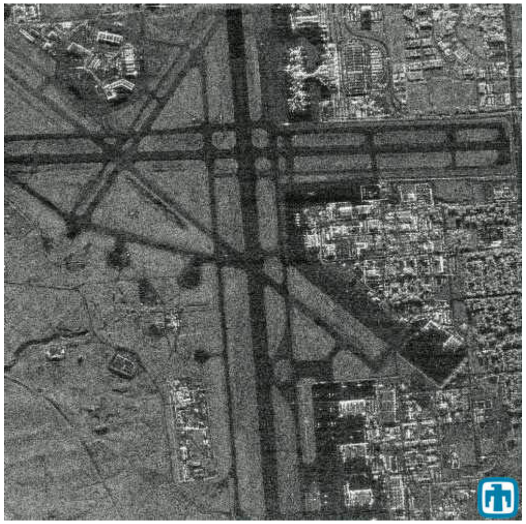
EXAMPLES
- RADARSAT
- SIR-C
- SRTM
- ERS
- Global Hawk
- ....

SAR Sensing Is Mature

- Sensors are becoming small and lightweight (<30lb)
- Image formation can 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

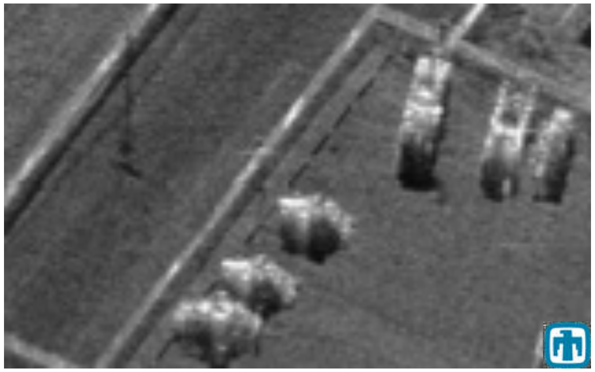
Examples: Scenes Vehicles

Albuquerque Airport (Ka-band, 1m)

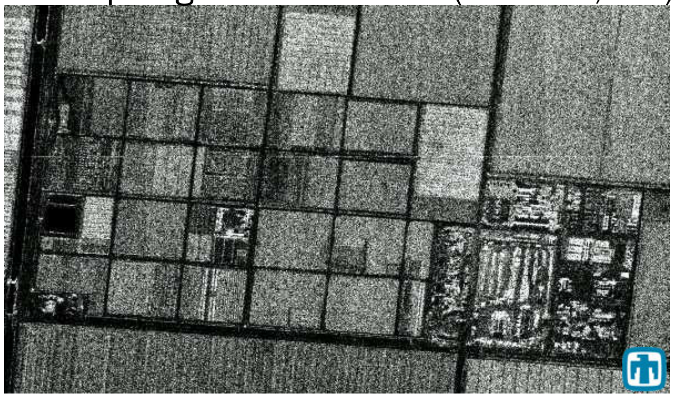


Isleta Lake (X-band, 1m)

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



Maricopa Agricultural Center (Ku-band, 1m)



Imagery provided by Sandia National Laboratory (http://www.sandia.gov/RADAR/imagery.html)
Used with permission

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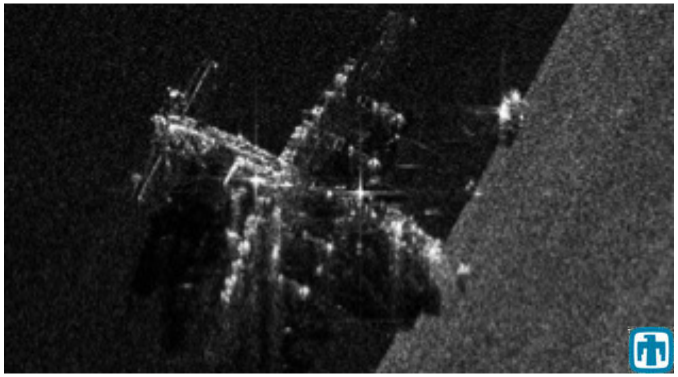
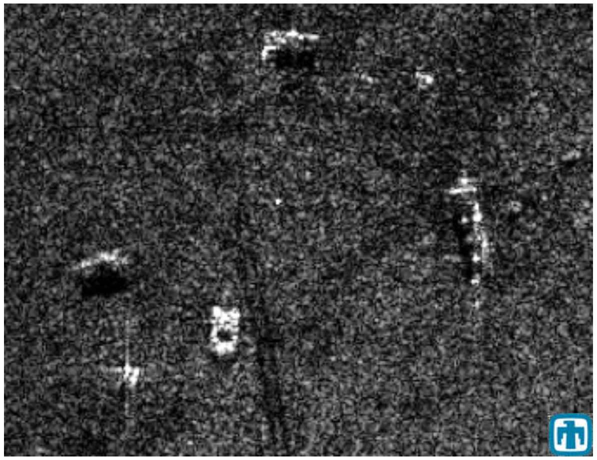
Examples: Real-time Onboard Image Formation

Sandia MINI-SAR: Ku-band, 27lb

C130: (4 inch)



Vehicles: (12 inch)



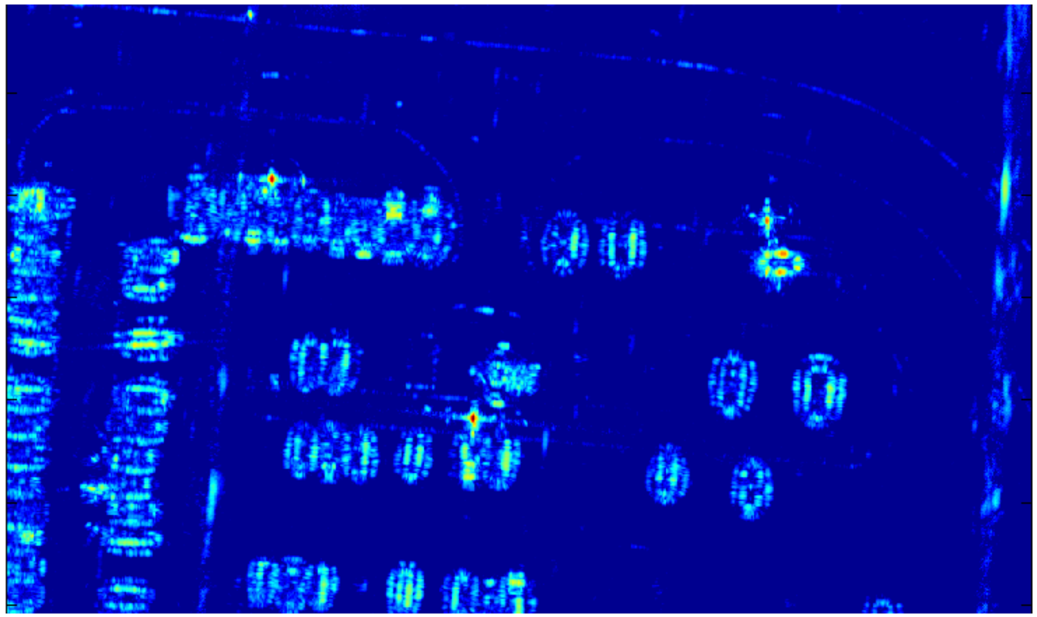
DC-3, Helicopter Static Display (4 inch)

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



Traditional SAR Imaging

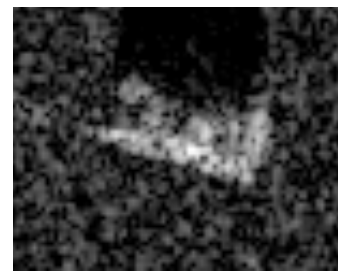
Sensing Hardware
- Antenna
- Receiver
- A/D
- ….

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

Display
- Detection
- Dynamic Range Mapping
- …

EM Interactions

They don't look anything like each other



MSTAR Public Data Set

Even with spectacular quality, SAR imagery from SAR systems isn't literal and must be "interpreted"

Imagery provided by Sandia National Laboratory (http://www.sandia.gov/RADAR/imagery.html)
Used with permission

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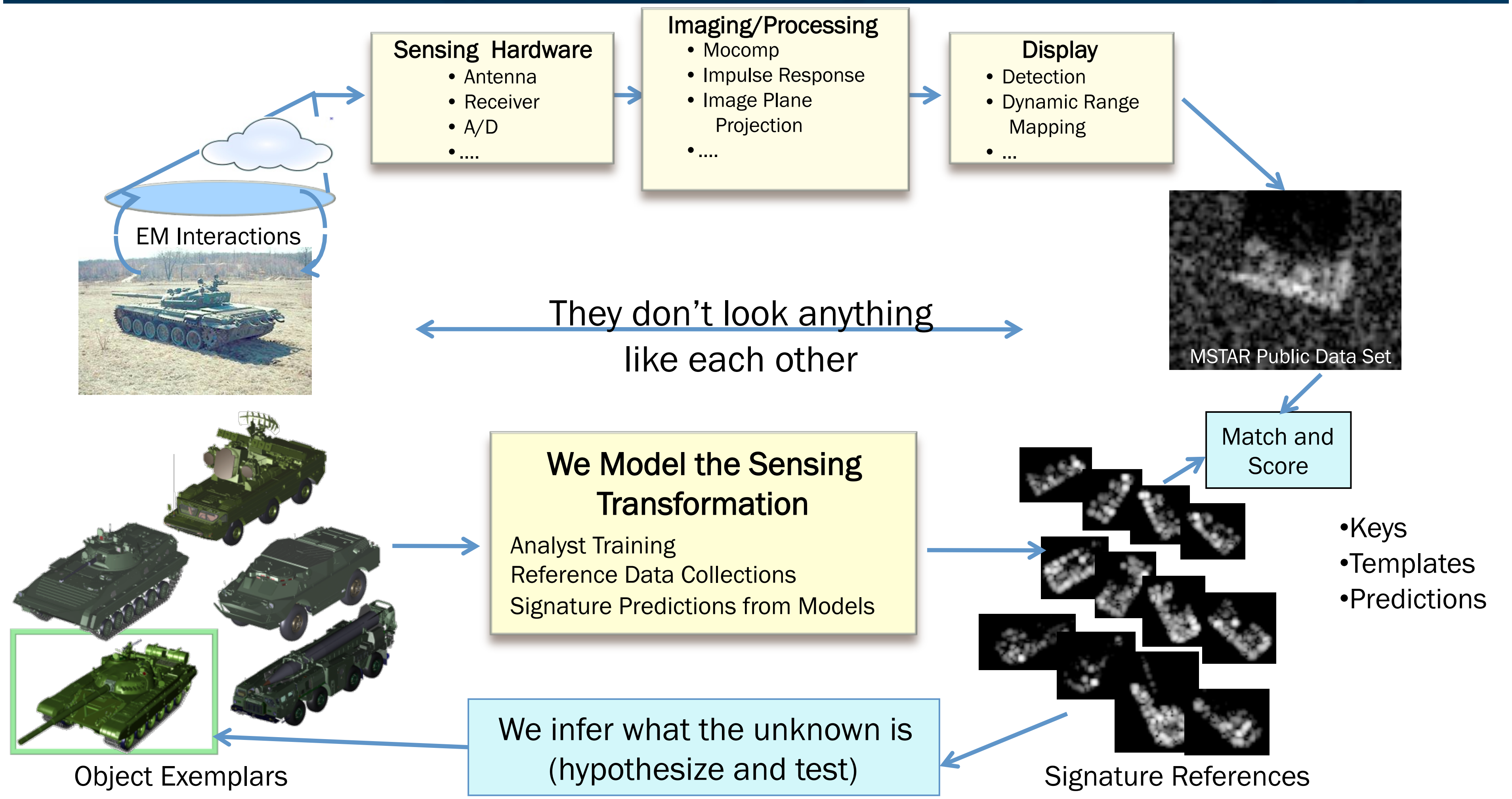
How We Exploit SAR Today



Comments On Today's SAR Exploitation

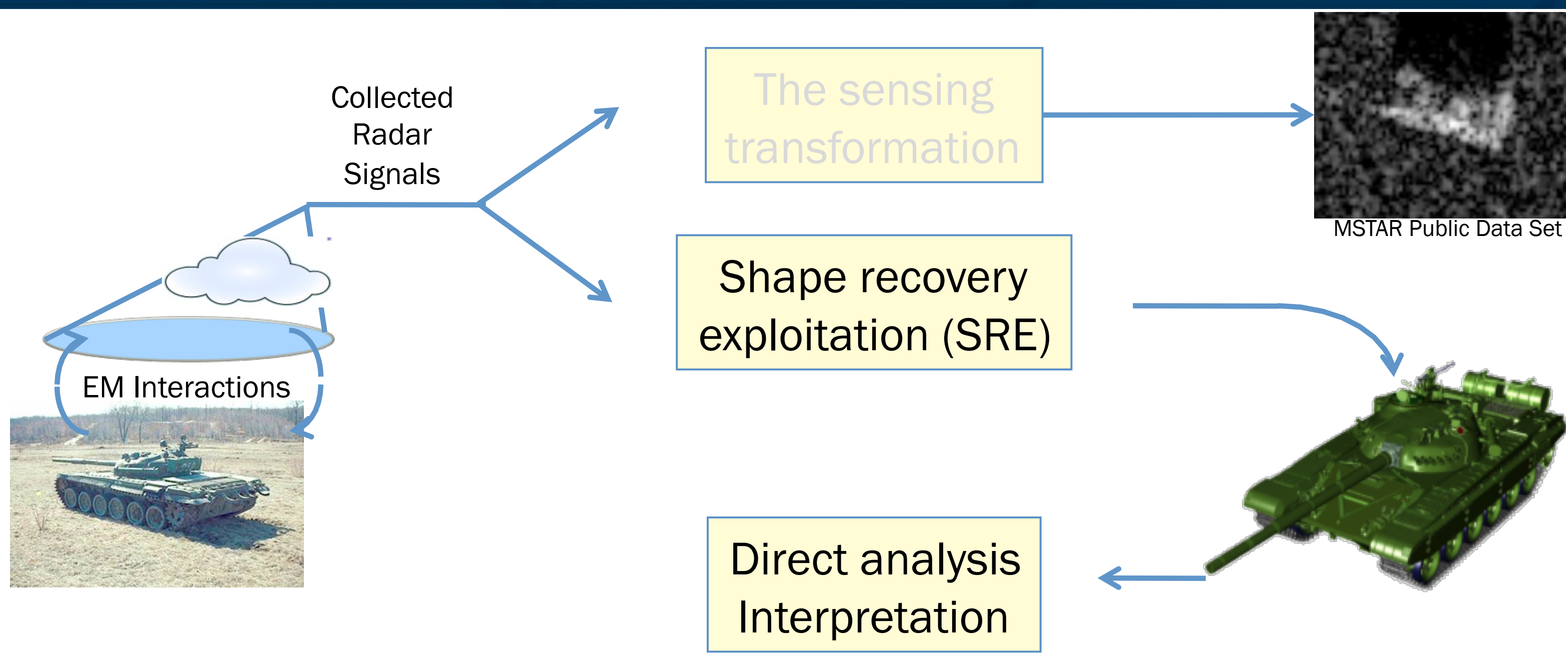
- Using analysts
  - Extensive interpretation training
  - In-depth domain expertise
  - Reference signature keys

- Using measured reference data
  - Collections must be representative/inclusive
  - Confounded when unknown signature $\notin$ 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



- Literal view
- Reduced need for deep SAR domain expertise

Excellent focused research has already provided key components for SRE

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  - **SAR imaging**
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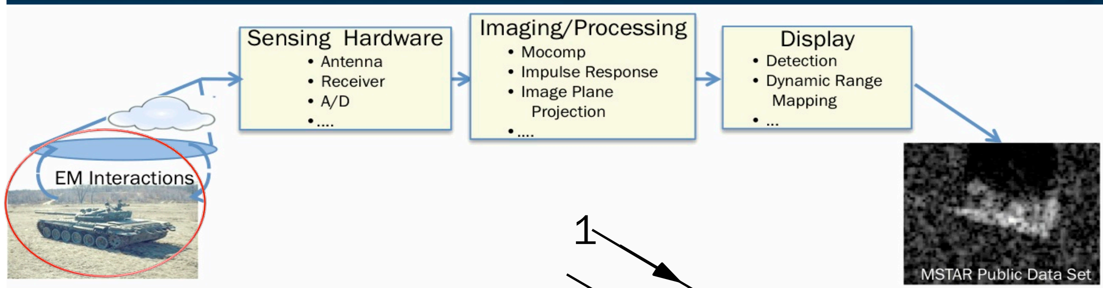
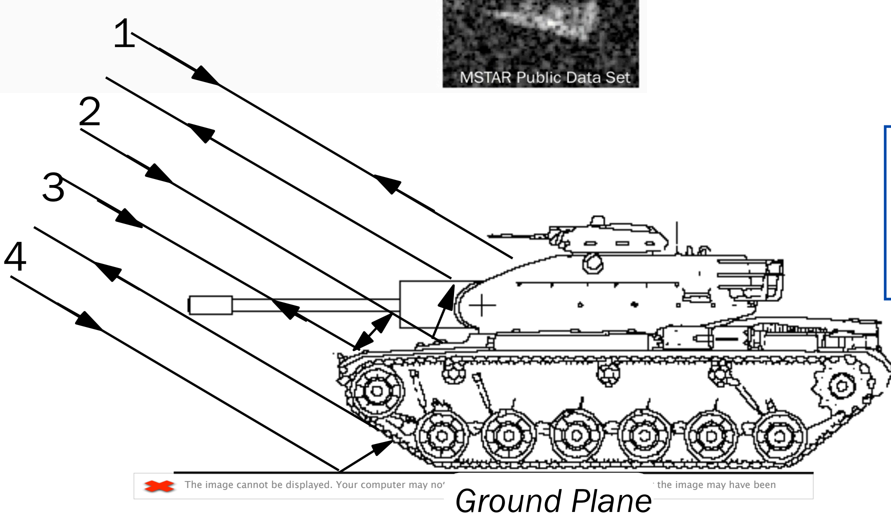
Object Electromagnetic Interactions





1: Direct return
2.3: Multipath return
4: Object/background interaction

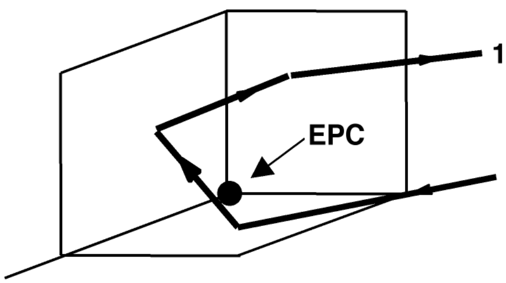
- Object signature determined by backscattered signal:
  - Incident waveform
  - Specific object geometry
  - Background characteristics

  } Interactions

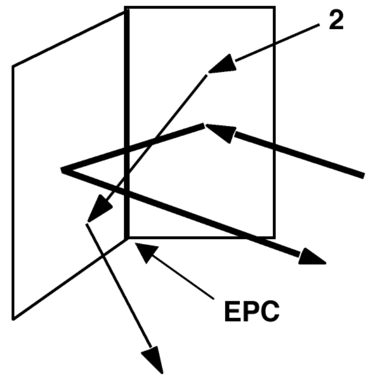
- Multiple mechanisms contribute to backscattered signal

Keydel, E.R., Lee, S.W. and Moore, J.T., "The MSTAR Extended Operating Conditions (EOCs) – A Tutorial," *Algorithms for Synthetic Aperture Radar VI, Proceedings of the SPIE 3721*, April 1996.

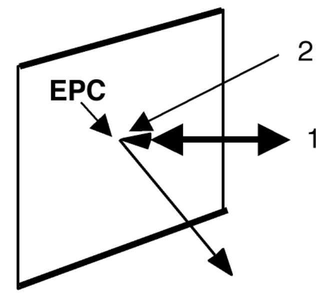
Elementary Structural Scattering Mechanisms



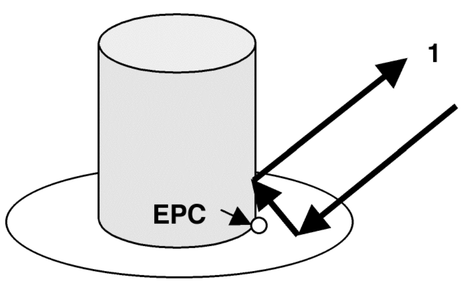
TRIHEDRAL



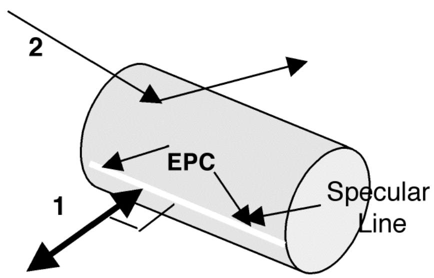
DIHEDRAL



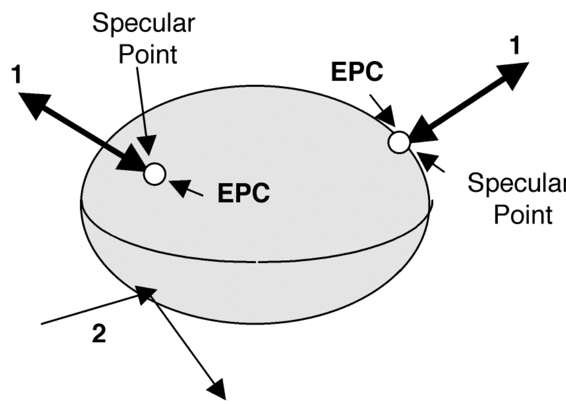
FLAT PLATE



TOP HAT



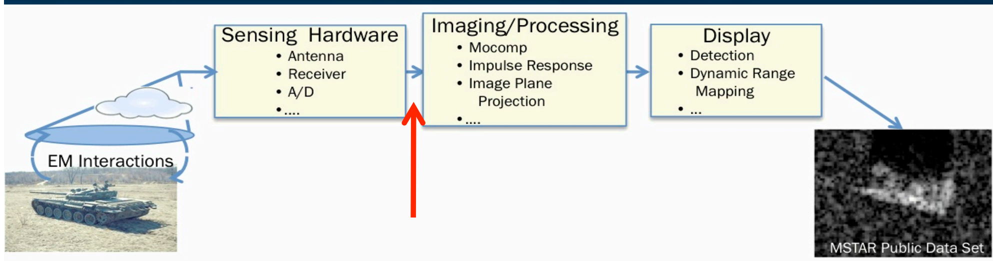
CYLINDER



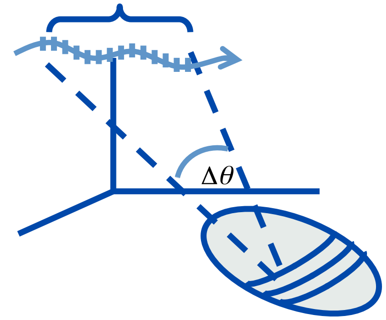
ELLIPSOID

EPC: “Effective Phase Center”

Signal Model



Coherent Integration Time, T



$\Delta\theta$: Angle subtended by synthetic aperture

θ_m : Aspect on object at aperture center

- Response from n[th] elementary scatterer (ab[th] polarization channel)

$$E_n^{ab}(f,\phi) = s_n^{ab}(f,\phi)e^{-j\psi(R_n,f)}$$

Scatterer amplitude — Function of: Size, Orientation, Shape, Material, Frequency, Polarization

Scatterer phase — Function of: Range, Frequency

- Signal collected over the synthetic aperture (m[th] aspect on object)

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

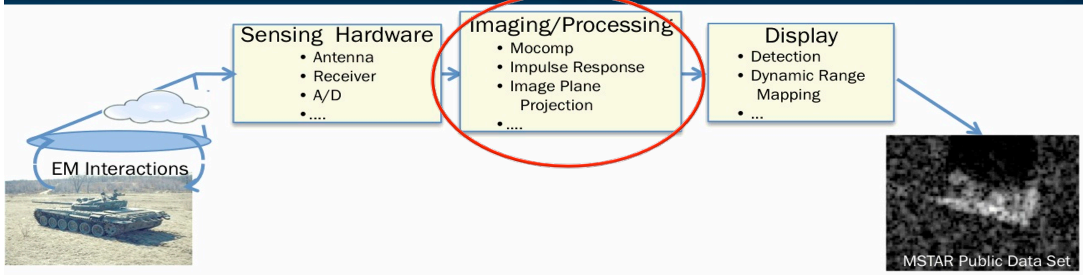
Aperture weighting — Radar constants

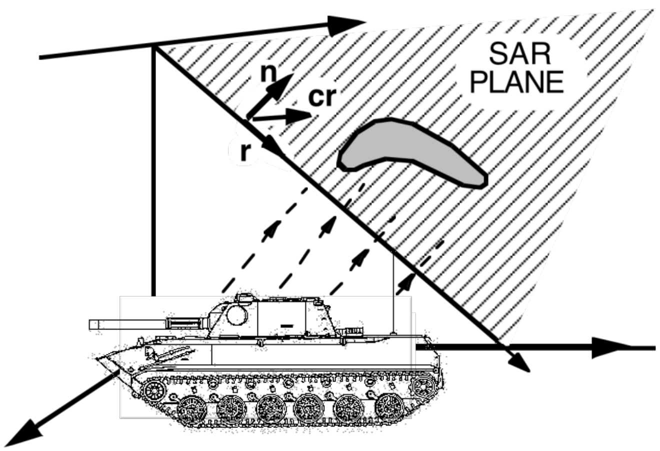
$$t \in \left[-\frac{T}{2},\frac{T}{2}\right]$$

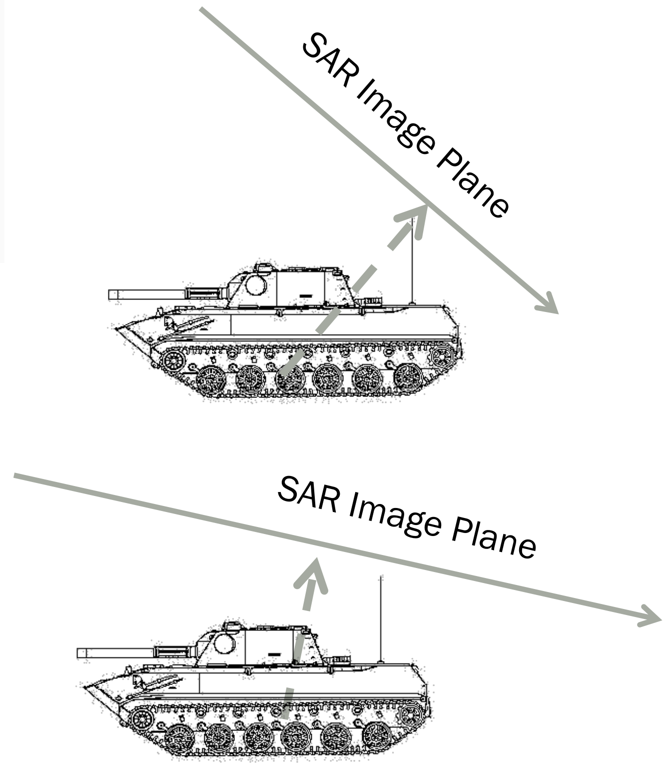
$$\phi \in \left[\theta_m - \frac{\Delta\theta}{2}, \theta_m + \frac{\Delta\theta}{2}\right]$$

$$f \in \left[f_o - \frac{BW}{2}, f_o + \frac{BW}{2}\right]$$

SAR Image Plane Projection





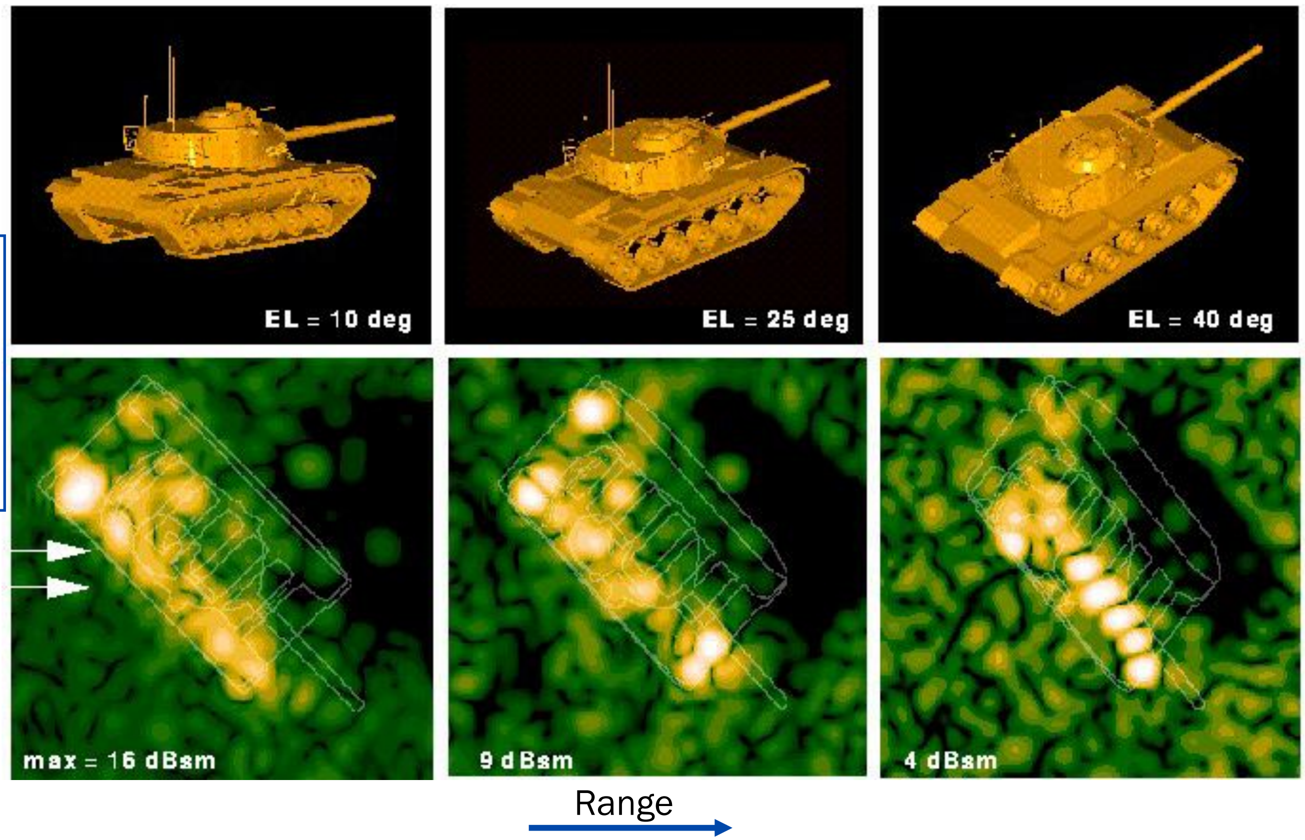


- SAR slant plane: contains line-of-sight and velocity vector
- Image pixels: coherent superposition of scatterer contributions along ambiguity contour ⊥ slant plane

Keydel, E.R., Lee, S.W. and Moore, J.T., "The MSTAR Extended Operating Conditions (EOCs) – A Tutorial," *Algorithms for Synthetic Aperture Radar VI, Proceedings of the SPIE 3721*, April 1996.

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

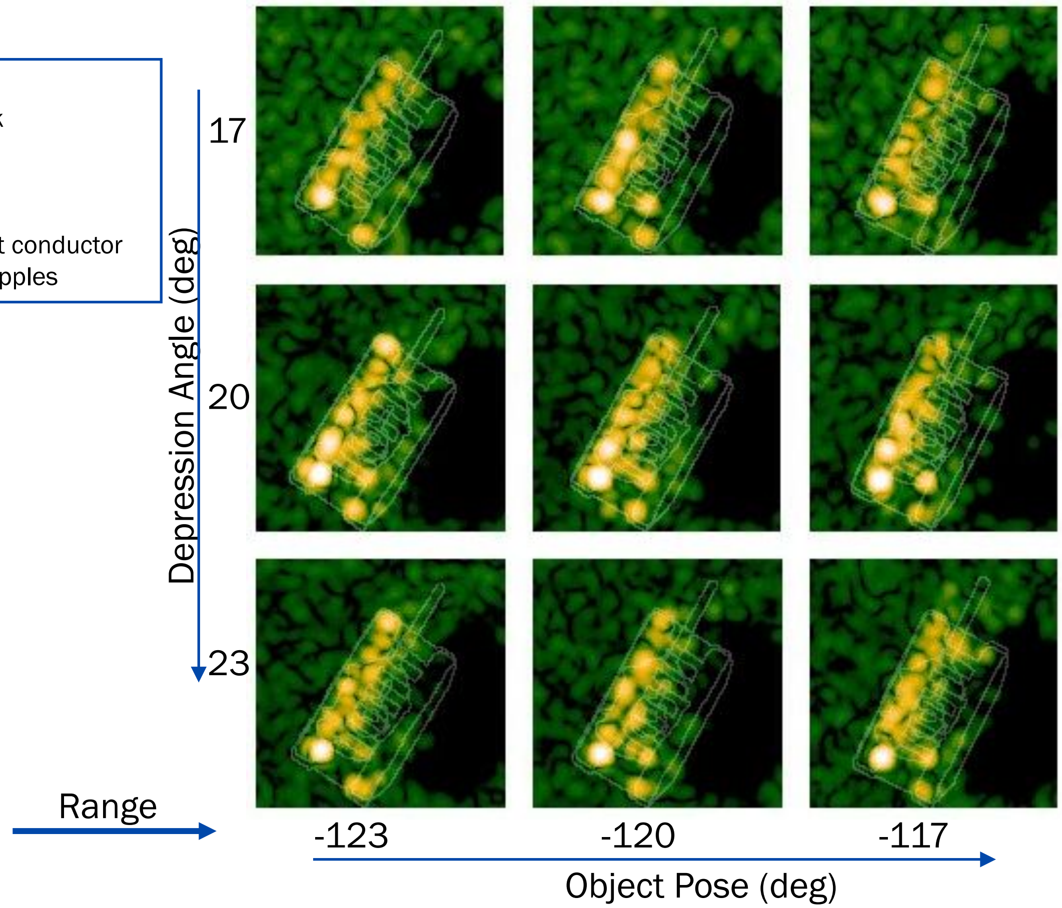


Impacts ambiguity of 3-D object geometry in slant SAR plane

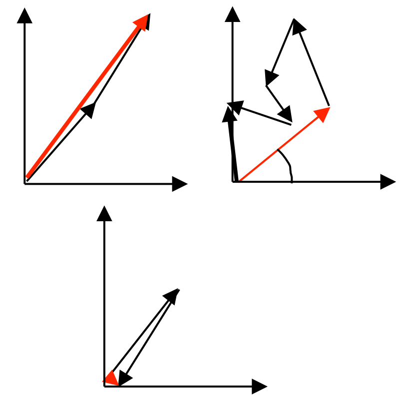
Keydel, E.R., Lee, S.W. and Moore, J.T., 1996

Pixel Scintillation

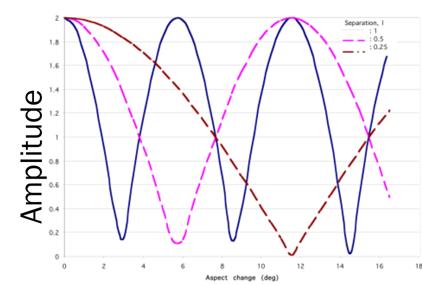
Simulator	: Xpatcht
Object	: M60 tank
Squint	: 90 deg
Resolution	: 1 ft
Frequency	: X-band
Background	: Imperfect conductor random ripples



Scatterer Phasors



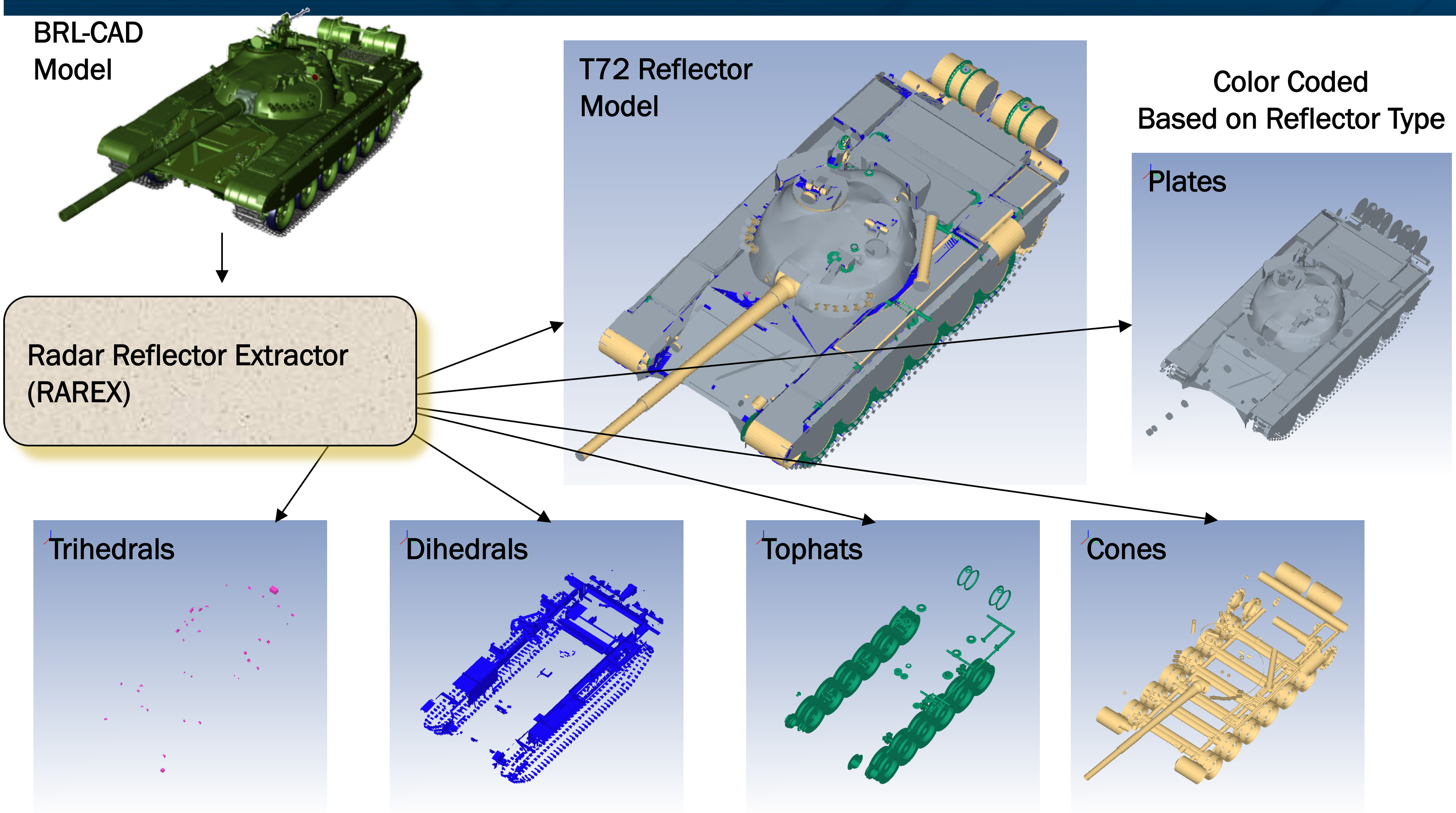
Coherent Sum Amplitude



Causes amplitude fluctuations in pixels containing the same scatterers

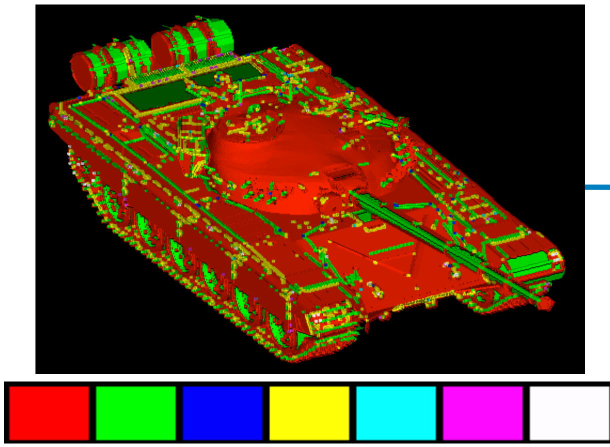
Keydel, E.R., Lee, S.W. and Moore, J.T., 1996.

Object Representation with Primitive Scatterers



Signature Synthesized from Primitive Scatterers

Full Primitive Model



PLAT CONE ELLG DHED THED TOPH SCAV

Aspect: -135
Depr: 30
Squint: -90

WIDE APPLICATION SIGNATURE PREDICTOR (WASP)

Synthetic Signature

- 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 mth aspect)

$$S_m^{ab}\left(f,\phi(t)\right) = w(f,t)K\sum_{n=1}^{N} E_n^{ab}(f,\phi(t),\theta_m) \qquad t \in \left[-\frac{T}{2},\frac{T}{2}\right]$$

$$\phi \in \left[\theta_m - \frac{\Delta\theta}{2}, \theta_m + \frac{\Delta\theta}{2}\right] \qquad m=1,\ldots.M_{aspects}$$

$$f \in \left[f_o - \frac{BW}{2}, f_o + \frac{BW}{2}\right]$$

Aperture Weighting   Radar Constants

- Postulate this (at aspect θ_m, abth polarization (Tx a, Rx b))

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

Polarization Dependence (Shape)

Frequency Dependence (Curvature)

Angular Dependence (Dimensions)

Location Dependence

- Estimate these:

$$S_n^{ab}(\theta_m)\left(j\frac{f}{f_c}\right)^{\alpha_n} A(f,\phi,\theta_m)e^{-j\frac{4\pi f}{c}(x_n\cos\phi + y_n\sin\phi)} \qquad m=1,\ldots.M_{aspects}$$

Lee C. Potter, and Randolph L. Moses, "Attributed Scattering Centers for SAR ATR", IEEE Transactions on Image Processing, Vol 5, No 1, January 1997

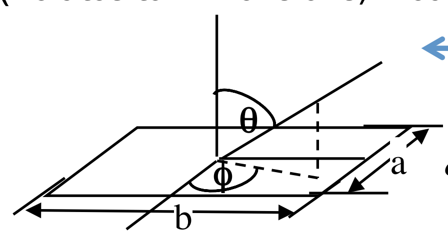
Angle and Frequency Response Interpretation

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

FREQUENCY DEPENDENCE
(Relates to Local Structure)

FREQUENCY EXPONENT, α	LOCAL SCATTERING GEOMETRY
-1	Corner
-1/2	Edge
0	Point Scatterer, Doubly-Curved Surface
1/2	Singly-Curved Surface
1	Flat Surface

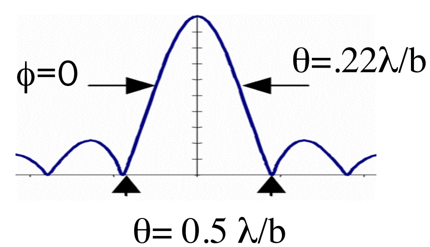
AMPLITUDE DEPENDENCE
(Relates to Dimensions, Area)



$$\sigma = \frac{2\sqrt{\pi}ab}{\lambda}\cos(\theta)\left[\frac{\sin(ka\sin\theta\cos\phi)}{ka\sin\theta\cos\phi}\right]\left[\frac{\sin(kb\sin\theta\sin\phi)}{kb\sin\theta\sin\phi}\right]$$

Analogies hold for other structures

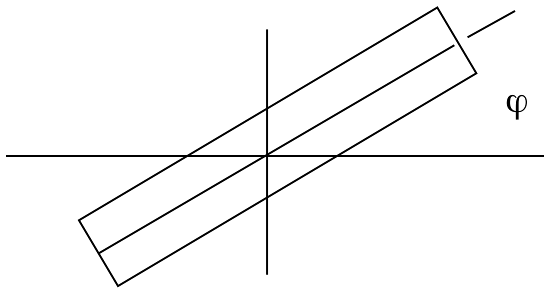
ANGULAR DEPENDENCE
(Relates to Azimuth Extent)



Polarimetric Response Interpretation:
Huynen Decomposition*

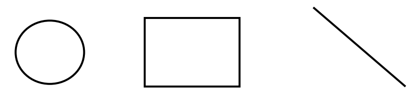
Descriptors computed from complex polarimetric scattering matrix

φ: orientation angle $-90^o < \varphi < 90^o$



τ: helicity angle $-45^o < \tau < 45^o$

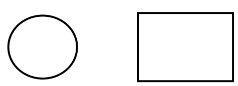
0^o symmetric



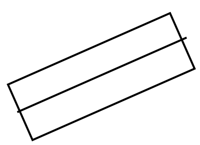
45^o non-symmetric

ν: skip angle $-45^o < \nu < 45^o$

0^o odd bounce

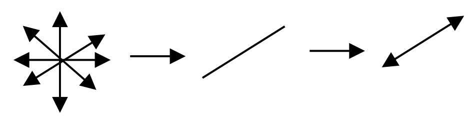


45^o even bounce

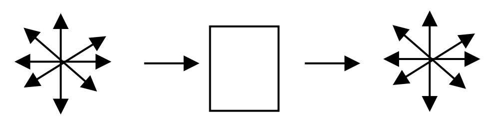


γ: polarizability angle $-45^o < \gamma < 45^o$

0^o full polarizability



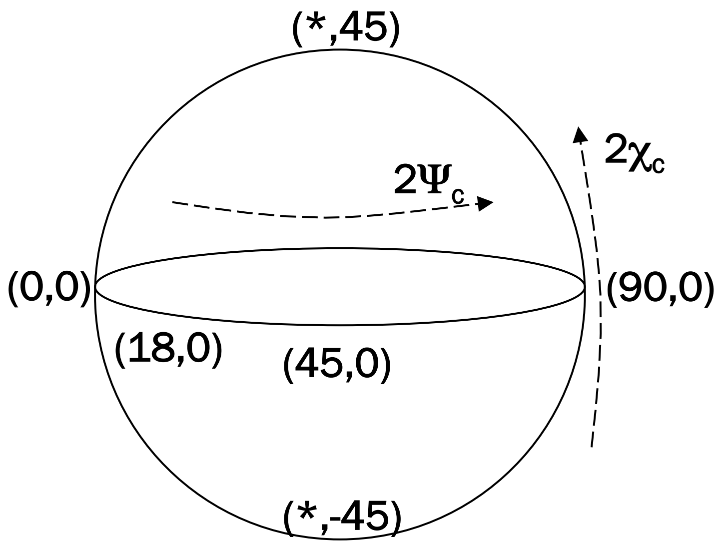
45^o no polarizability



* One of several polarimetric decompositions derived from polarization scattering matrix [S^{aa},S^{ab}, S^{ba}, S^{bb}]

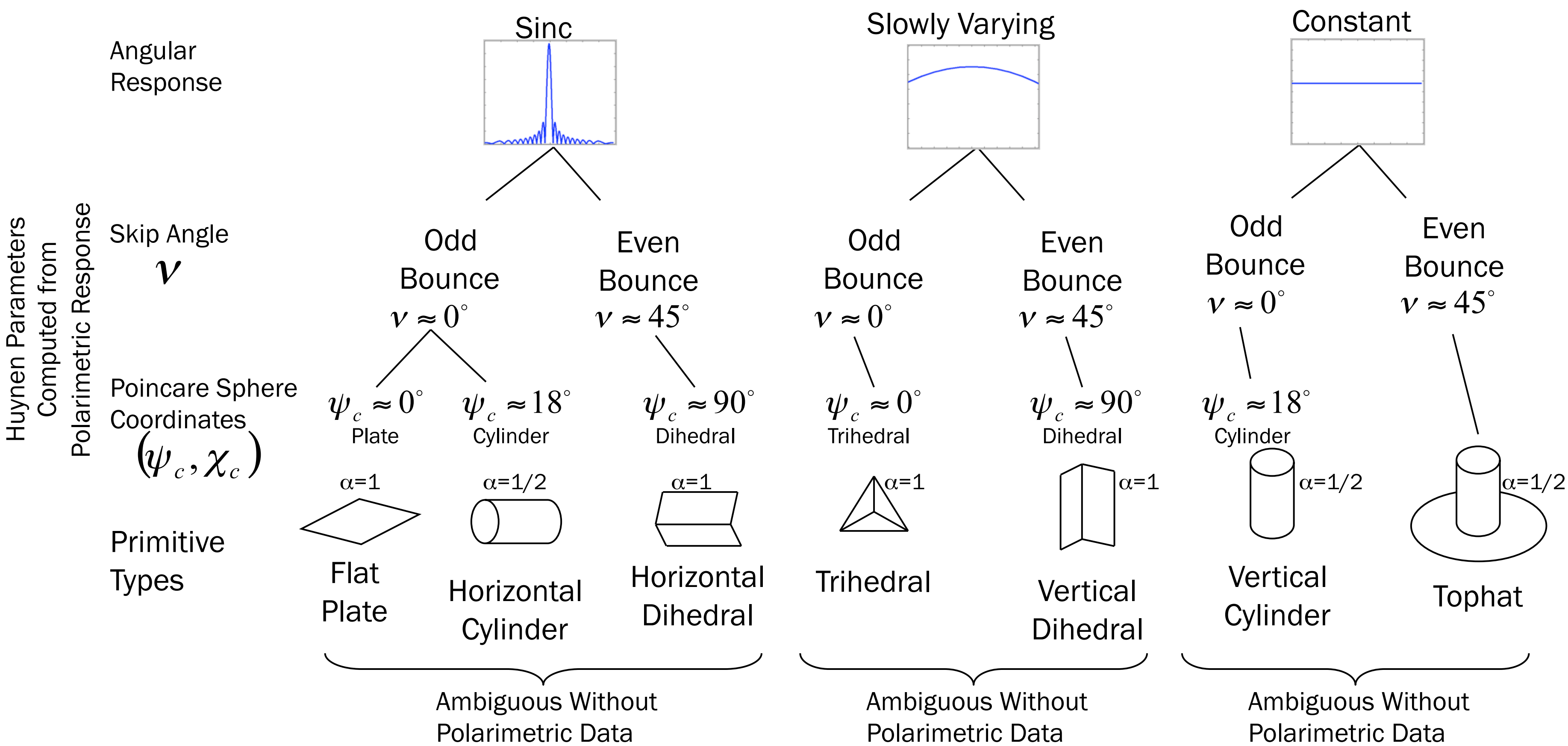
Polarimetric Response Interpretation:
Poincare Sphere Mapping

Descriptors computed from complex polarimetric scattering matrix



Ψ_c	χ_c	**Scatterer Type**
0^o	0^o	Plate / Trihedral
18^o	0^o	Cylinder
45^o	0^o	Dipole
90^o	0^o	Dihedral
Any	+/- 45^o	Helix

One Taxonomy for Shape Recovery



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  - Exploitation and ATR

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Inverse Path

Mechanisms

Primitives

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

$\sum_{n=1}^{N} E_n^{ab}(f,\phi(t),\theta_m)$ → DECOMPOSE SIGNAL

$S_n^{ab}(\theta_1), a_n, A(f,\phi,\theta_1)$ → PUT INTO 3-D

Primitives → SCULPT INTO MODEL

Sensing	CONDITION SIGNAL	DECOMPOSE SIGNAL	PUT INTO 3-D	ESTABLISH SPATIAL RELATIONS	DEFINE CANDIDATE SHAPES	SCULPT INTO MODEL	ANALYST DISPLAY/ DECISION AIDS
Collect Mode Mocomp Acquisition Geometry Resolution …….	Calibrate Remove Weighting ….	Estimate Parameters Derive Mechanisms	Resolve z Refine (x,y,z)	Register to Common Frame	Manage Ambiguities	Transition: Ideal → Actual Infer Surfaces	Display Mensurate Assess

INFLUENCES/ENABLERS

Sensing	CONDITION SIGNAL	DECOMPOSE SIGNAL	PUT INTO 3-D	ESTABLISH SPATIAL RELATIONS	DEFINE CANDIDATE SHAPES	SCULPT INTO MODEL	ANALYST DISPLAY/ DECISION AIDS
Sensor Capabilities System Design Frequency Polarimetry Bandwidth Aspects Altitudes Navigator Quality	Calibration data Processing Design	Sensing Diversity -angle -polarization -bandwidth	Trajectory Diversity Navigation Accuracy	Exquisite Registration Navigation Accuracy	Uncertainty Models in all Parameters	Uncertainty Models in all Parameters Geometric reasoning under uncertainty	Confidences Inferred surface display

SAIC

Early History*

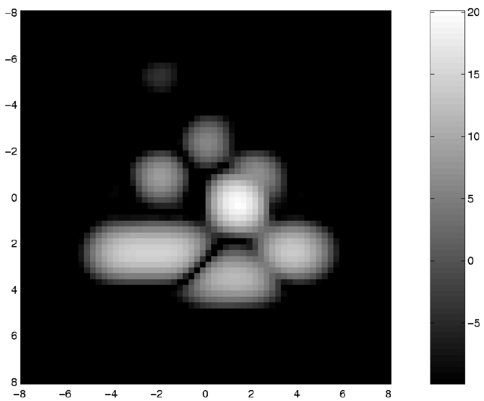
Lee C. Potter et al "A GTD-Based Parametric Model for Radar Scattering", IEEE Transactions on Antennas and Propagation, Vol 43, No 10 October 1995.	Laid out signal model as a superposition of attributed scattering centers, showed early capability to estimate scattering center parameters from the signal
Lee C. Potter, and Randolph L. Moses, "Attributed Scattering Centers for SAR ATR", IEEE Transactions on Image Processing, Vol 5, No 1, January 1997	Demonstrated detection of attributed scatterers, estimation of image plane locations, polarimetric amplitudes, aspect dependence, and geometric type
N.S. Subotic, J.W. Burns, and D. Pandelis, "Scattering Mechanism Characterization Using Matching Pursuits with a Weighted Exponential Dictionary", 1997 North American Radio Science Mtg., Montreal, CA, p. 258	Demonstrated dictionary-based extraction of scattering centers from synthetic aperture signal data
N. S. Subotic, and J.W. Burns, 'Scattering Mechanism Characterization Using Adaptive Decomposition with a Vectorized Dictionary", 1998 USNC/URSI National Radio Sci. Mtg. Digest, Atlanta, GA, p. 326	Demonstrated the ability to separate and characterize different scattering mechanisms in synthetic aperture radar data
Emre Ertin and Lee C. Potter, "Polarimetric Classification of Scattering Centers Using M-ary Bayesian Decision Rules", IEEE Transactions on Aerospace and Electronic Systems, Vol 36, No 3, July 2000.	Showed the feasibility of classifying scattering centers in polarimetric data
Hung-Chih Chiang, and Randolph L. Moses, "Model-Based Classification of Radar Images", IEEE Transactions on Information Theory, Vol 46, No. 5, August 2000.	Showed the use of attributed scattering to classify objects in a 10-class problem. Avg Pc = 86.8%
J.W. Burns and N.S. Subotic, "Adaptive Decomposition in Electromagnetics", in Frontiers in Electromagnetics, Douglas Werner and Raj Mitraeds IEEE Press, New York, 2000.	Demonstrated sparse dictionary-based approaches for signal decomposition in synthetic aperture radar

Remaining discussion focuses on recent advances building on this foundation

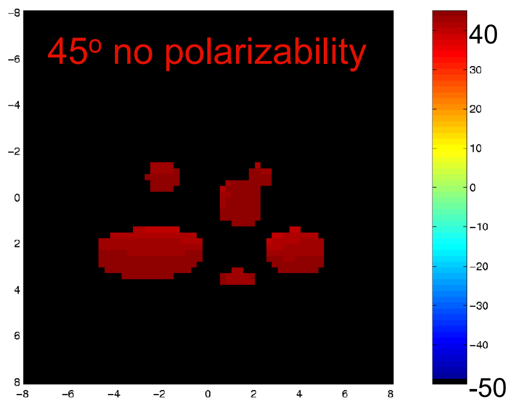
* Representative and a only *subset* of prior research

Polarimetric Analysis
Huynen Parameter Estimation: Slicey

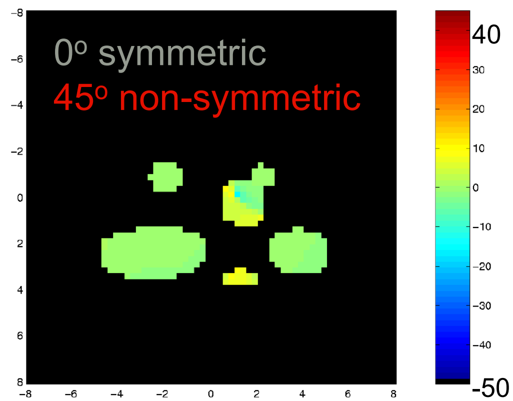
HH pol Intensity Image

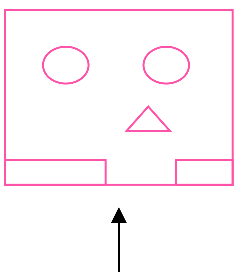


Polarizability Angle - γ

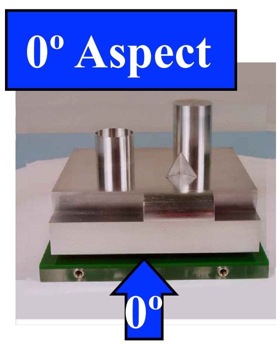


Symmetry Angle - τ



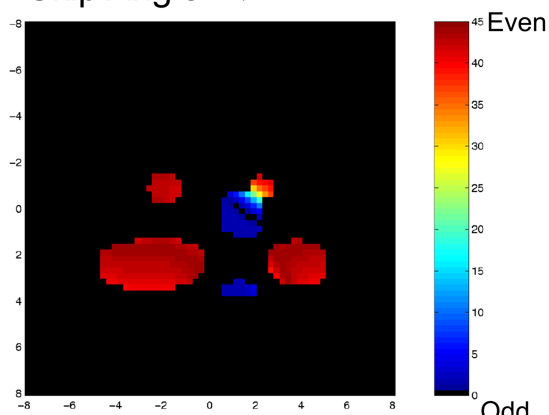


illumination



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

Skip Angle - ν



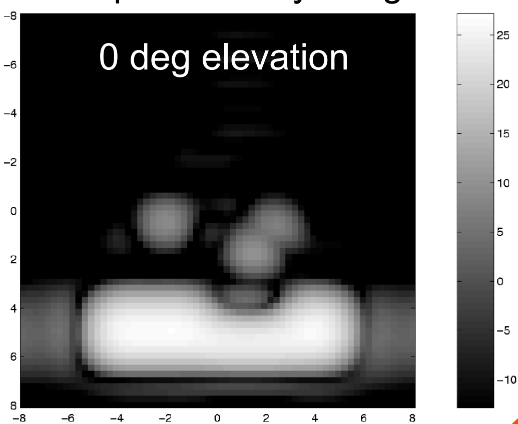
Blue - odd bounce
Red - even bounce

Created by N Subotic, J,W. Burns, Michigan Tech Research Institute, Used with permission

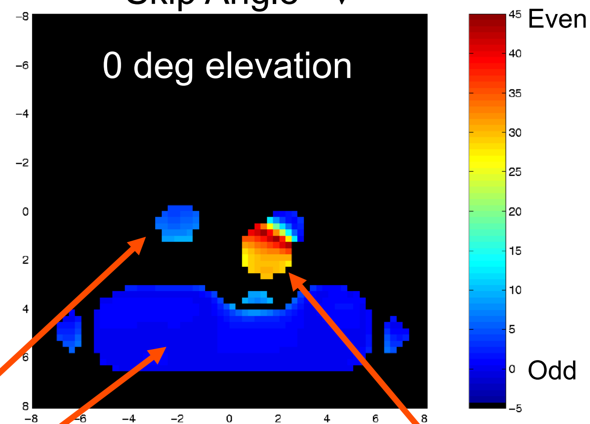
Impact of Elevation Angle:

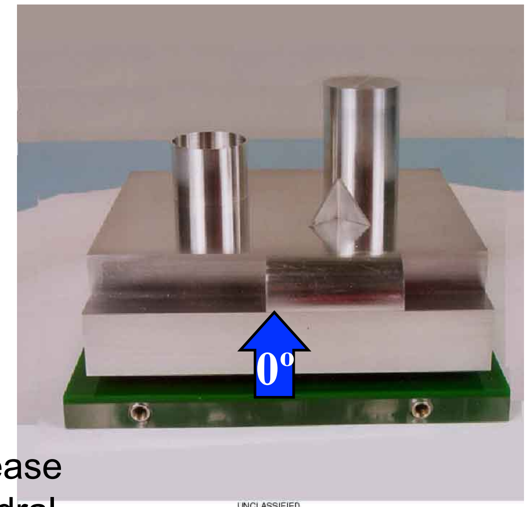
Changing Angle Changes Scattering

HH pol Intensity Image



Skip Angle - ν





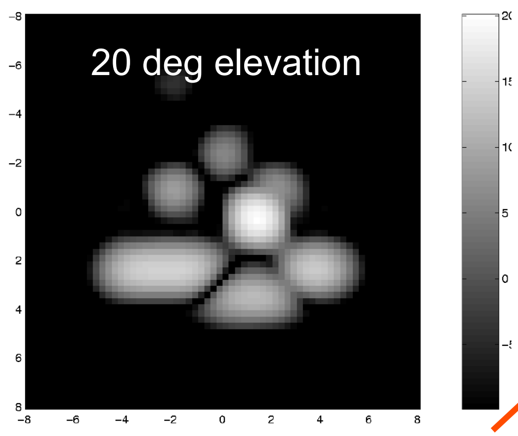
Cylinder

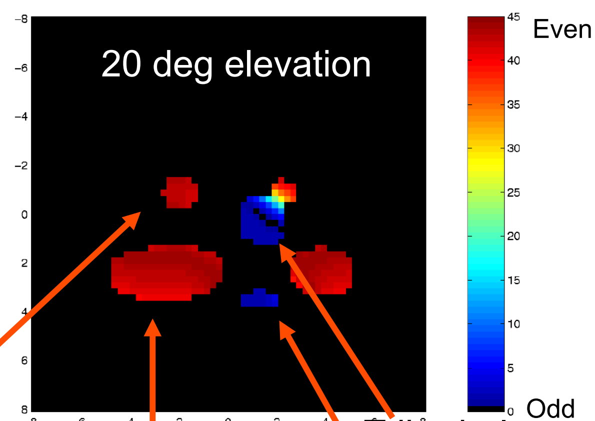
Plate

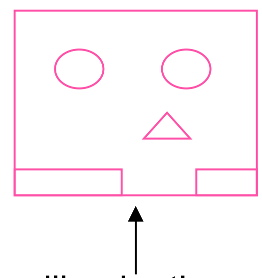
Blue - odd bounce

Red - even bounce

Top crease of trihedral







illumination

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

Base of tophat

Dihedral

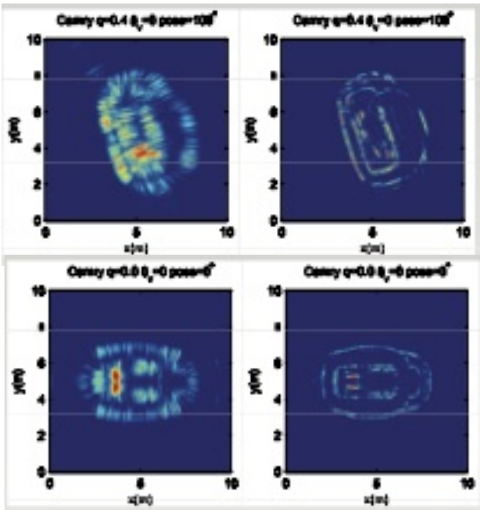
Trihedral

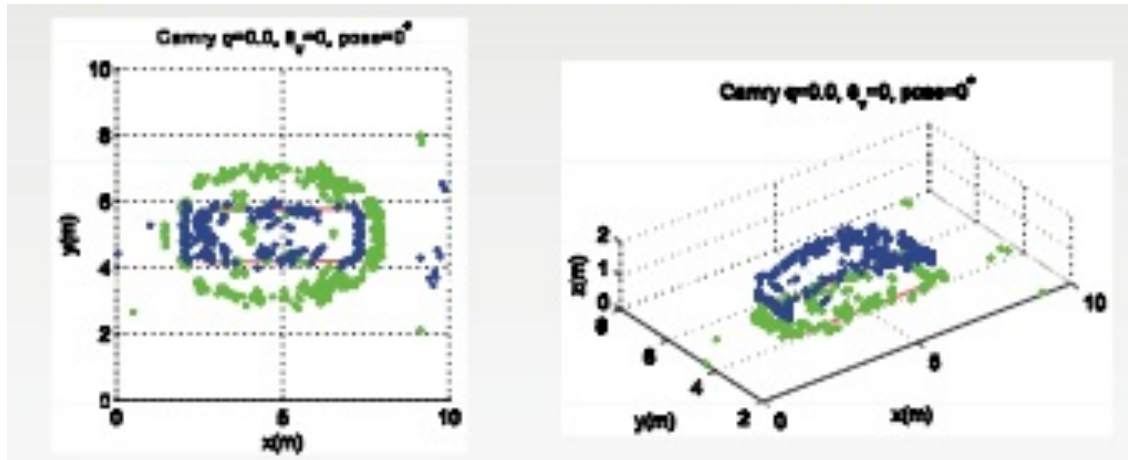
Cylinder

Created by N Subotic, J,W. Burns, Michigan Tech Research Institute, Used with permission

Attributed Scatterers to Sort Out Layover

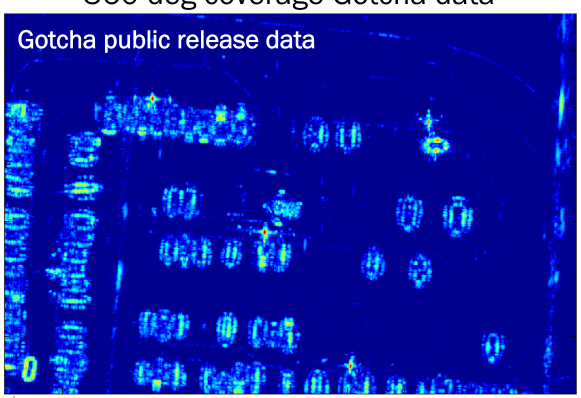
2D, 22cm, and 3cm res Synthetic Data

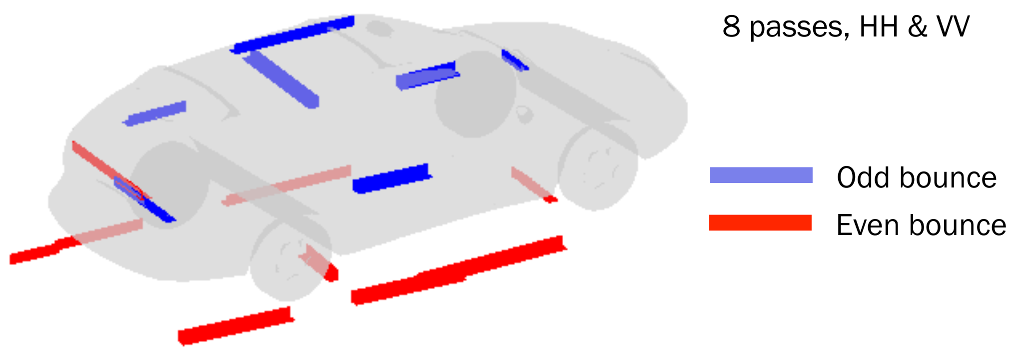




Kerry Dungan, Christian Austin, John Nehrbass, Lee C. Potter, "Civilian Vehicle Radar Data Domes, SPIE1-a Poster
Used with permission of authors

360 deg coverage Gotcha data





Lee Potter, "Compressive Sensing for Radar and Turbo Reconstruction of Structured Images", AFRL ATR Center; NSF Center for Surveillance Research.
Used with permission of authors

SAIC

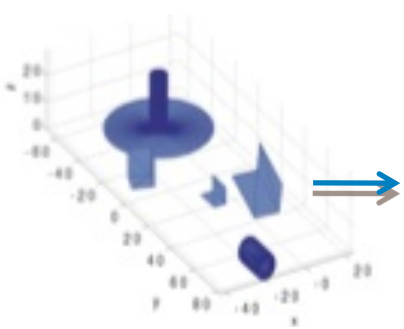
Multi-Dimensional Attribute Extraction

DECOMPOSE SIGNAL → PUT INTO 3-D → ESTABLISH SPATIAL RELATIONS → DEFINE SHAPES → SCULPT INTO MODEL

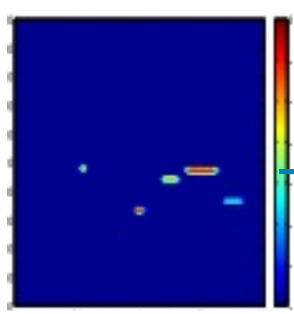
Canonical Scattering Models

Canonical Shape	Icon	Scattering Model $S_{T(m)}$
Top-hat		$S_{top} = \left(j\frac{f}{f_c}\right)^{1/2}\sin(\theta-\theta_m)$ $\theta \in (\theta_m, \theta_m + \frac{\pi}{4})$
Trihedral		$S_{trih} = \left(j\frac{f}{f_c}\right)\sin(\phi-\phi_m)\cos\theta\sin(\theta-\theta_m)$ $\theta \in (\theta_m, \theta_m + \frac{\pi}{4}) \quad \phi \in (\phi_m, \phi_m + \frac{\pi}{4})$
Dihedral		$S_{dih} = \left(j\frac{f}{f_c}\right)\sin(\theta-\theta_m)$ $\cdot\,\mathrm{sinc}\left[\frac{2\pi f}{c}L_m\cos\psi_m\cos\phi_m\sin(\phi-\phi_m)\cos(\theta)\right]$ $\theta \in (\theta_m, \theta_m + \frac{\pi}{4}) \quad \phi \in (\phi_m - \frac{\pi}{2}, \phi_m + \frac{\pi}{2})$
Cylinder		$S_{cyl} = \left(j\frac{f}{f_c}\right)^{1/2}\mathrm{sinc}\left[\frac{2\pi f}{c}L_m\cos\psi_m\cos\phi_m\sin(\phi-\phi_m)\cos(\theta)\right]$ $\phi \in (\phi_m - \frac{\pi}{2}, \phi_m + \frac{\pi}{2})$

Original Test Scene

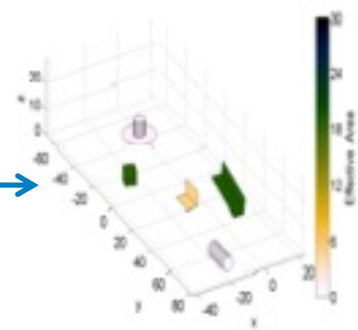


Synthetic Image

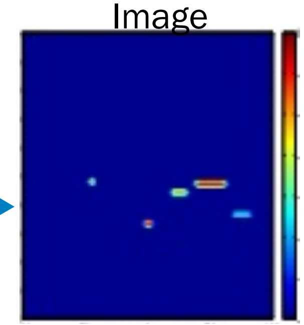


PARAMETER ESTIMATION

Estimated Scene



Reconstructed Image



Julie Ann Jackson and Randolph L. Moses, "Feature Extraction Algorithm for 3D Scene Modeling and Visualization Using Monostatic SAR, Ohio State University, Dept or Electrical and Computer Engineering
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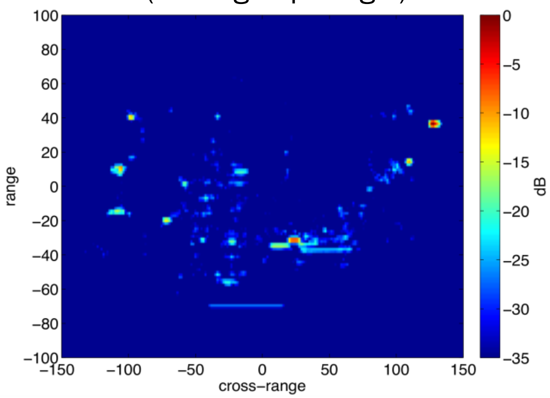
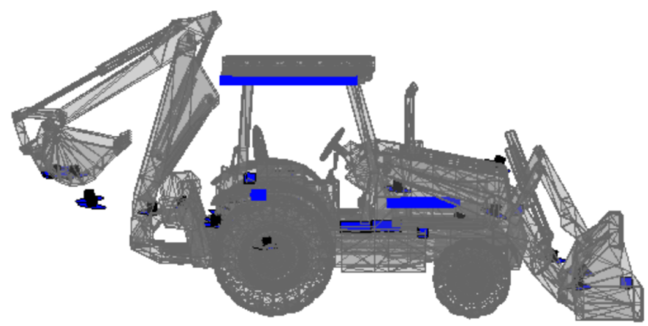
Multi-dimensional Attribute Extraction

Interferometric Processing for 3-D

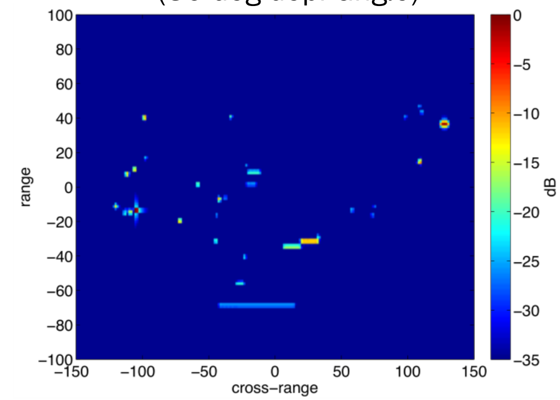
Synthetic Broadside View
(30 deg depr angle)



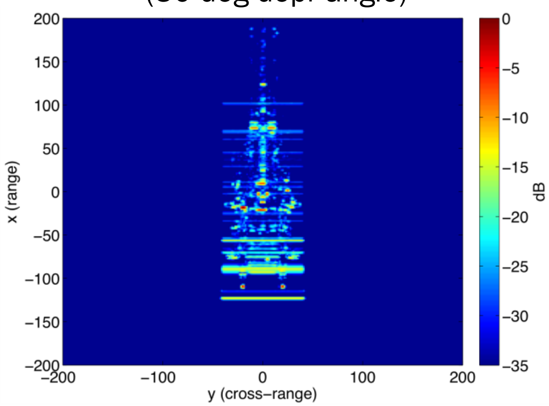
3-D Extracted Shape Primitives



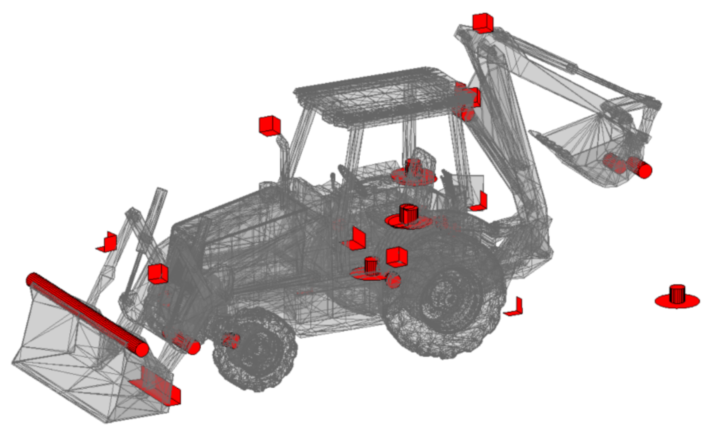
Reconstructed Broadside View
(30 deg depr angle)



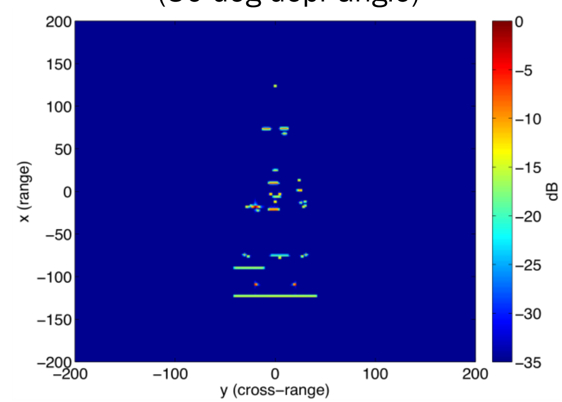
Synthetic End-On View
(30 deg depr angle)



3-D Extracted Shape Primitives



Reconstructed End-On View
(30 deg depr angle)



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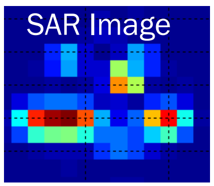
SAIC

Shape Estimation

DECOMPOSE SIGNAL → PUT INTO 3-D → ESTABLISH SPATIAL RELATIONS → DEFINE SHAPES → SCULPT INTO MODEL

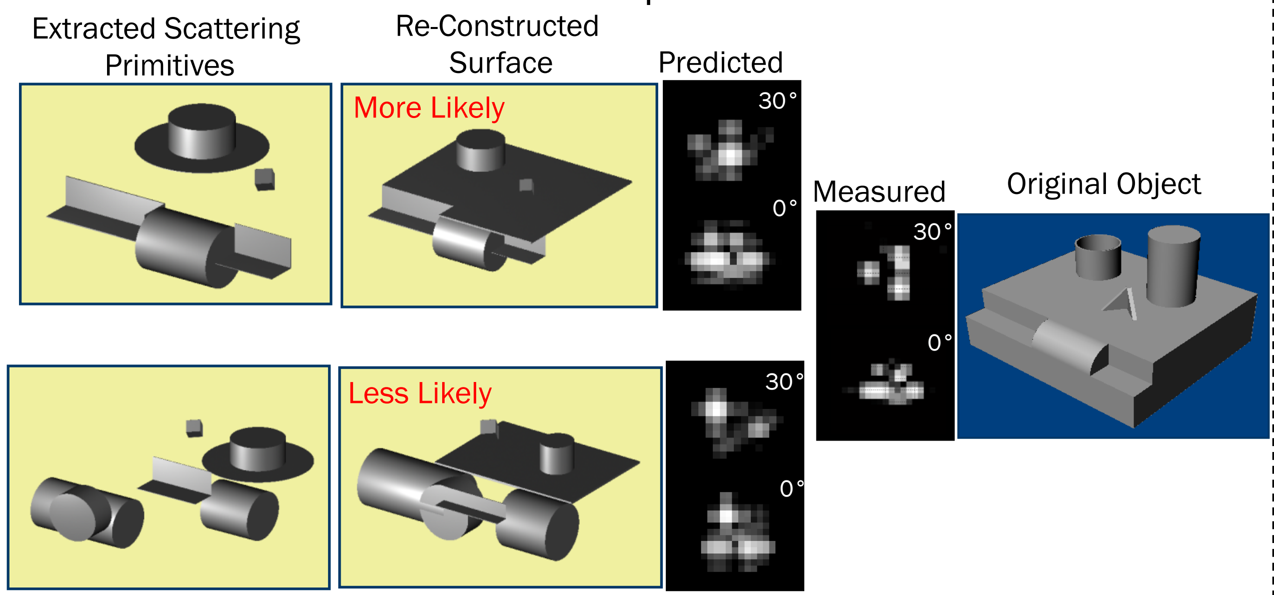
Turntable Data



Complex Phase History

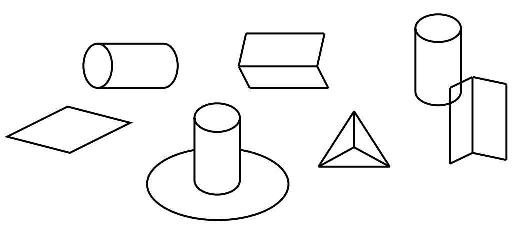
Wideband
Wide Angle
Polarimetric

Example Results

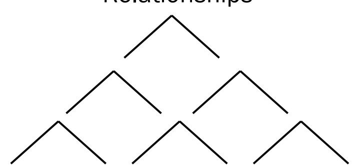


COMPLEX PHASE HISTORY EXPLOITATION → AMBIGUITY MANAGEMENT → CAD RECONSTRUCTION

Elementary Primitives



Plausible Relationships



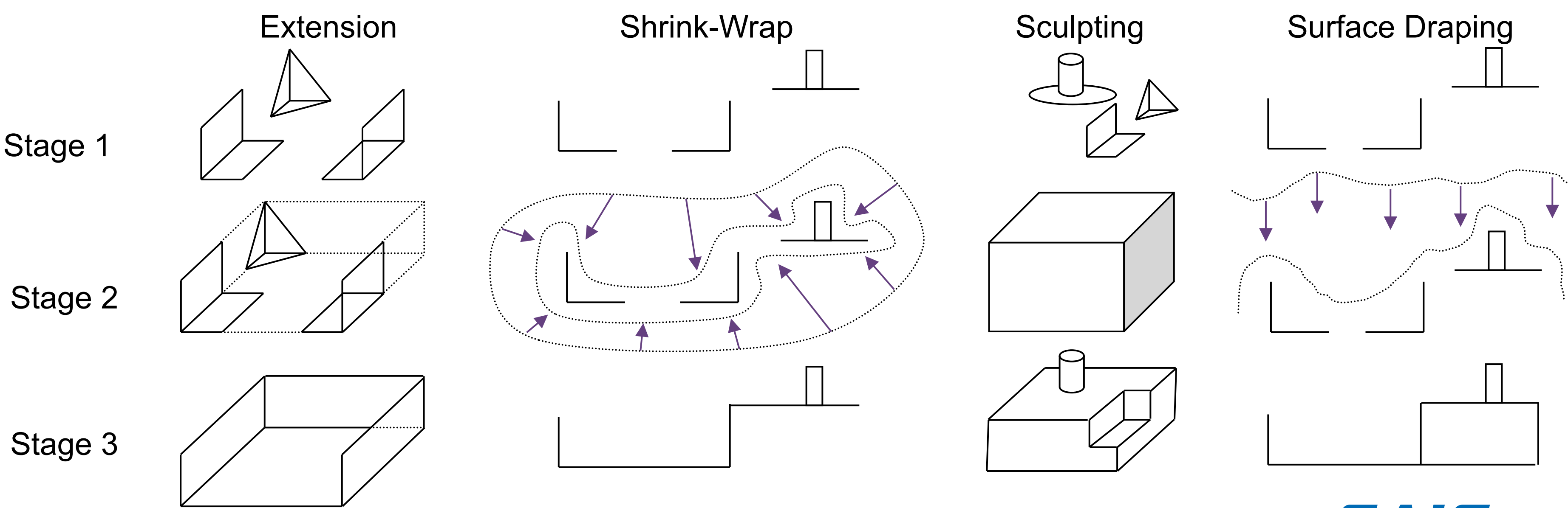
Surface Reconstruction

Local physical structures and 3-D locations

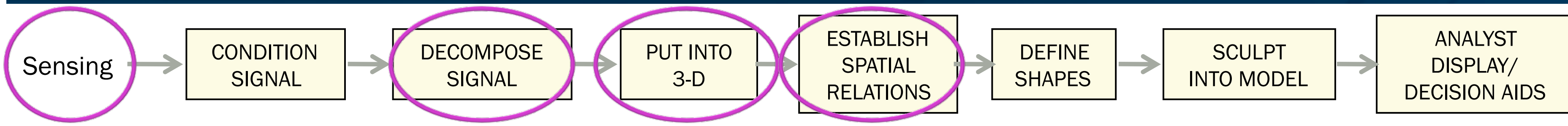
- Combine structures from multiple views
- Bootstrap surface boundary
- Refine surface boundary
  - Surface extension
  - "Shrink-Wrap"
  - Block sculpture
  - Surface draping

Object model

- Local physical surfaces
- Occlusion boundaries
- Uncertainties



Comments
Shape Recovery Exploitation (SRE)



- 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

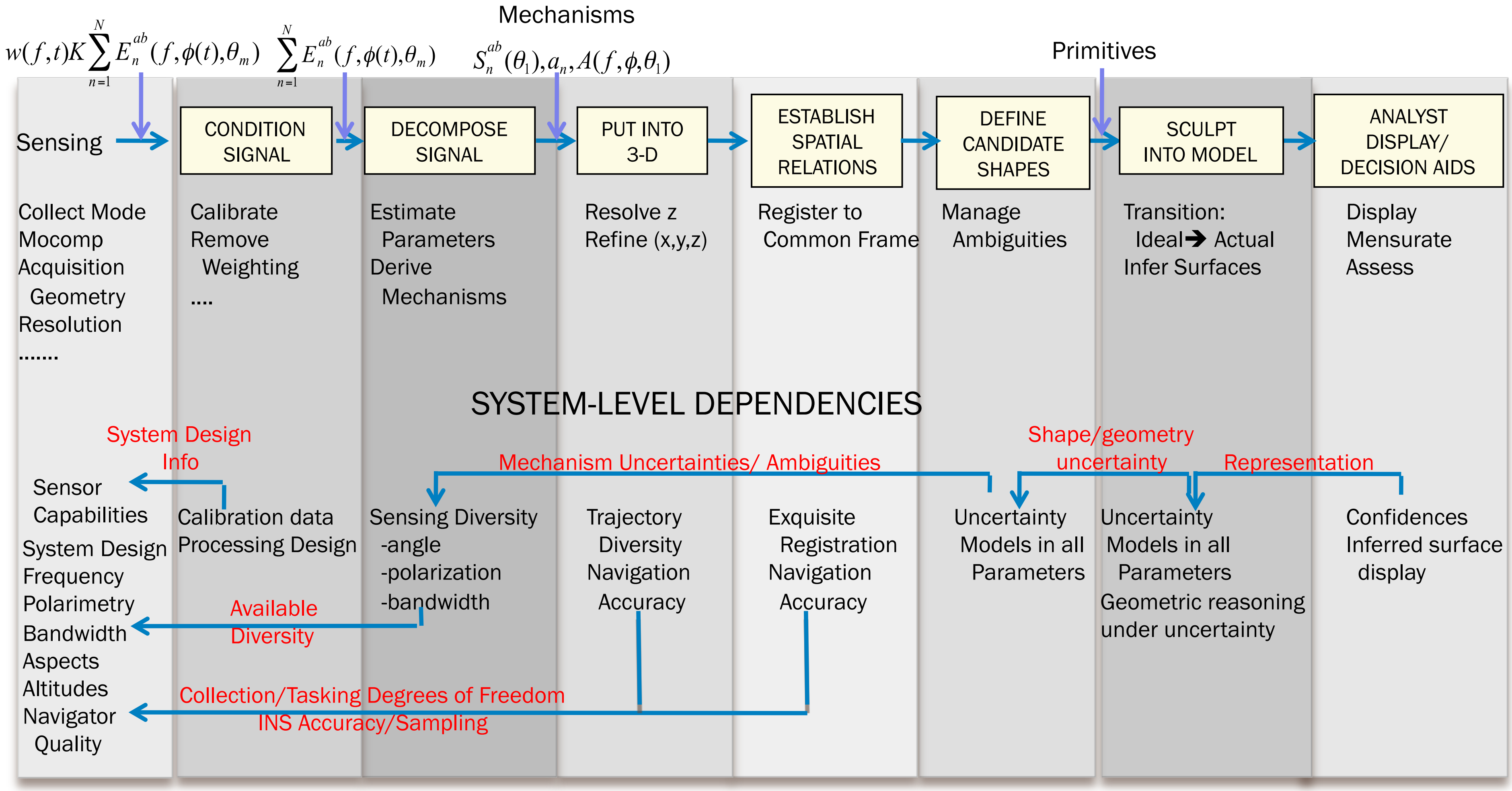
  Revolutionized object recognition and high confidence declaration

- SRE needs now to be thought about and developed in a *system* context

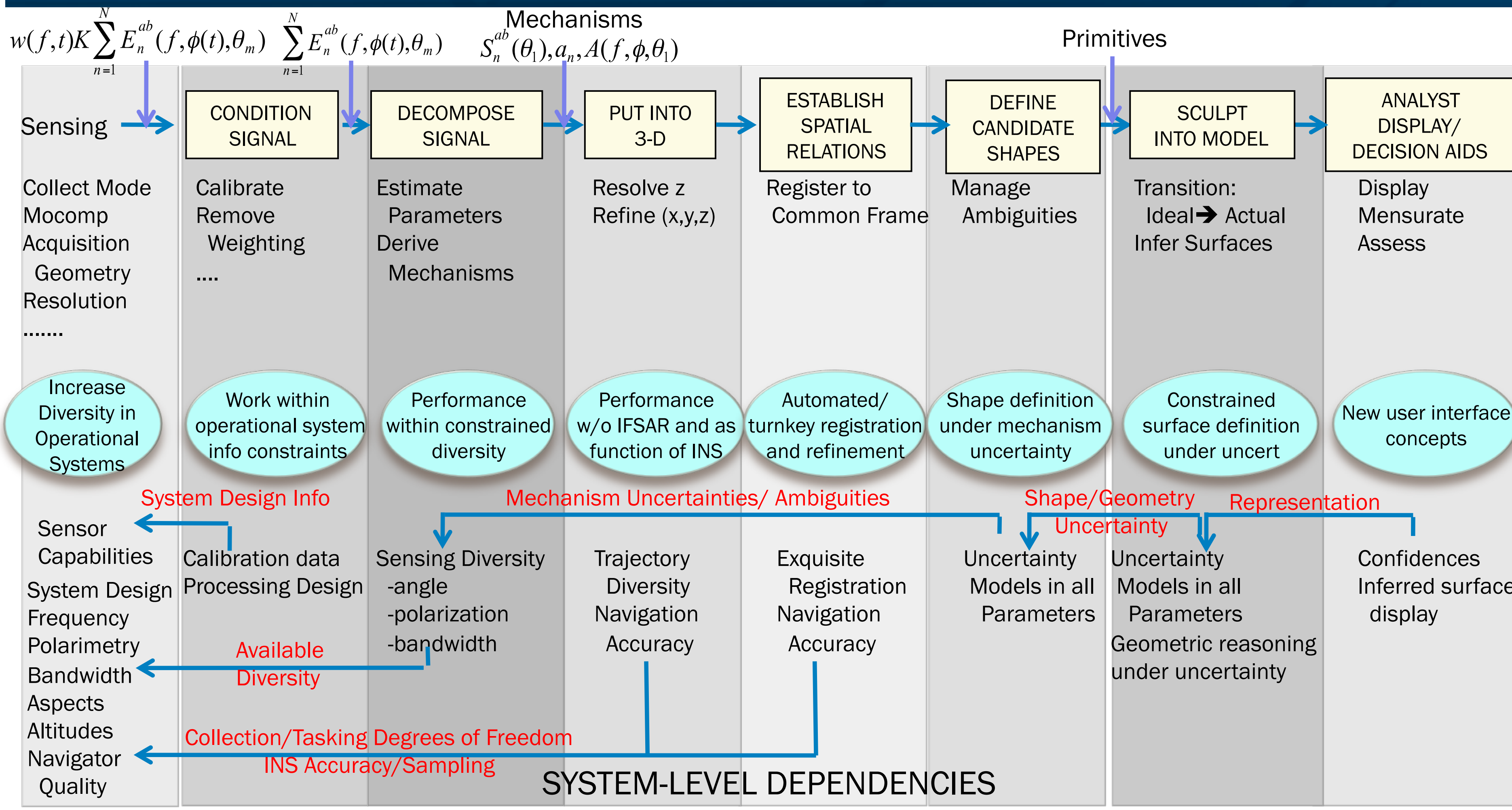
  Fill in weak research areas

  Make demonstrated capabilities robust to real-world collection system issues

System-Level Considerations



Areas Needing More Research



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?