Innovative Front-End Signal Processing

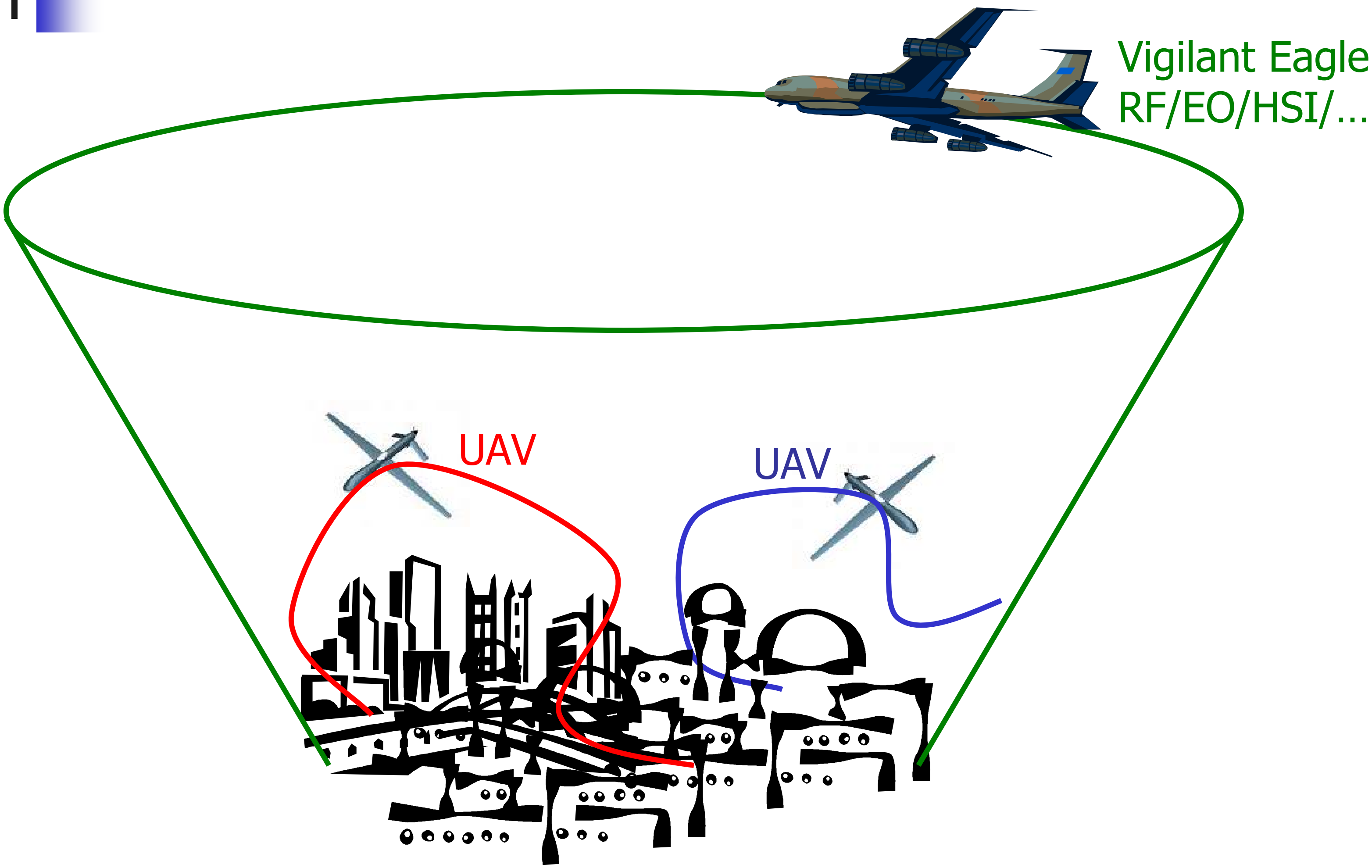
MURI Kickoff Meeting

Integrated Fusion, Performance Prediction, and Sensor Management for Automatic Target Exploitation

Randolph L. Moses

July 21, 2006

A multi-sensor, multi-modal, dynamic environment.



Begin with the End in Mind

- Front-end processing (e.g. image formation) is not done for its own sake, but rather to *feed into ATE systems*
  - Processing should be tuned to optimize ATE objectives.
- Front-end processing is part of a closed-loop ATE system
  - ATE Objectives
  - Sensor Management

  and must be designed to fit into this loop.

What is needed: Robust, directable feature extraction

- Capable of incorporating prior knowledge about sensor physics and phenomenology
- Capable of incorporating prior knowledge about context, current hypothesis state, etc. from fusion process
- Capable of providing features and feature uncertainties to higher-level processing.
  - Interface with fusion (graphical model inputs)
- Capable of providing performance predictions:
  - Cost/performance metrics for sensor management
- A common framework for multiple signal modalities.
- Flexible:
  - Different signal modalities
  - Waveform diversity; jamming, etc.

Signal Processing: Key Research Questions

ATE Objectives
Sensor Resources

Optimal, Robust Information Fusion (A. Willsky, lead)

...sures
...e Propagation
...s
- Learning and Adaptation

ATR/ATE Inferences and Confidences

Problem formulations that admit context, priors and directed queries

Features and Uncertainties

Priors and Learned Statistics

Measurement Constraints

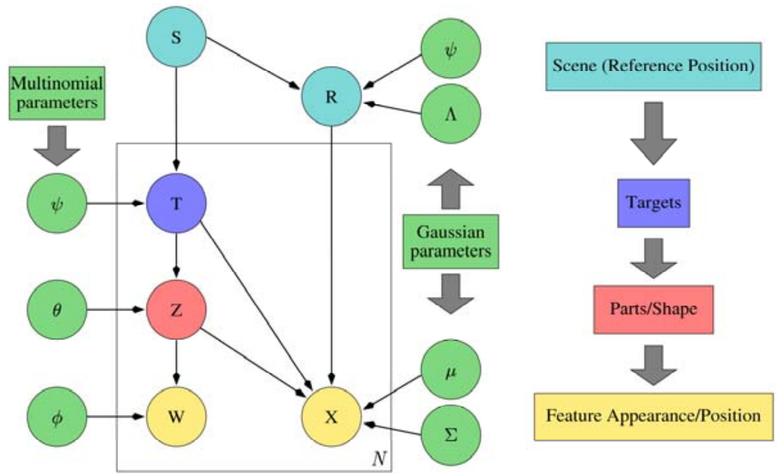
Adaptive Front-End Signal Processing (R. Moses, lead)

- Decision-directed Imaging and Reconstruction
- Modeling and Feature Extraction
- Statistical Shape Estimation

- ***Flexible imaging and reconstruction***
- ***Unified Parametric/Nonparametric processing***
- ***Statistical shape estimation***
- ***Adaptation and Learning***
- ***Uncertainty characterization***

algorithms
- Multi-level planning
- Performance uncertainty

Front-end Processing Interfaces



SENSOR #N

SENSOR #2

SENSOR #1

Features and
Feature uncertainties

Priors and decision-directed requests.

Our Approach:
A Unified Statistical Sensing Framework

- Sensor observations:

measurements → features or reconstruction

$$g = Tf + n \quad \longleftarrow \text{Nonparametric}$$

$$g = T(f) + n \quad \longleftarrow \text{Parametric}$$

$$\hat{f} = \arg\min_{f} \{-\log p(g|f) + \Psi(f)\}$$

- Statistical framework provides features and feature uncertainties (pdfs)
  - Not just point estimates

Two Questions

- Why should we believe this framework is the right approach for this MURI?

- What are we going to do?

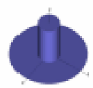
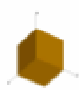
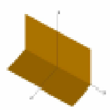
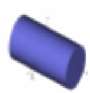
Advantages of Our Approach

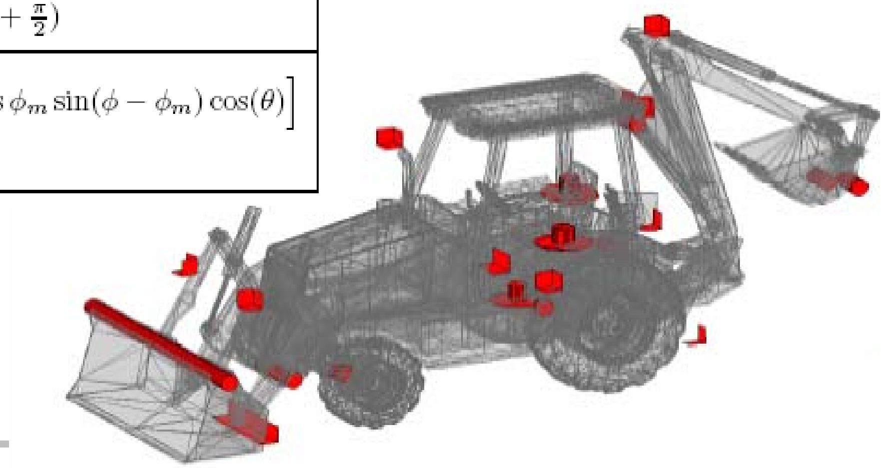
- Unified parametric and nonparametric techniques
  - Continuum of methods that trade performance with robustness
  - Unified framework for
    - Analytical performance and uncertainty characterization
    - Directed processing from Information Fusion level
- Statistical framework
  - Feeds into graphical model for fusion
  - Analytical predictions for sensor mgmt
- Adaptable
  - Sparse, nonlinear apertures
  - Dynamic signal environment (e.g. jamming)
- Directable
  - Regions/features of interest

Flexible, Relevant feature sets

- Use physics, priors to identify 'good' basis sets:
  - Sparse, high information content
    - Attributed scattering primitives (RF)
    - Multi-resolution corners (EO)
    - Shape (RF+EO)
- Use context, hypotheses to manage complexity

RF: Attributed Scattering Models

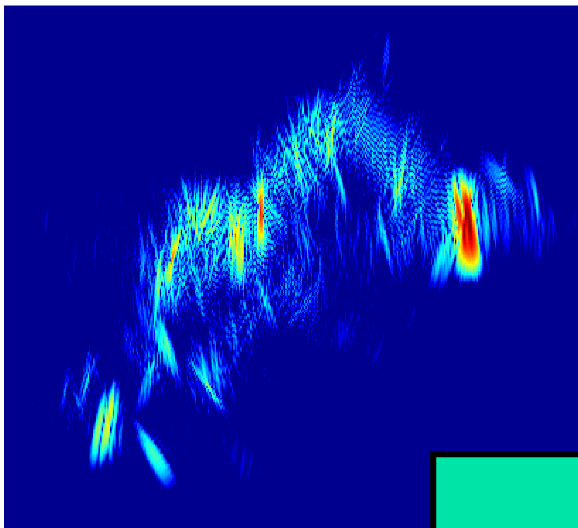
Canonical Shape	Icon	Scattering Model $S_{T(m)}$
Top-hat		$S_{top} = \left(j\frac{f}{f_c}\right)^{1/2} \sin(\theta - \theta_m)$ $\theta \in (\theta_m, \theta_m + \frac{\pi}{4})$
Trihedral		$S_{trih} = \left(j\frac{f}{f_c}\right) \sin(\phi - \phi_m) \cos\theta \sin(\theta - \theta_m)$ $\theta \in (\theta_m,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

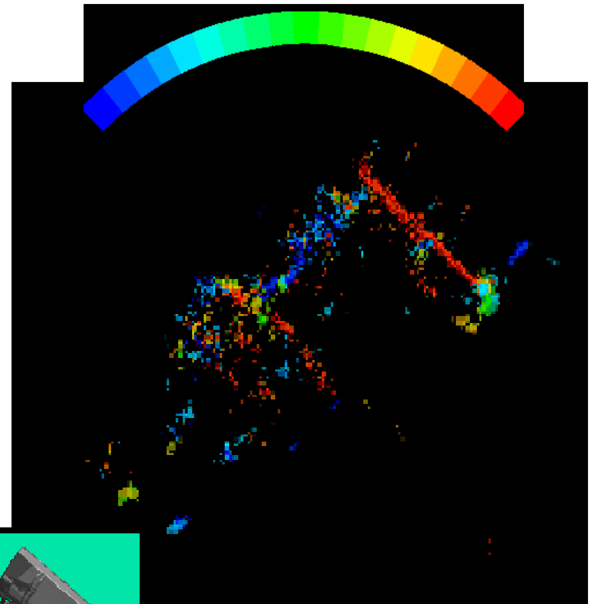


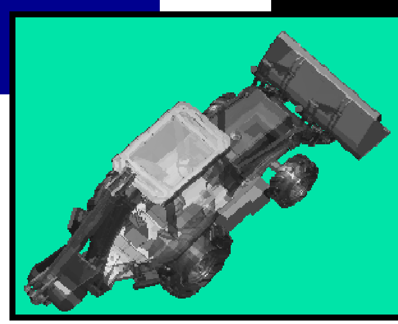
Jackson + Moses (OSU)

Phenomenology-based reconstruction

Backhoe
500 MHz BW
-10°–100° az





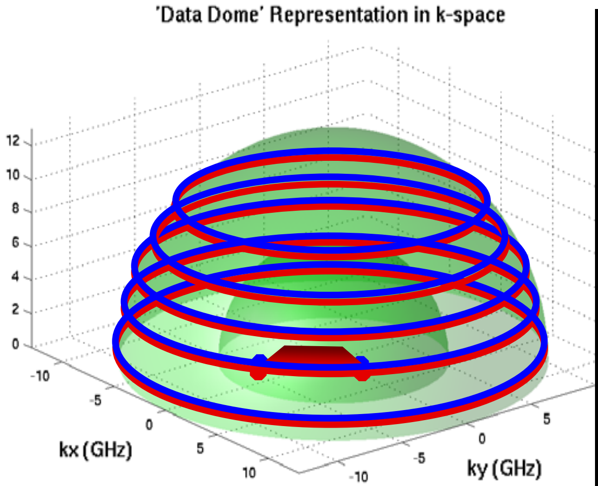


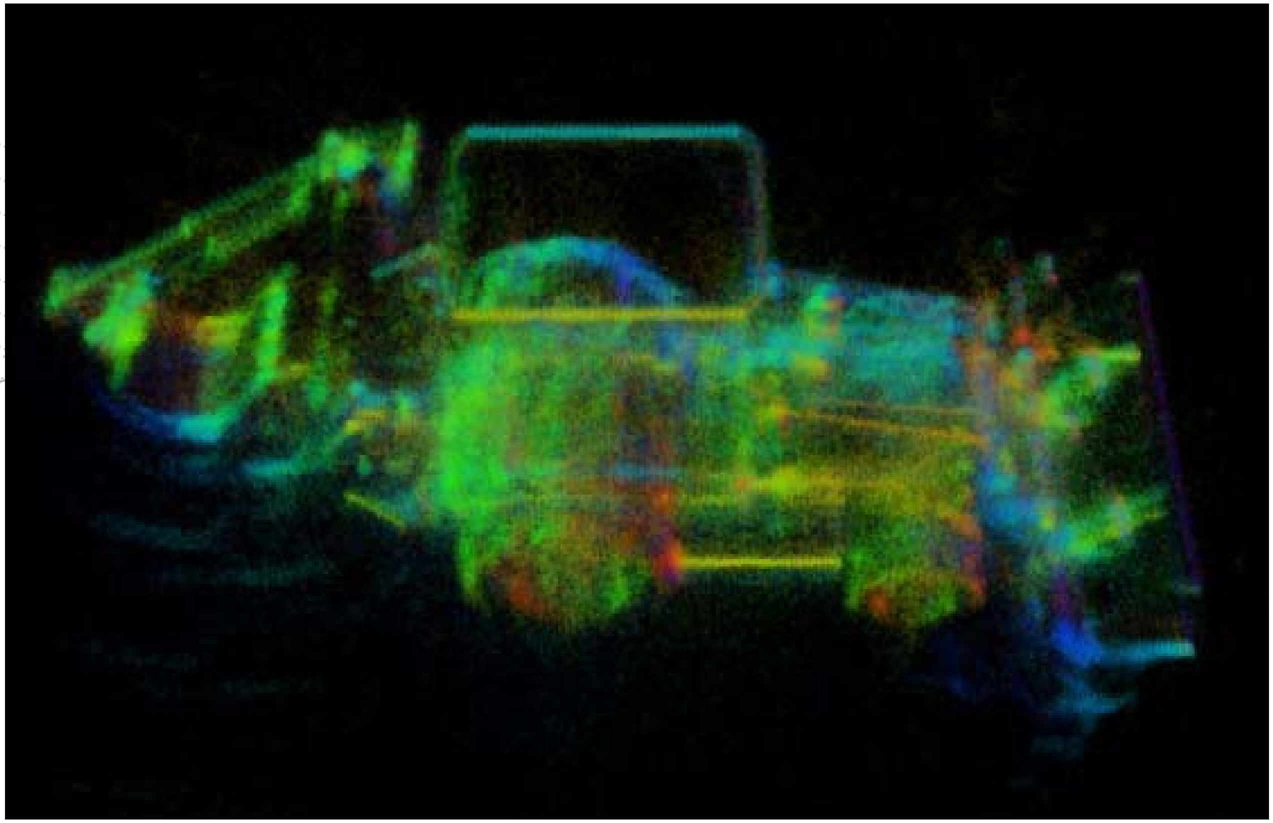
$$g = \boxed{T} f + n$$

$$\hat{f} = \arg\min_{f} \{ -\log p(g|f) + \Psi(f) \}$$

Cetin (MIT) + Moses (OSU)

Wide-Angle SAR

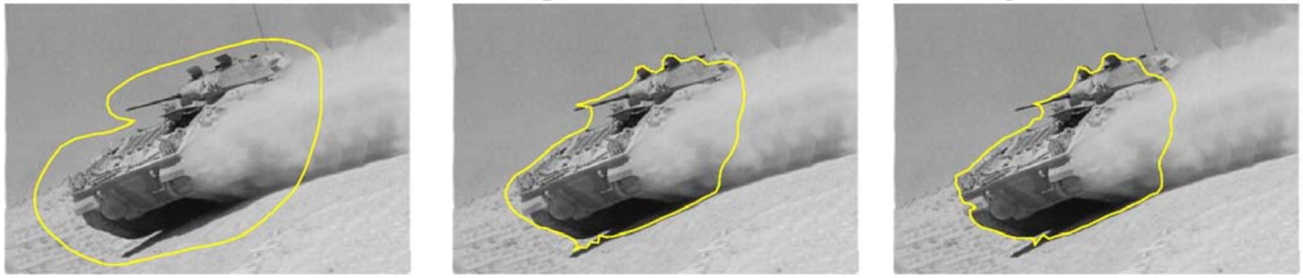




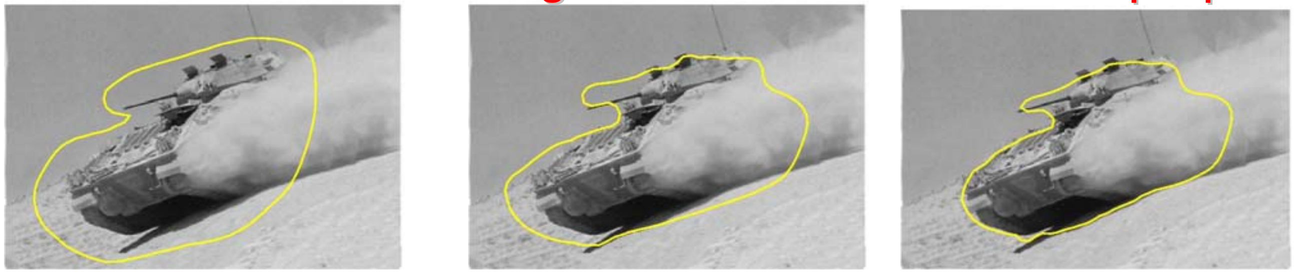
Shape as a Statistical Feature

- Statistical models for shape
  - Across modalities
- Bayesian shape estimation
  - Uncertainty
- Invariance of shape across wavelength (HSI), sensor modality

Contour evolution using data likelihood only

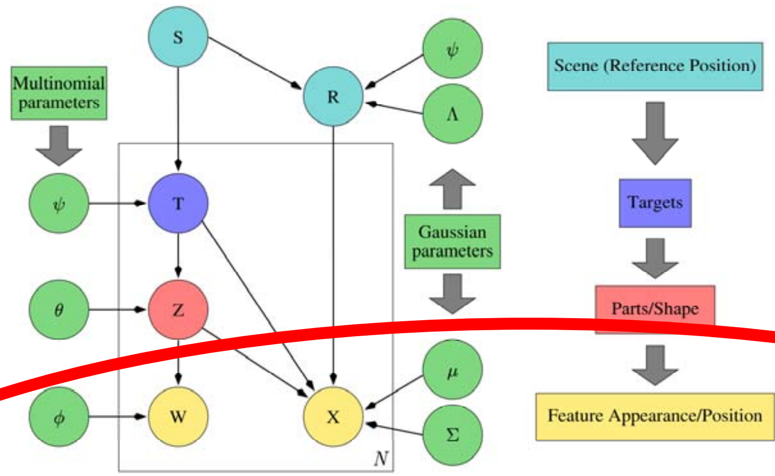


Contour evolution using data likelihood and shape prior



Srivastava (FSU)

Combined Signal Processing and Fusion



$$g = Tf + n$$

$$\hat{f} = \arg\min_{f} \{-\log p(g|f) + \Psi(f)\}$$

SENSOR #N

SENSOR #2

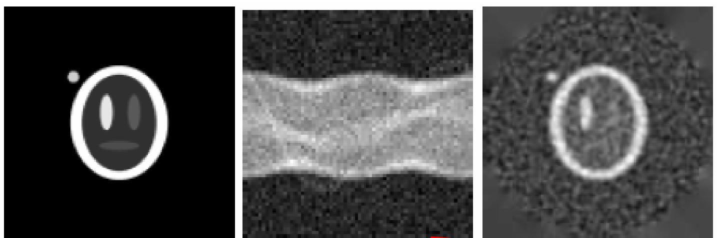
SENSOR #1

Features and Feature uncertainties

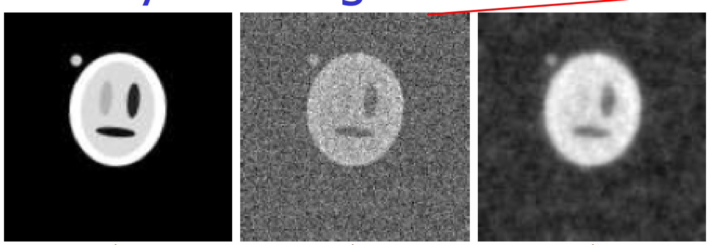
Combine front-end signal processing and lower-tier fusion for, e.g. co-located sensors.

Cross-Modality Processing

Modality 1: Tomographic



Modality 2: Image



true

msmts

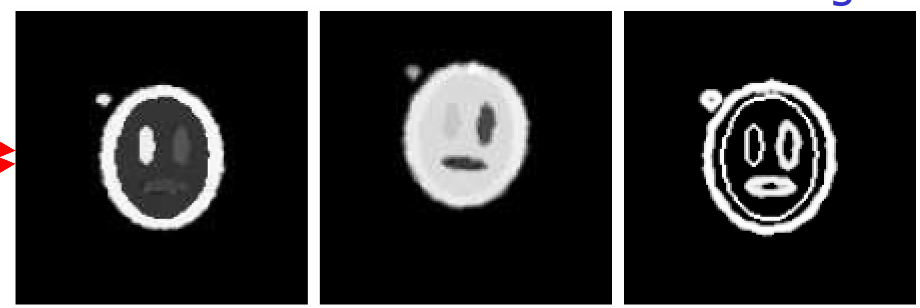
single mode
reconstructions

Combined-Mode Reconstructions

Mode 1

Mode 2

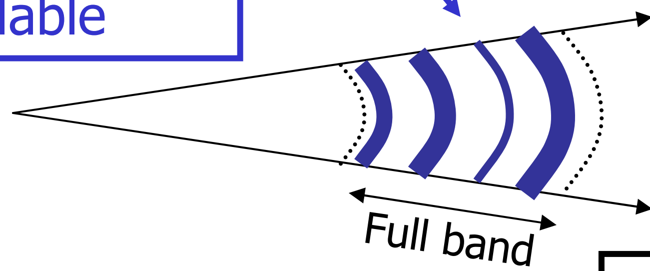
Fused Edges

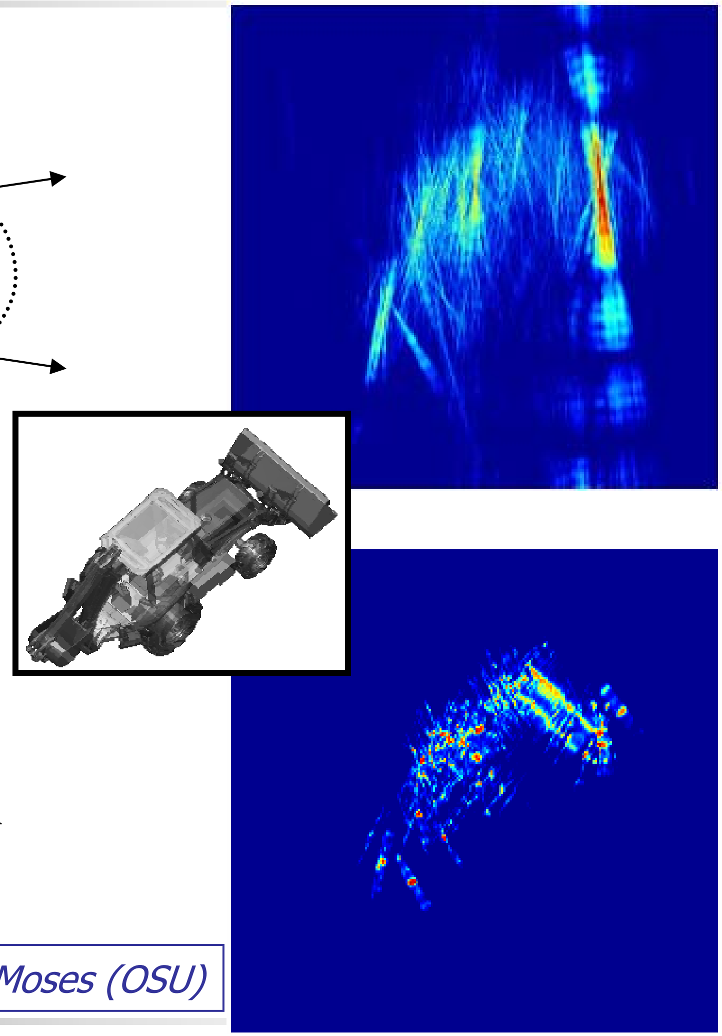


Karl (BU)

Adaptation in Imaging

Only 30% of the freq band is available





Change T on-the-fly.

$$g = \boxed{T} f + n$$

$$\hat{f} = \arg\min_{f} \{-\log p(g|f) + \Psi(f)\}$$

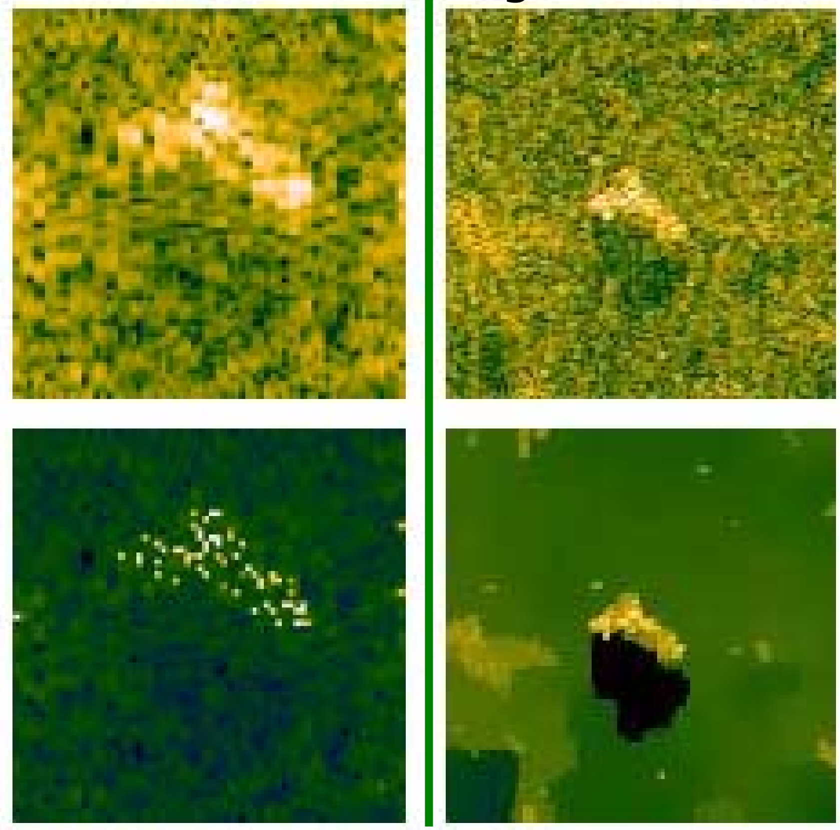
Cetin (MIT) + Moses (OSU)

Decision-Directed Imaging

$$\hat{f} = \arg\min_{f} \{-\log p(g|f) + \Psi(f)\}$$

Changing $\Psi(f)$ changes image and enhances/suppresses features of interest.

Point-enhanced | Region-enhanced



Cetin (MIT) + Karl (BU)

What we'll be doing
I: Topics where we're up and running

- Attributed Scattering Centers
  - Models for sparse, multistatic, 3D apertures
  - Robust parameter estimation
    - Links to priors, decision-directed FE
- Model-based, decision-directed image formation
  - Sparse and non-standard apertures
  - Feature uncertainty
  - Joint multi-sensor inversion and image enhancement
- Statistical Shape Models
  - Represent shapes as elements of infinite-dimensional manifolds
  - Analyze shapes using manifold geometry
  - Develop statistical tools for clustering, learning, recognition

What we'll be doing
II: Topics that are on the horizon

- Decision-Directed Feature Extraction
  - Higher-level hypotheses-driven signal processing (for feature extraction and to answer "queries")
    - For example: High-level information to guide choice of sparse representation dictionaries
    - Think PEMS
  - Object-level models in the signal processing framework
- Unified Parametric/Nonparametric Processing
  - Basis sets and sparseness metrics derived from parametric models
  - Sampling/linearization connection between parametric and nonparametric
    - Feature extraction and feature uncertainty

What we'll be doing
II: Topics that are on the horizon

- Shape/object-regularized inversion.
  - Include object shape information into front-end processing
- Multi-modal imaging and feature extraction
  - Joint multi-modal approaches.
- Compressed sensing
  - Focus sensing on information of interest.
  - Links to model-based formulations