Radar Signal Processing: Opportunities for SSPers

Randy Moses

Dept. of Electrical and Computer Engineering
The Ohio State University

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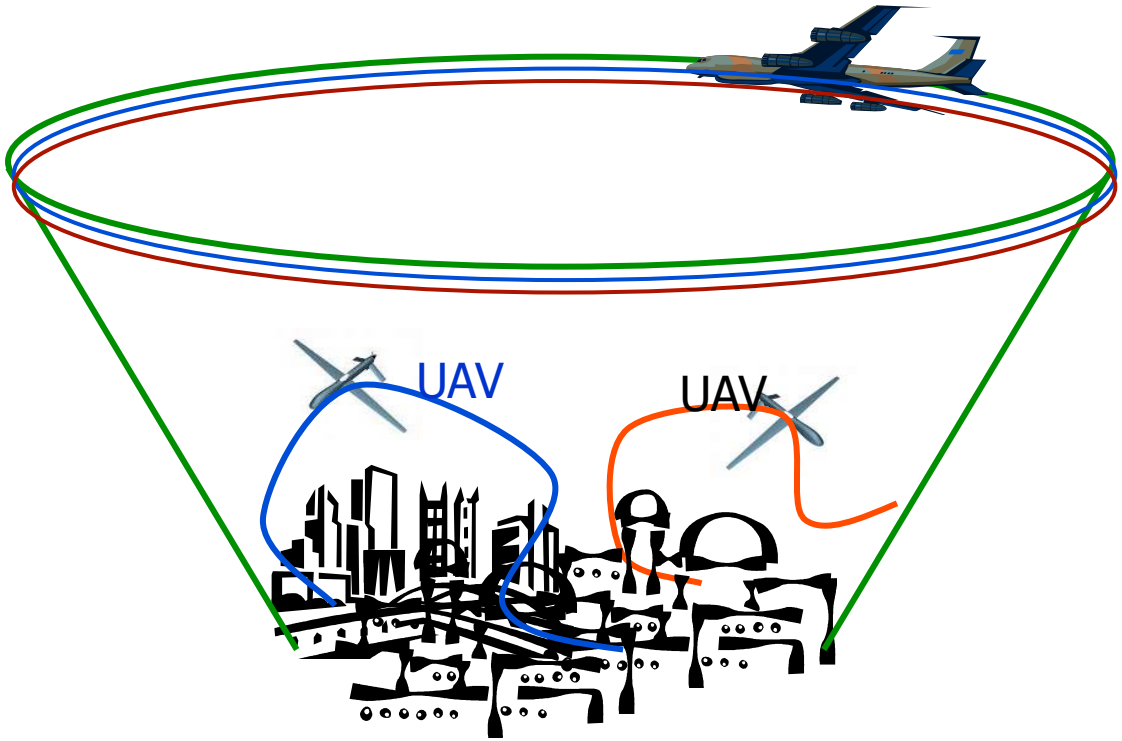
Context

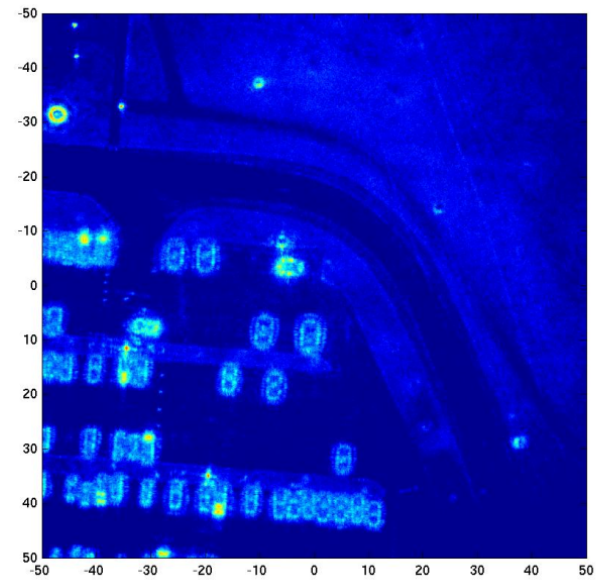
- Advances in digital processing are enabling revolutionary opportunities for radar signal processing

- Opportunities for Statistical Signal Processing
  - Persistent sensing over space and time
  - More sophisticated radar image/volume reconstructions
  - Multi-function radars that can simultaneously perform imaging, detection, moving object tracking and recognition, …
  - Uncertainty analysis and estimation bounds

- Challenges
  - Traditional models for radar backscattering may not apply over wide angles
  - Large data, processing, and communications tasks

Persistent, Wide-Angle Radar





Persistent Sensing enables:

- ***High resolution, volumetric imaging of stationary objects and scenes***
- ***Continuous tracking of moving objects***

Outline

- Radar 101
- Revisit modeling assumptions for wide angle radar
- How can sparsity play a role?
  - Parametric Modeling
  - Sparse Reconstruction
- Feature-Based Classification
- Transmit adaptation

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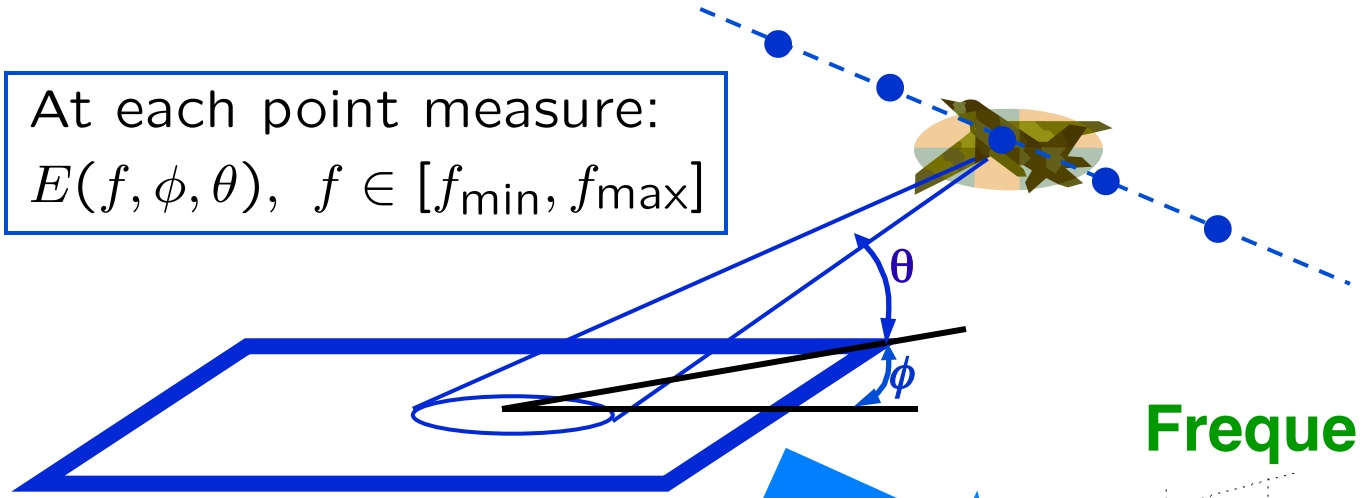
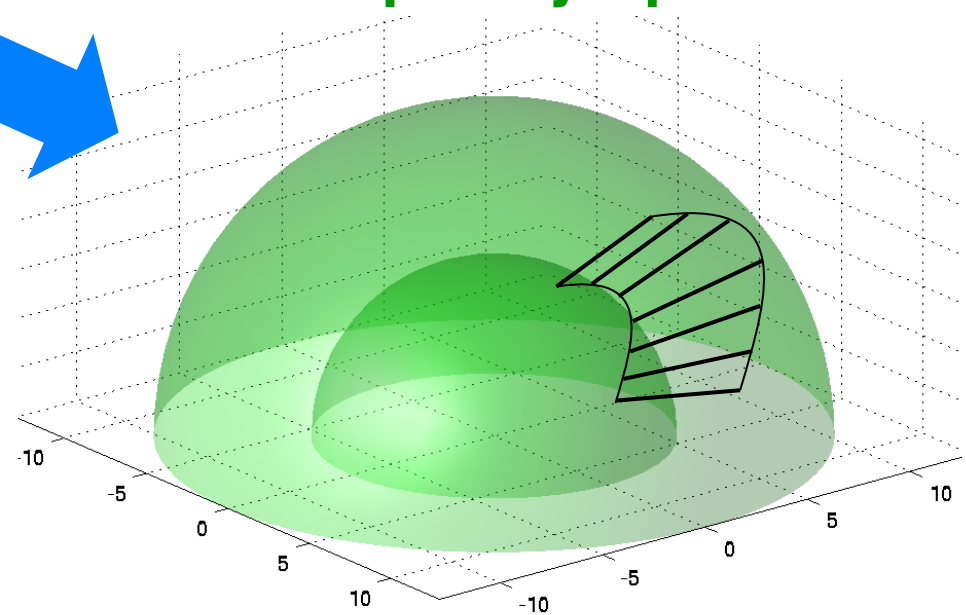
SAR Data Collection

At each point measure:

$E(f, \phi, \theta), \;\; f \in [f_{\text{min}}, f_{\text{max}}]$

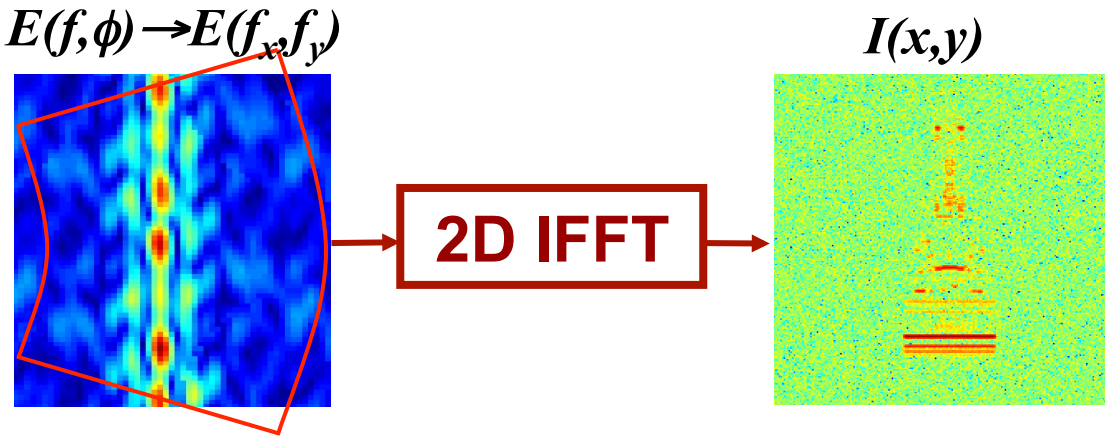


Frequency Space



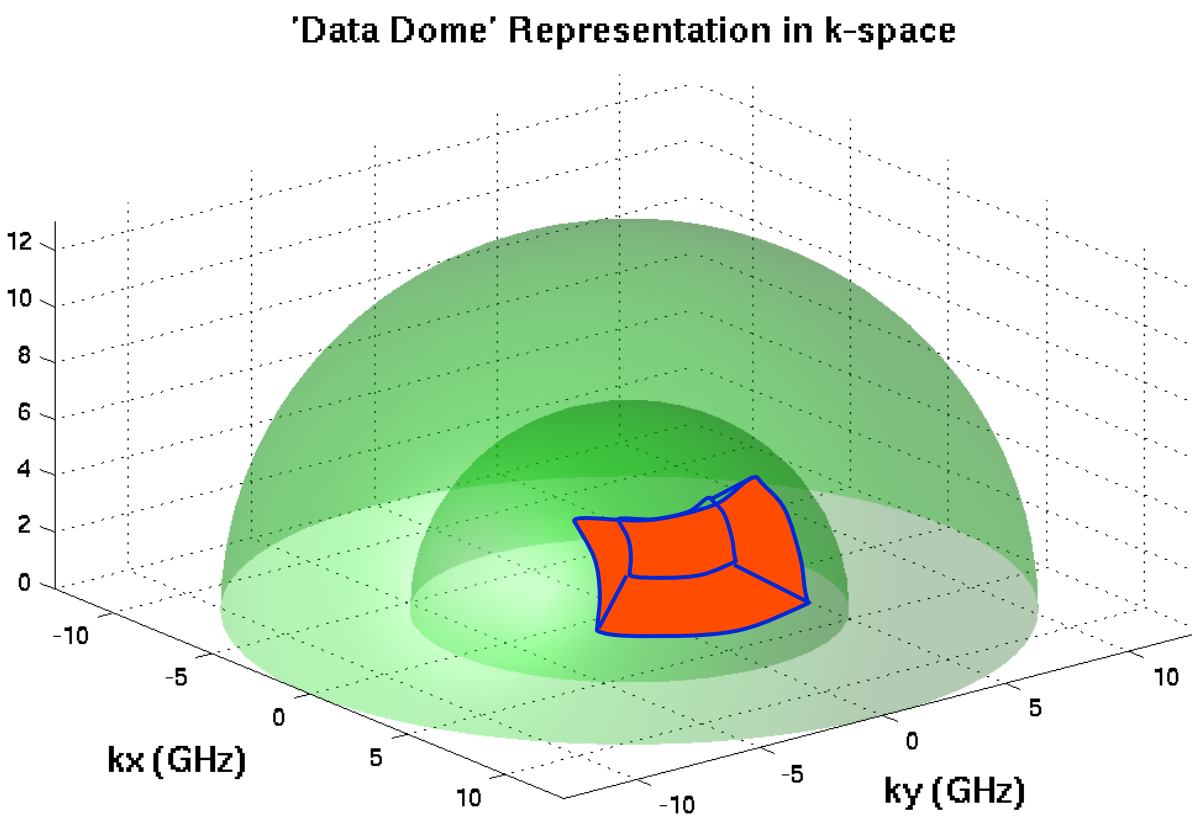
SAR Image Formation

- Traditional approach: tomography



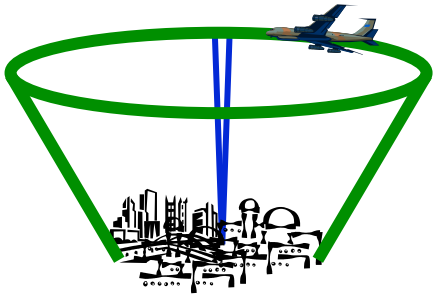
- Tomographic image $I(x,y)$ is a **matched filter** for an isotropic point scatterer at location (x,y). [Rossi+Willsky]

3D Reconstruction



- Large data size and processing requirements
- Filled aperture is difficult to collect

Example: Ohio Stadium



X-Band Radar
3° aperture
1ft x 1ft res

SAR Image Detail

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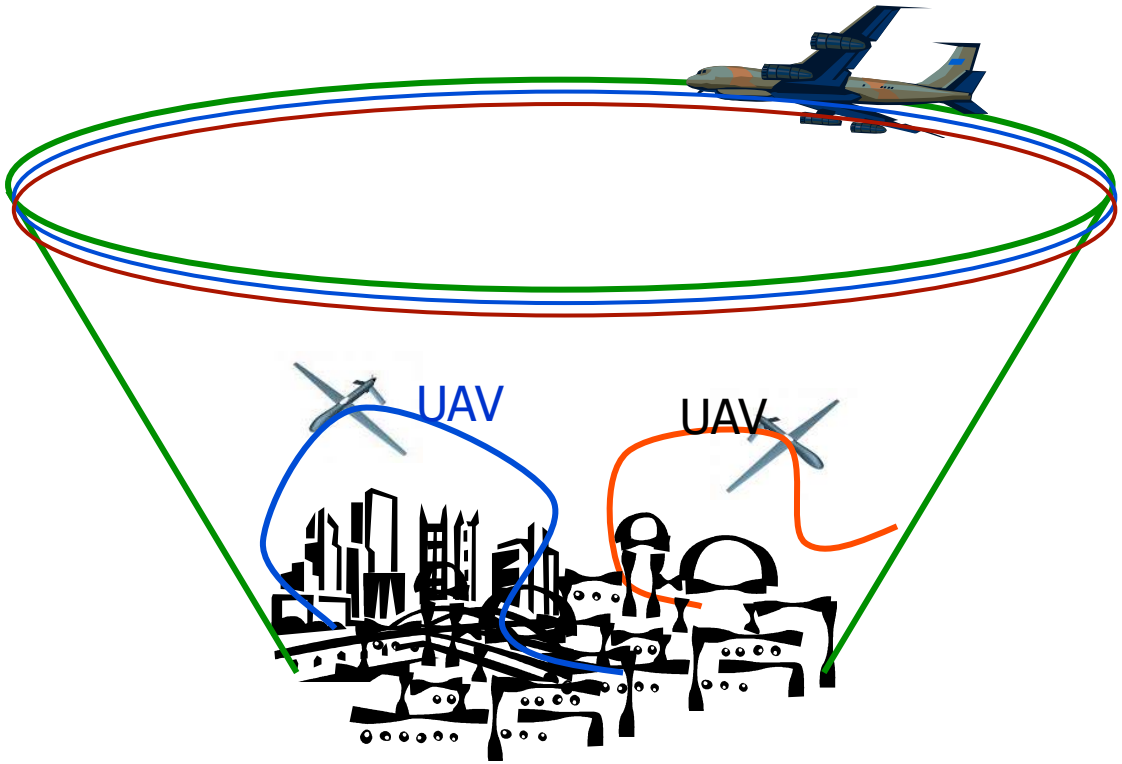
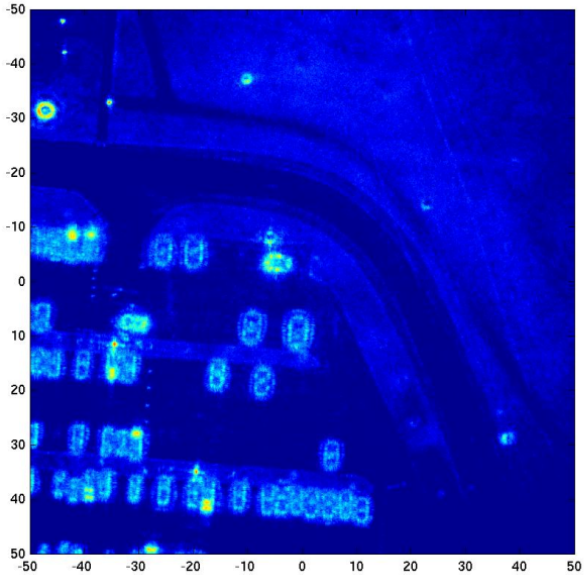
Persistent, Wide-Angle SAR

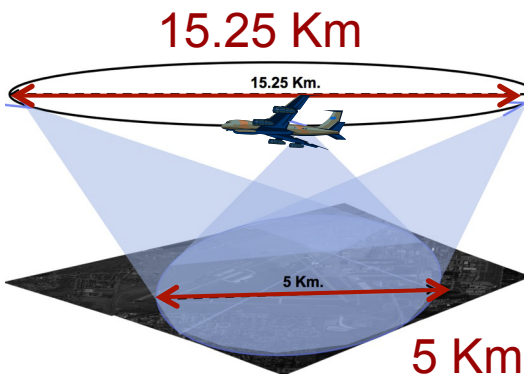




Persistent Sensing enables:

- ***High resolution, volumetric imaging of stationary objects***
- ***Continuous tracking of moving objects***

AFRL Gotcha Radar



Data Storage:

90 G samples/circle

Image formation:

45 Tflops/sec

Communications:

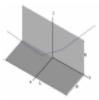
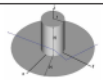
190 M samples/sec

Wide Angle Scattering Behavior

- At high frequencies, radar backscatter is well-modeled as a sum of responses from canonical scattering terms.
- EM scattering theory provides a rich characterization of backscatter behavior as a function of object shape
  - Azimuth, elevation, frequency dependence
  - Polarization dependence
  - Phase response - range
- Most backscatter does NOT behave like a point scatterer over wide angles
  - Standard imaging is not statistically (close to) optimal

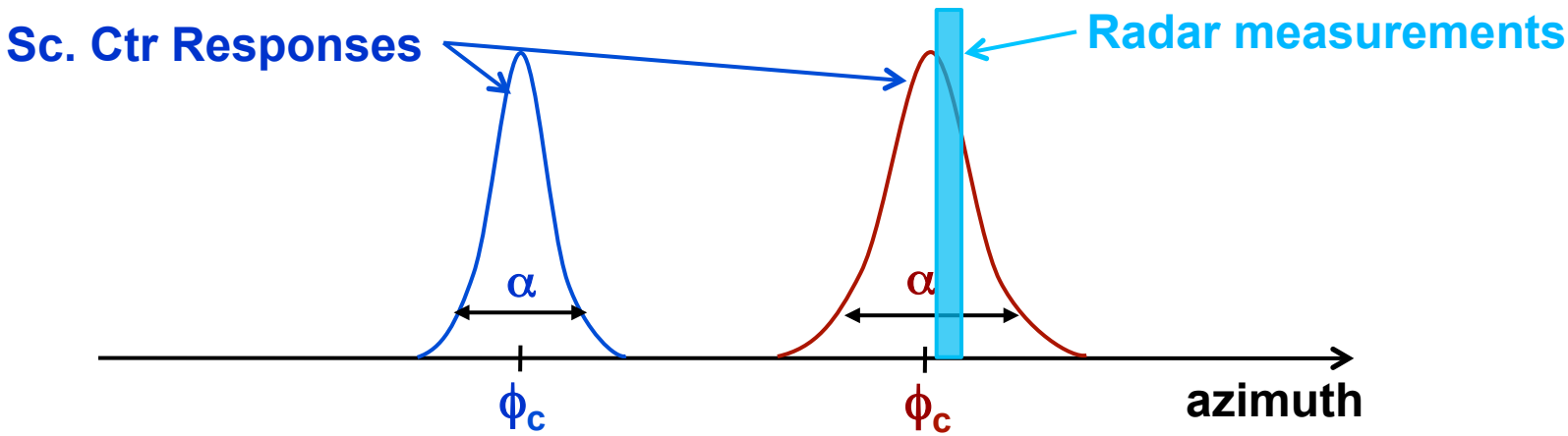
Scattering Model

$$S(f,\phi,\theta) = \underbrace{\begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}}_{\text{Polarization Dependence}} \underbrace{\left(\frac{jf}{f_c}\right)^{\gamma}}_{\text{Frequency Dependence}} \underbrace{M(\phi,\theta)}_{\text{Aspect Dependence}} \underbrace{e^{j\frac{4\pi f}{f_c}\Delta R(x,y,z;a)}}_{\text{Location Dependence}}$$

Canonical Shape Type Γ	Icon	Polarization Type β	Amplitude Response $M_\Gamma(k,\hat{\phi},\hat{\theta};\Theta)$	Calibration Factor A	Range Offset ΔR_r
Plate		odd	$M_{\text{plate}}(\Theta_{\text{plate}}) = \frac{jkA}{\sqrt{\pi}}\,\text{sinc}\left[kL\sin\hat{\phi}\cos\hat{\theta}\right]\text{sinc}\left[kH\sin\hat{\theta}\right]$ $\hat{\phi}\in\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$	LH	0
Dihedral		even	$M_{\text{dih}}(\Theta_{\text{dih}}) = \frac{jk}{\sqrt{\pi}}A\,\text{sinc}\left[kL\sin\hat{\phi}\cos\hat{\theta}\right] \times \begin{cases}\sin\hat{\theta}, & \hat{\theta}\in\left[0,\frac{\pi}{4}\right]\\ \cos\hat{\theta}, & \hat{\theta}\in\left[\frac{\pi}{4},\frac{\pi}{2}\right]\end{cases}, \quad \hat{\phi}\in\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$	$2LH$	0
Trihedral		odd	$M_{\text{tri}}(\Theta_{\text{tri}}) = \frac{jkA}{2\sqrt{\pi}} \times \begin{Bmatrix}-\cos\left(\hat{\phi}-\frac{\pi}{4}\right), & \hat{\phi}\in\left[\frac{-\pi}{4},0\right]\\ \sin\left(\hat{\phi}-\frac{\pi}{4}\right), & \hat{\phi}\in\left[0,\frac{\pi}{4}\right]\end{Bmatrix} \times \begin{Bmatrix}\sin\left(\hat{\theta}+\frac{\pi}{4}-\tan^{-1}\left(\frac{1}{\sqrt{2}}\right)\right), & \hat{\theta}\in\left[0,\tan^{-1}\left(\frac{1}{\sqrt{2}}\right)\right]\\ \cos\left(\theta+\frac{\pi}{4}-\tan^{-1}\left(\frac{1}{\sqrt{2}}\right)\right), & \hat{\theta}\in\left[\tan^{-1}\left(\frac{1}{\sqrt{2}}\right),\frac{\pi}{2}\right]\end{Bmatrix}$	$2\sqrt{3}H^2$	0
Cylinder		odd	$M_{\text{cyl}}(\Theta_{\text{cyl}}) = jk\sqrt{\cos\hat{\phi}}A\,\text{sinc}\left[kL\sin\hat{\phi}\right] \quad \hat{\phi}\in\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$	$L\sqrt{r}$	$2r\cos\phi$
Top-hat		even	$M_{\text{top}}(\Theta_{\text{top}}) = A\sqrt{jk} \times \begin{cases}\sin\hat{\theta}, & \hat{\theta}\in\left[0,\frac{\pi}{4}\right]\\ \cos\hat{\theta}, & \hat{\theta}\in\left[\frac{\pi}{4},\frac{\pi}{2}\right]\end{cases}$	$\sqrt{\frac{8r}{\sqrt{2}}}H$	$2r\cos\theta$
Sphere		odd	$M_{\text{sphere}}(\Theta_{\text{sphere}}) = A\sqrt{\pi}r$	1	$2r$

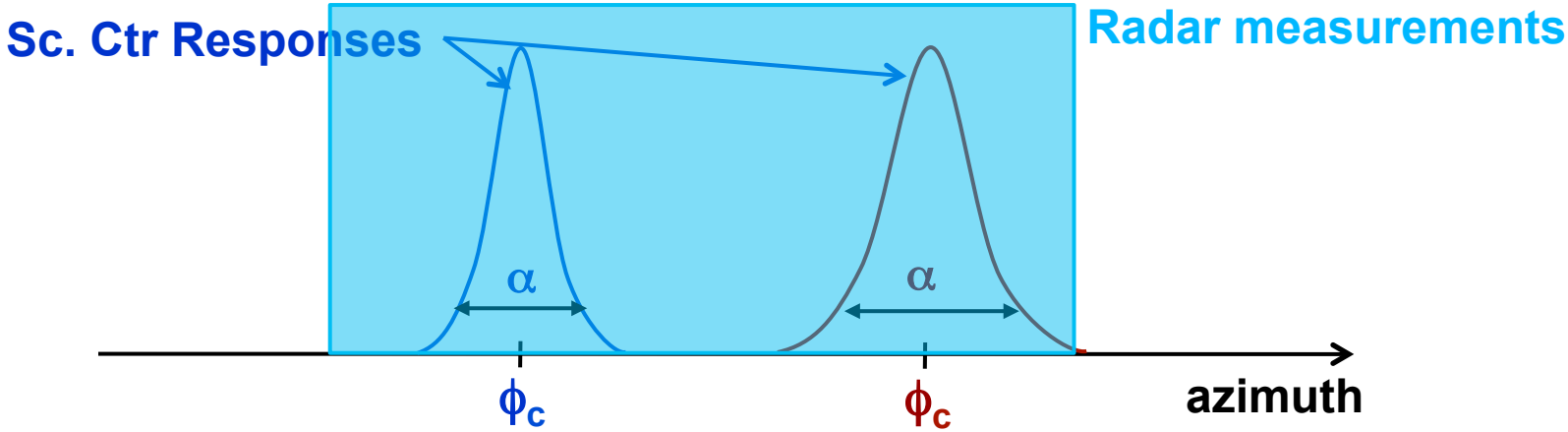
Jackson & RLM: *2009*

Wide-Angle Data Collections



When the radar measurement extent is ≤ scattering persistence, the isotropic assumption is ~satisfied, and tomographic imaging is ~a matched filter.

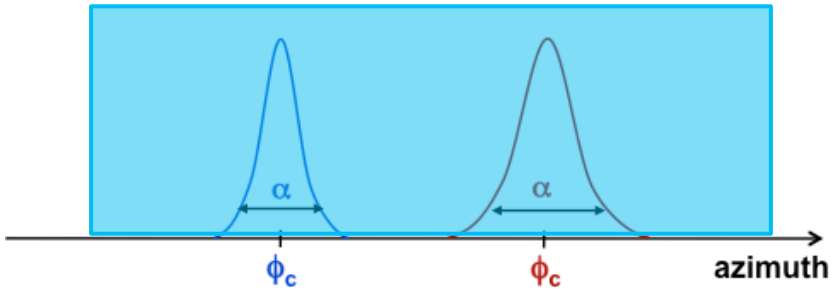
Wide-Angle Data Collections

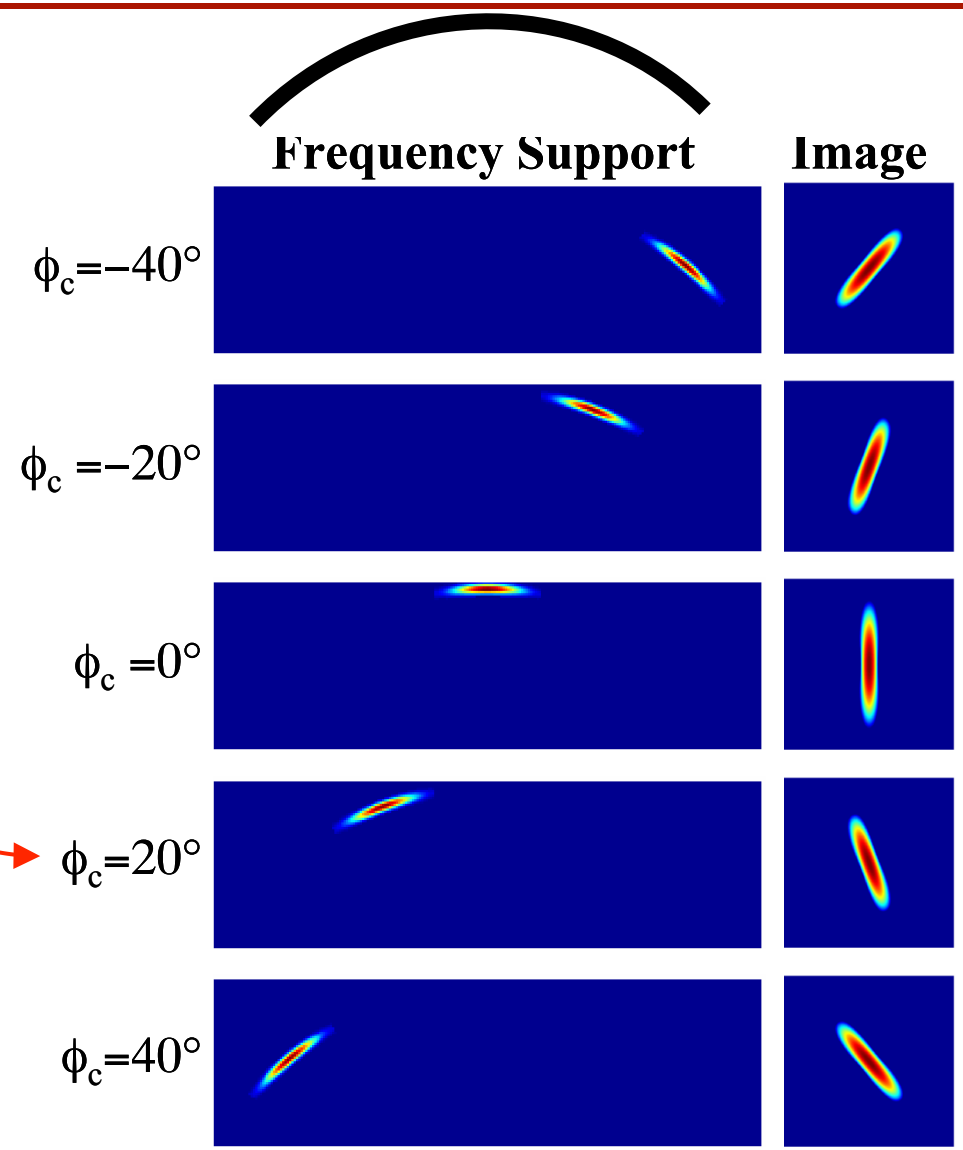


For wide-angle measurements the isotropic scattering assumption breaks down.

– Tomography is no longer a matched filter

Scattering Aspect Dependence

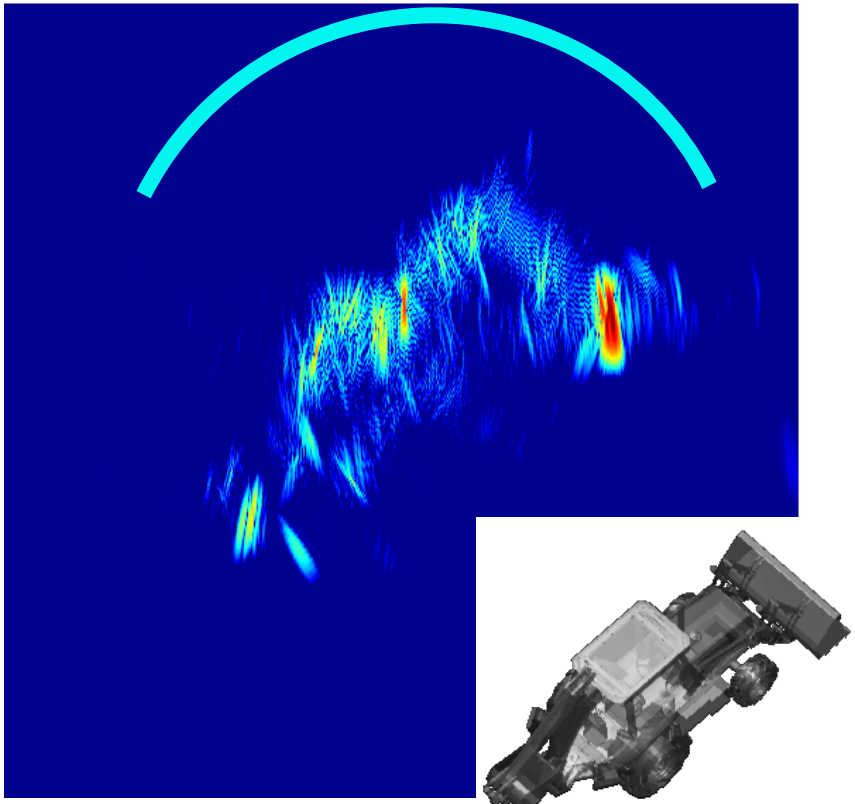




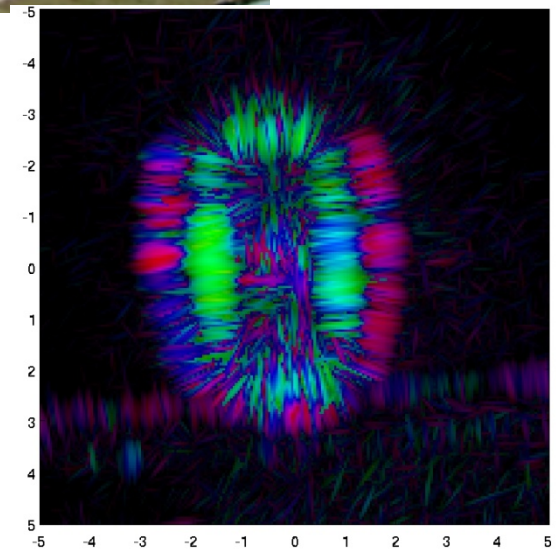
Most scattering centers have limited response persistence 20° or less [Dudgeon et al, 1994]

Image response is no longer characterized by a single impulse response shape.

Coherent wide-angle SAR Images



500 MHz Bandwidth
110 degrees az

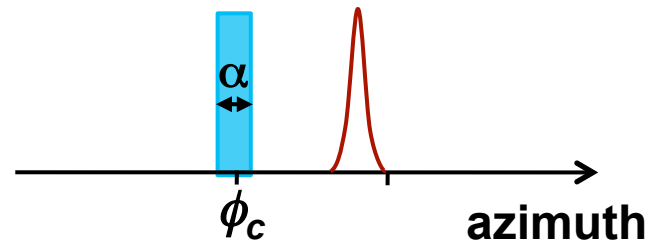


Coherent wide-angle image is not well-matched to limited persistence scattering behavior

GLRT Image Formation

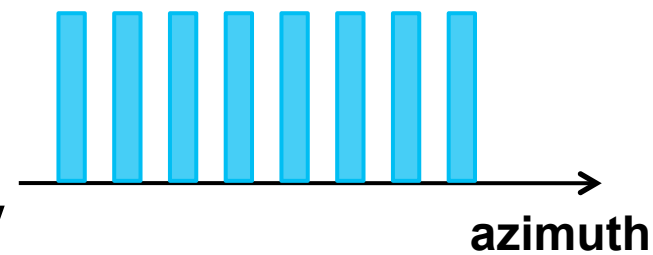
GLRT Image: Image $I(x,y)$ is GLRT output at (x,y) to a limited-persistence scattering center with center ϕ_c and width α.

$$I(x,y) = \arg\max_{\phi_c,\alpha} R(x,y,\phi_c,\alpha)$$



$$R(x,y,\phi_c,\alpha) = \text{std image with center } \phi_c\text{, width } \alpha$$

Approximation: fix width α; quantize ϕ_c.

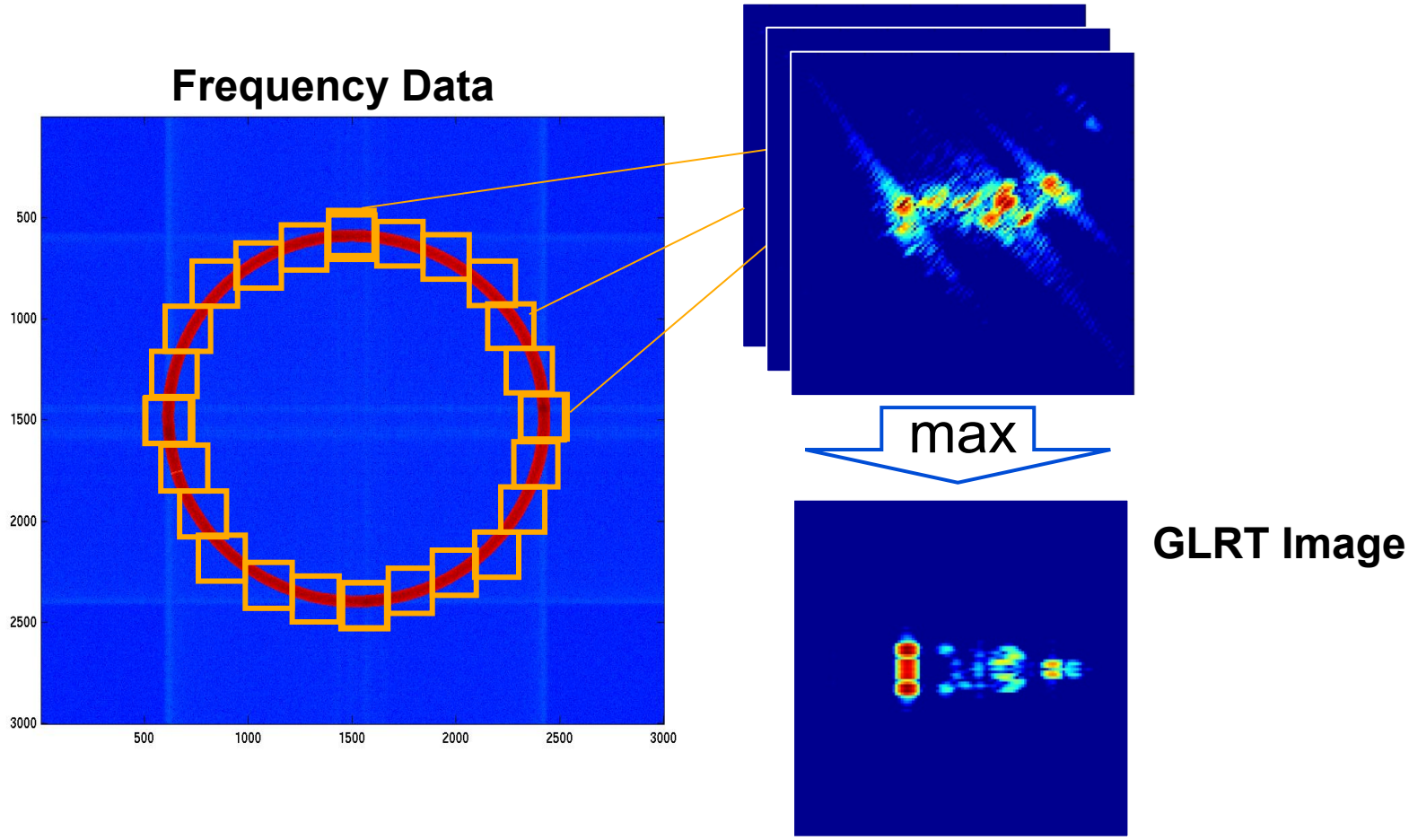


Then the GLRT image is approximately max over sub-aperture images.

GLRT Image: pixel $p_{ij} = \arg\max_{\phi_c} p_{ij}^{\phi_c} \approx \arg\max_{k} p_{ij}^{k}$

RLM, Potter, Cetin: *2004*

GRLT Imaging

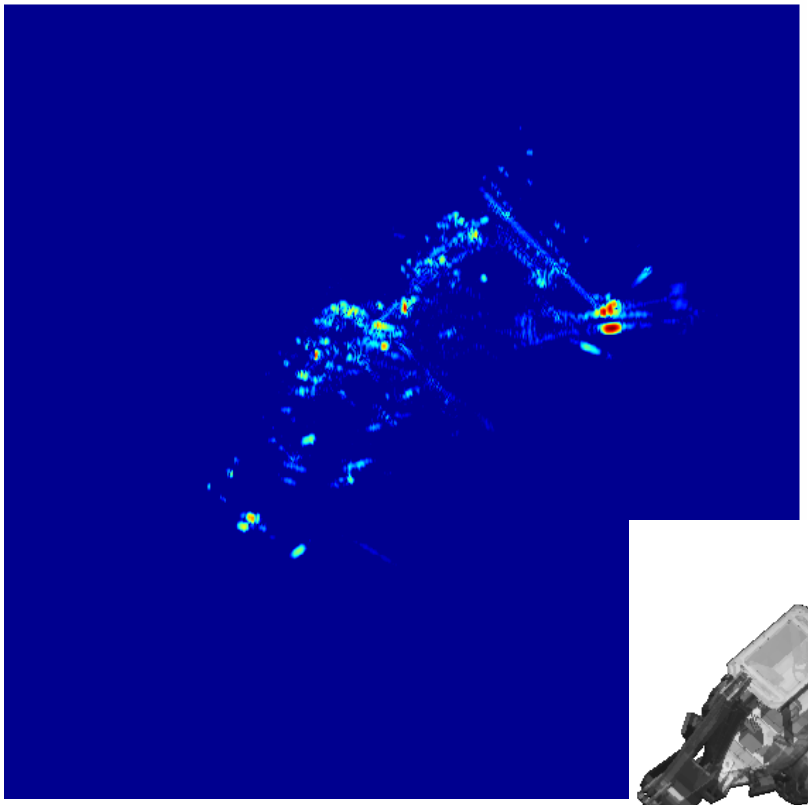


Generalizes Rossi+Willsky matched filter result to wide-angle imaging with limited-persistence scattering

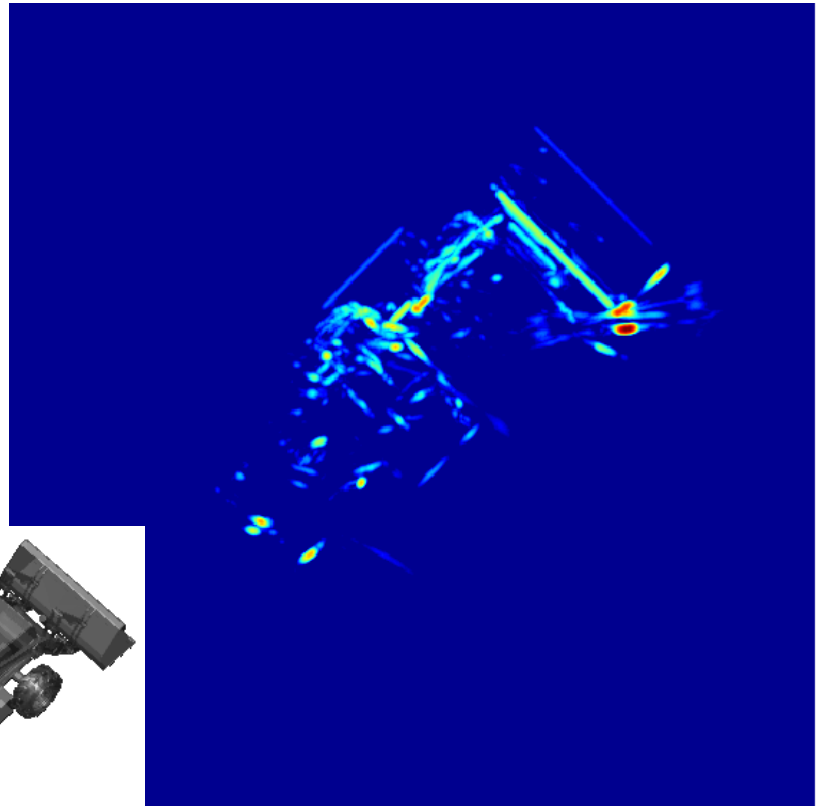
RLM, Potter, Cetin: *2004*

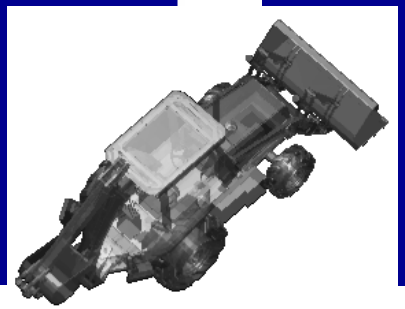
Coherent and GLRT Image

110° Coherent Image



110° GLRT Image





4 GHz bandwidth

RLM, Potter, Cetin: *2004*

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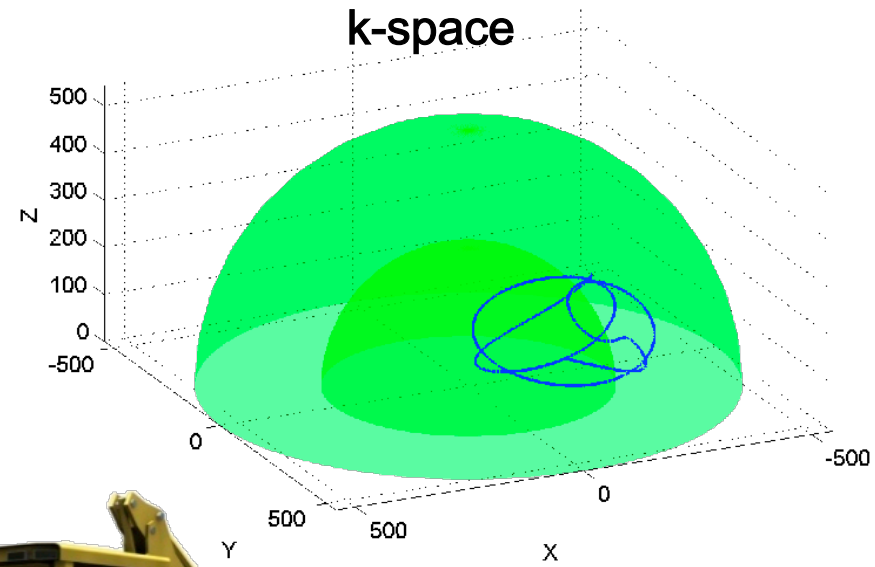
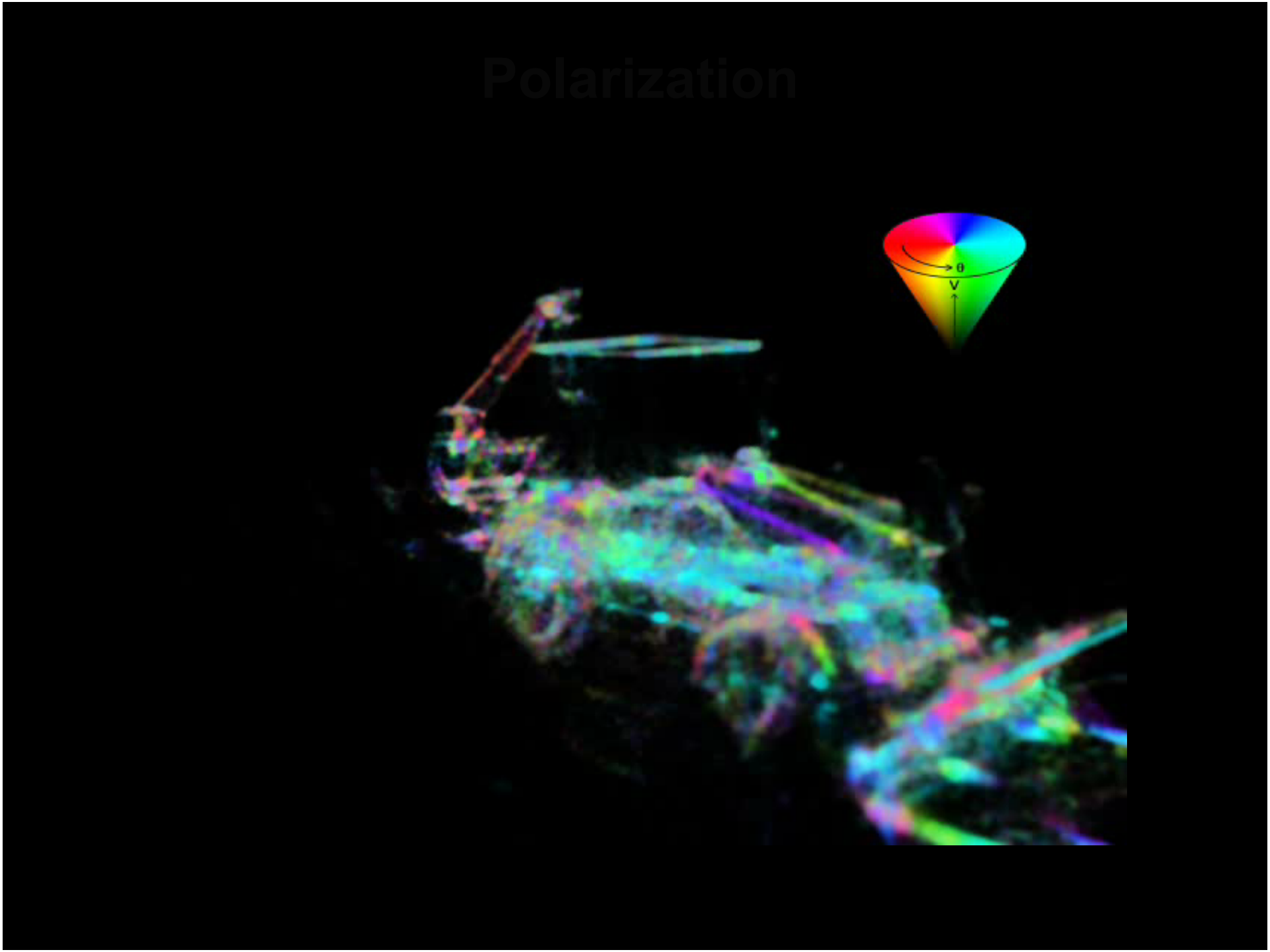
Sparse 3D Radar Reconstruction

- 3D radar reconstruction necessarily will use (very) sparse measurements
- Is the radar reconstruction sufficiently sparse to overcome measurement sparsity?



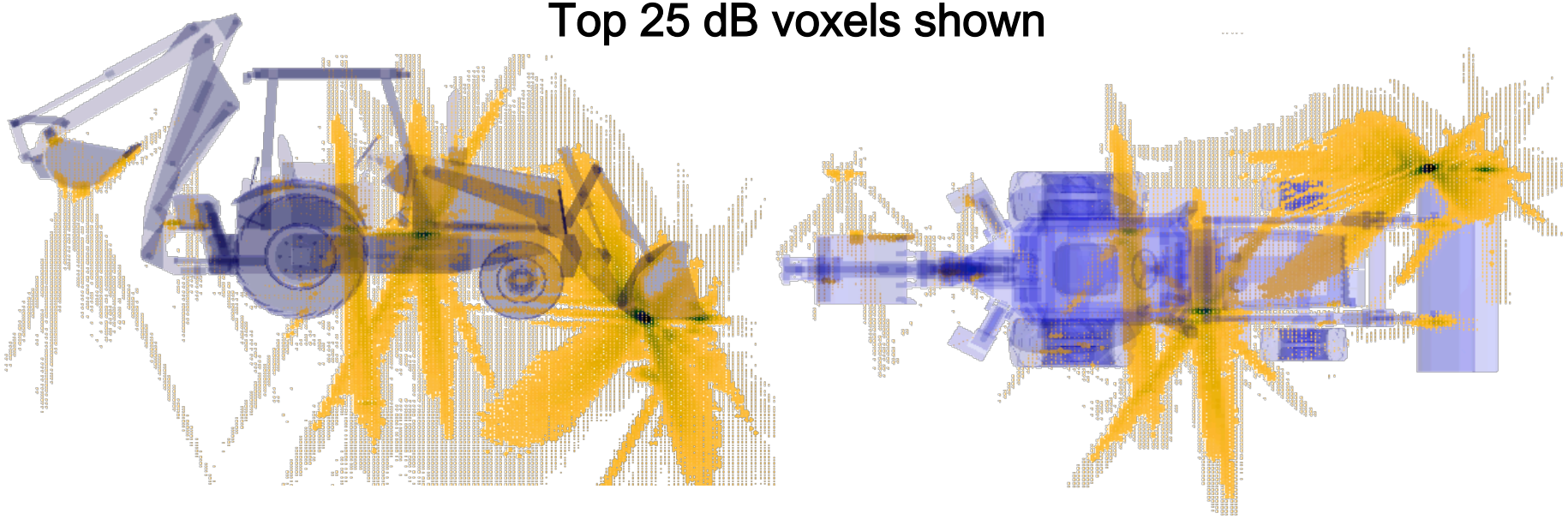
AFRL Backhoe Data Dome, with sparse “squiggle path” shown

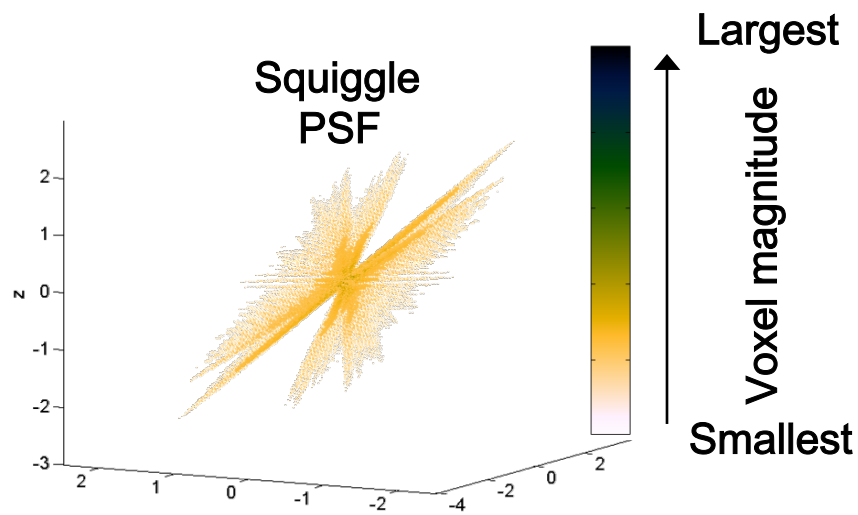
Polarization



Squiggle Path 3D Tomographic Reconstruction

Top 25 dB voxels shown

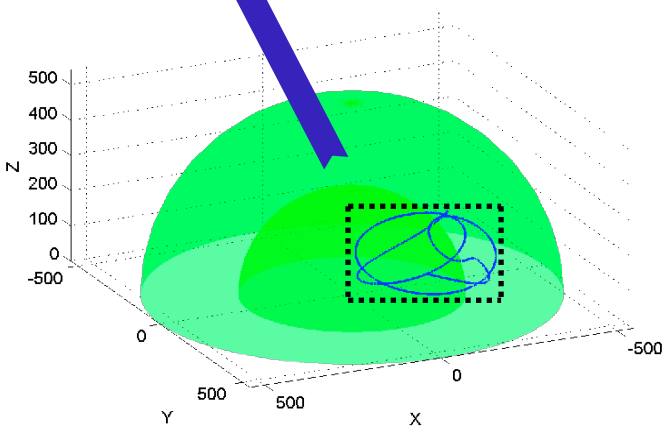


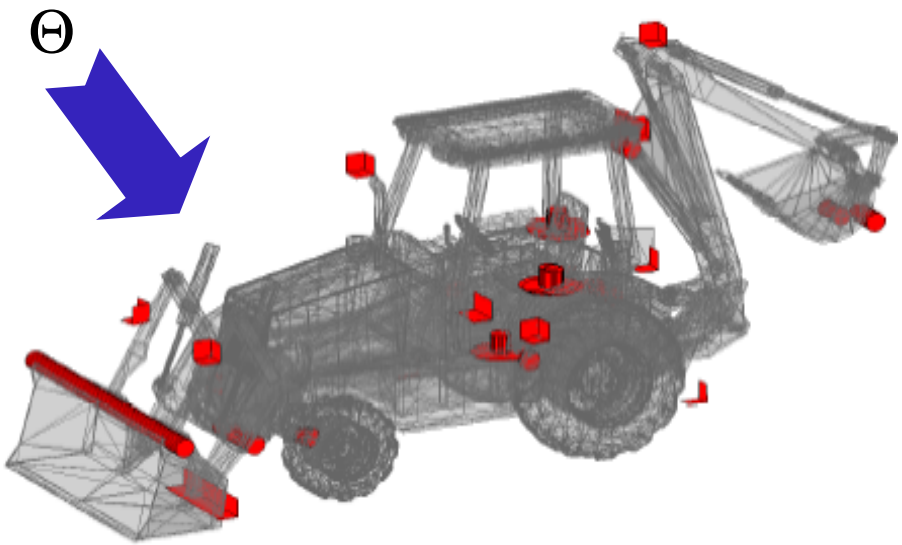


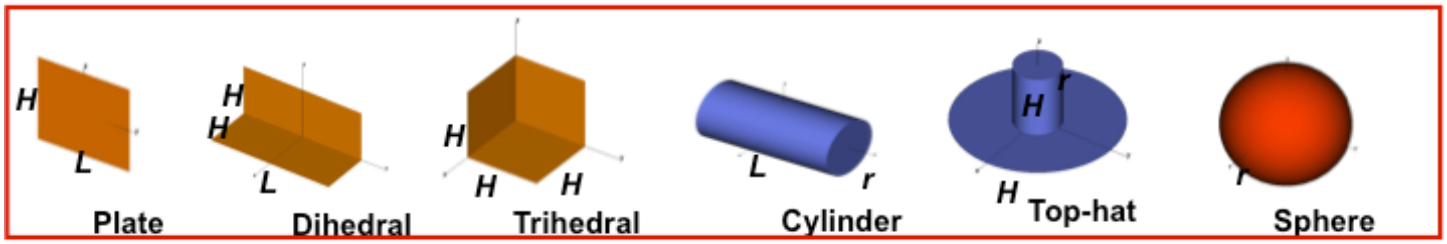
Presented at: the 2012 Statistical Signal Processing Workshop, Ann Arbor

Parametric: Canonical Scattering Model

$$S(f,\phi,\theta) = \sum_{k=1}^{K} \underbrace{\begin{bmatrix} A_{HH} & A_{HV} \\ A_{VH} & A_{VV} \end{bmatrix}_k}_{\text{Polarization Dependence}} \underbrace{\left(\frac{jf}{f_c}\right)^{\gamma_k}}_{\text{Frequency Dependence}} \underbrace{M_k(\phi,\theta)}_{\text{Aspect Dependence}} \underbrace{e^{j\frac{4\pi f}{f_c}\Delta R(x_k,y_k,z_k;a_k)}}_{\text{Location Dependence}}$$







Jackson & RLM: *2009*

Nonparametric: l_p Regularized Least-Squares

Sparsity

- Measurements y ($M \times 1$) : sparse sampling of full (f,az,el) radar measurement space
- Reconstruction: x ($N \times 1$): sparse set of (x,y,z) locations with significant radar scattering energy

$$y = Ax + \nu$$

$$A = \left[e^{-j(k_{x,m}x_n + k_{y,m}y_n + k_{z,m}z_n)} \right], \quad M \times N$$

Sparse reconstruction:

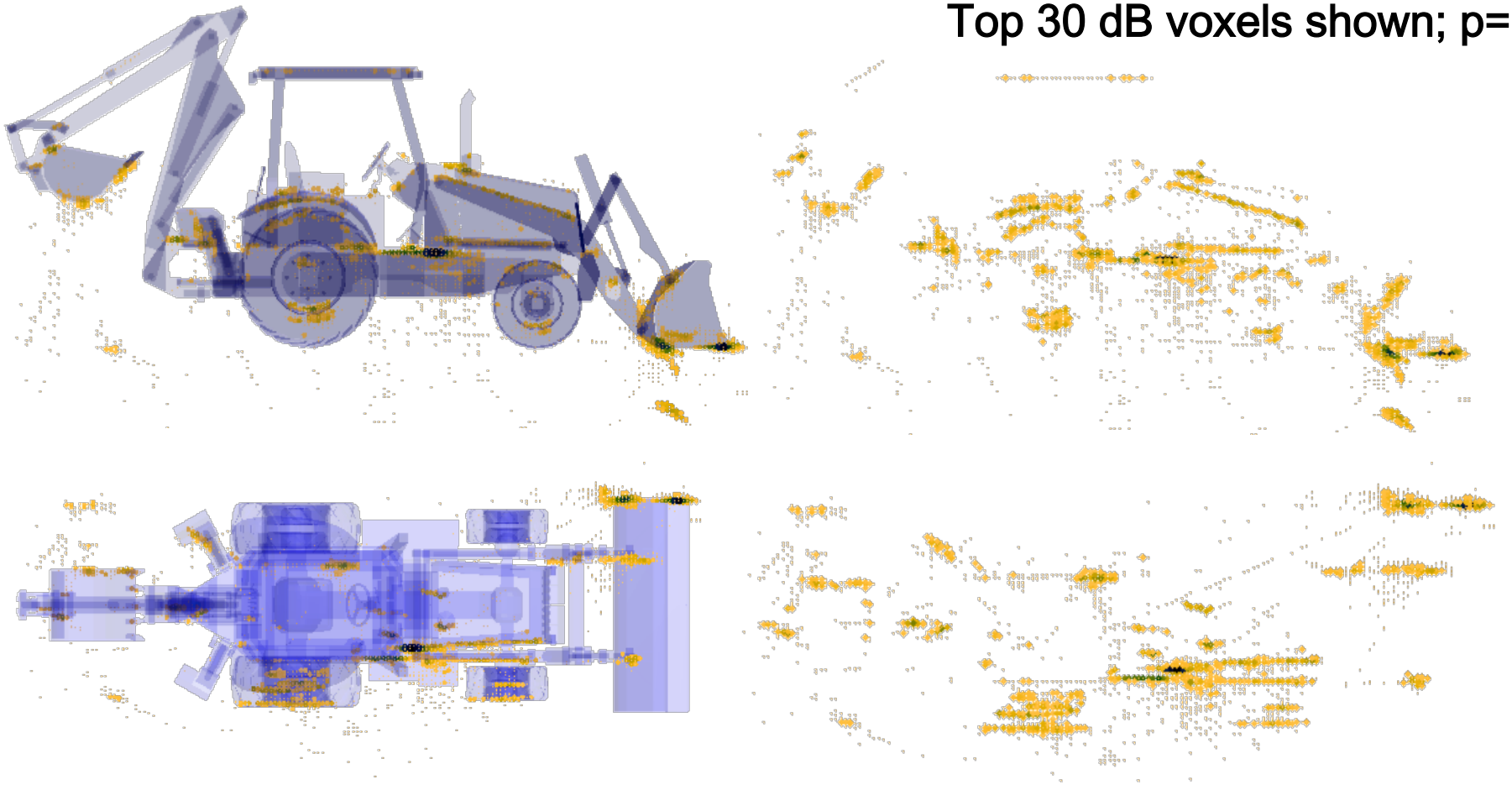
$$\hat{x} = \arg\min_x \ \|y - Ax\|_2^2 + \lambda \|x\|_p^p \quad p \leq 1$$

Algorithmic Challenges

- For large scale problems, the algorithm can become very memory and computationally expensive.
  - E.g. for backhoe squiggle problem:
    - $M \approx 10^5$
    - $N \approx 10^7$
- A is structured and may not satisfy RIP for reconstruction samplings of interest.
  - Recent advances [e.g Austin, Fannjiang] incorporate structure in x to allow high coherence in A.

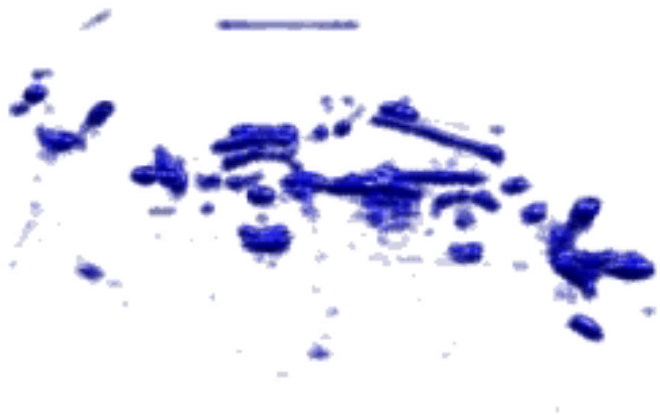
Squiggle Path Collection: l_p Regularized LS Reconstruction

Top 30 dB voxels shown; p=1

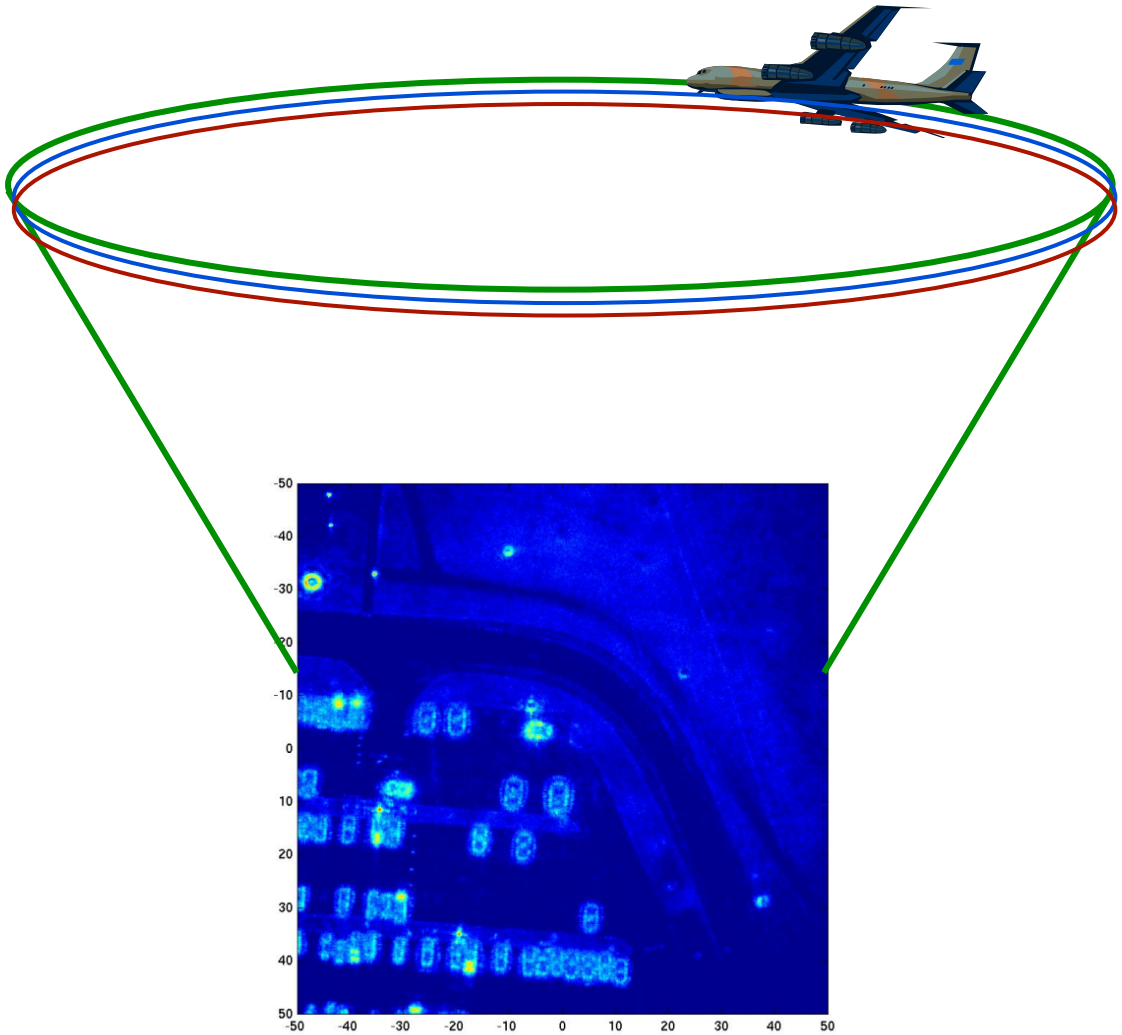


Austin, Ertin, RLM, 2011

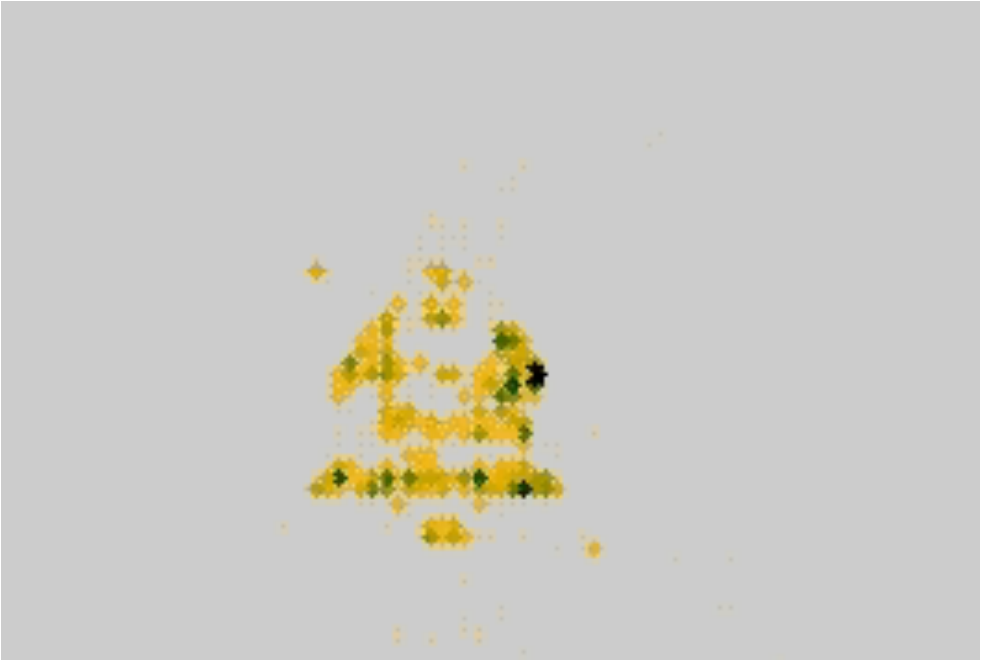
Backhoe Squiggle Image



Gotcha Vehicle Data



Gotcha l_p Reconstructions: Camry



Austin, Ertin, RLM, 2011

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Vehicle Classification

Malibu

Sentra

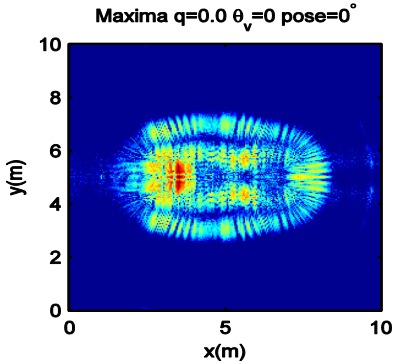
Camry

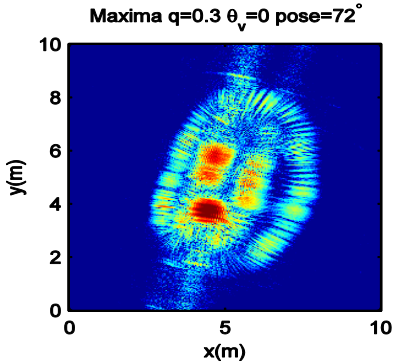
Taurus

Prism

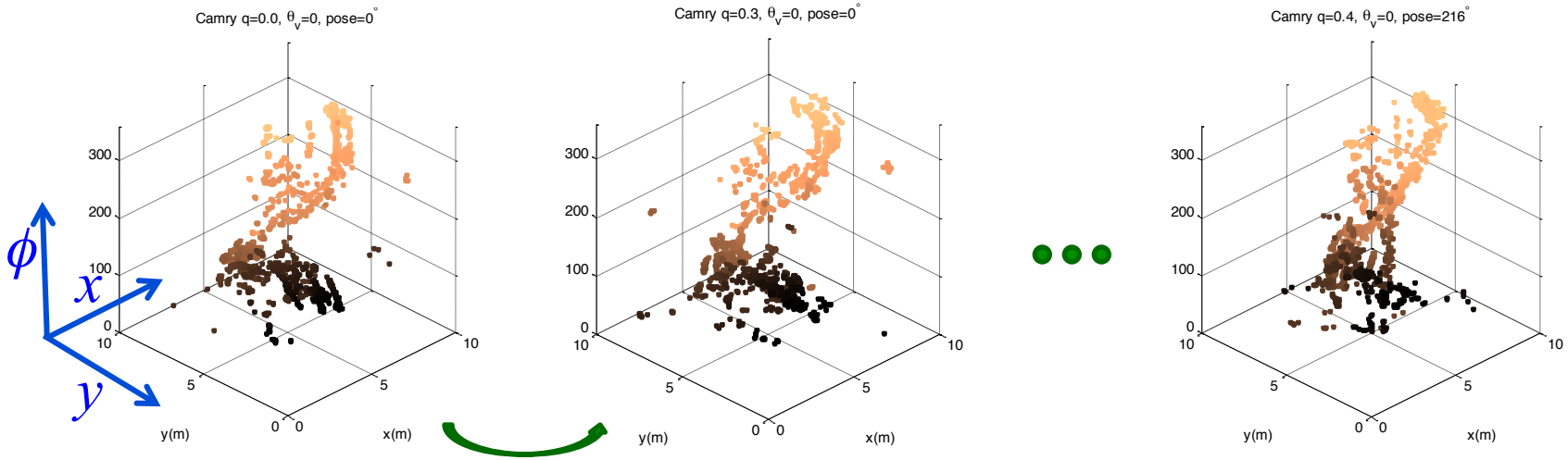
Maxima

- Six sedans from a 10-class problem
- Spatially-varying signatures across large scene





Vehicle Classification; Attributed Point Sets

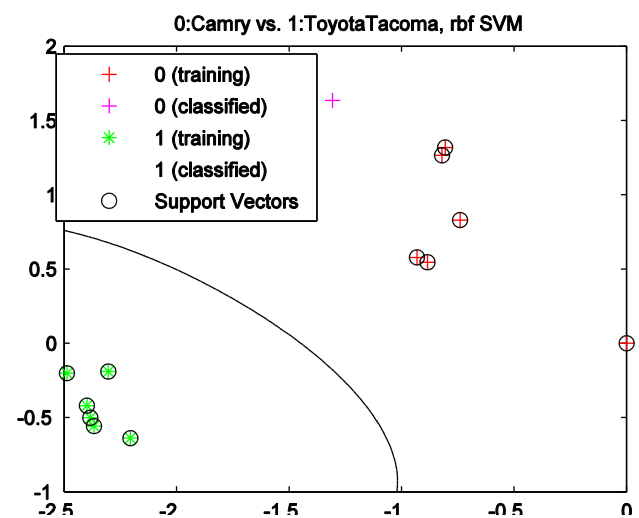


PHD, d_{ij}

$$D = \begin{bmatrix} 0 & d_{12}^2 & \cdots & d_{1m}^2 \\ d_{21}^2 & 0 & \cdots & d_{2m}^2 \\ \vdots & & \ddots & \vdots \\ d_{m1}^2 & \cdots & & 0 \end{bmatrix}$$

Squared Euclidian Distance Matrix

MDS



>95% correct classification

Dungan and Potter, 2011

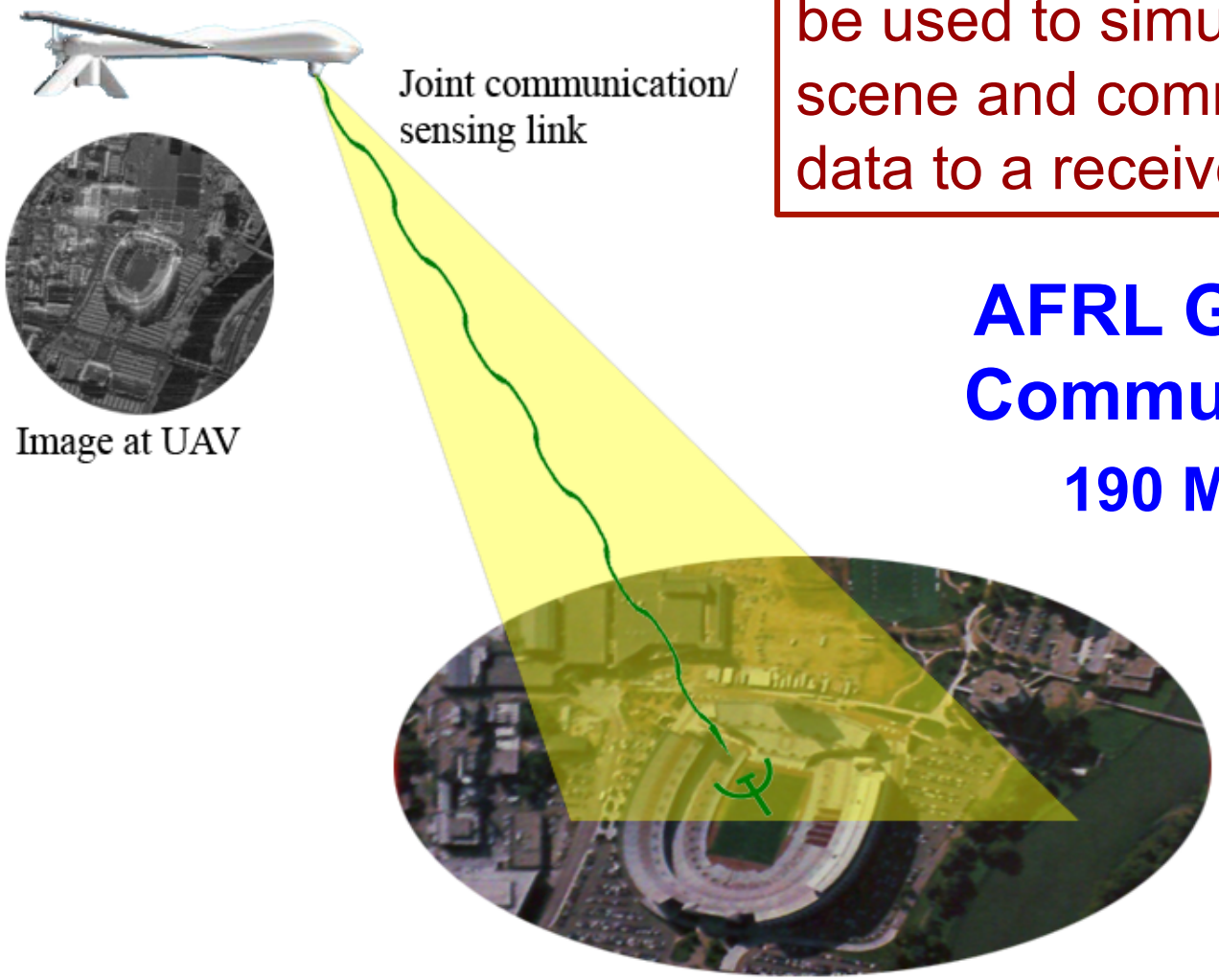
Presented at: the 2012 Statistical Signal Processing Workshop, Ann Arbor

Outline

- Radar 101
- Revisit modeling assumptions for wide angle radar
- How can sparsity play a role?
  - Parametric Modeling
  - Sparse Reconstruction
- Feature-Based Classification
- Transmit adaptation

Joint Communication and Radar Sensing

Can adaptive transmit waveforms be used to simultaneously sense a scene and communicate sensed data to a receiver?



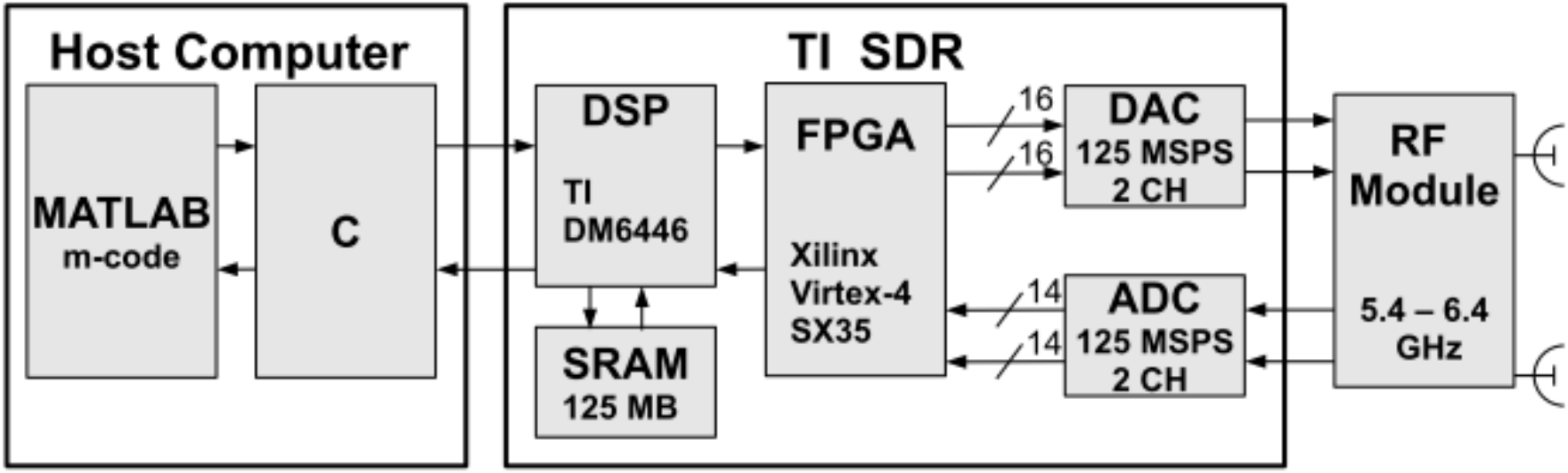
AFRL Gotcha Radar Communications:

190 M samples/sec

Communicated image at base station

OSU Software Defined Radar

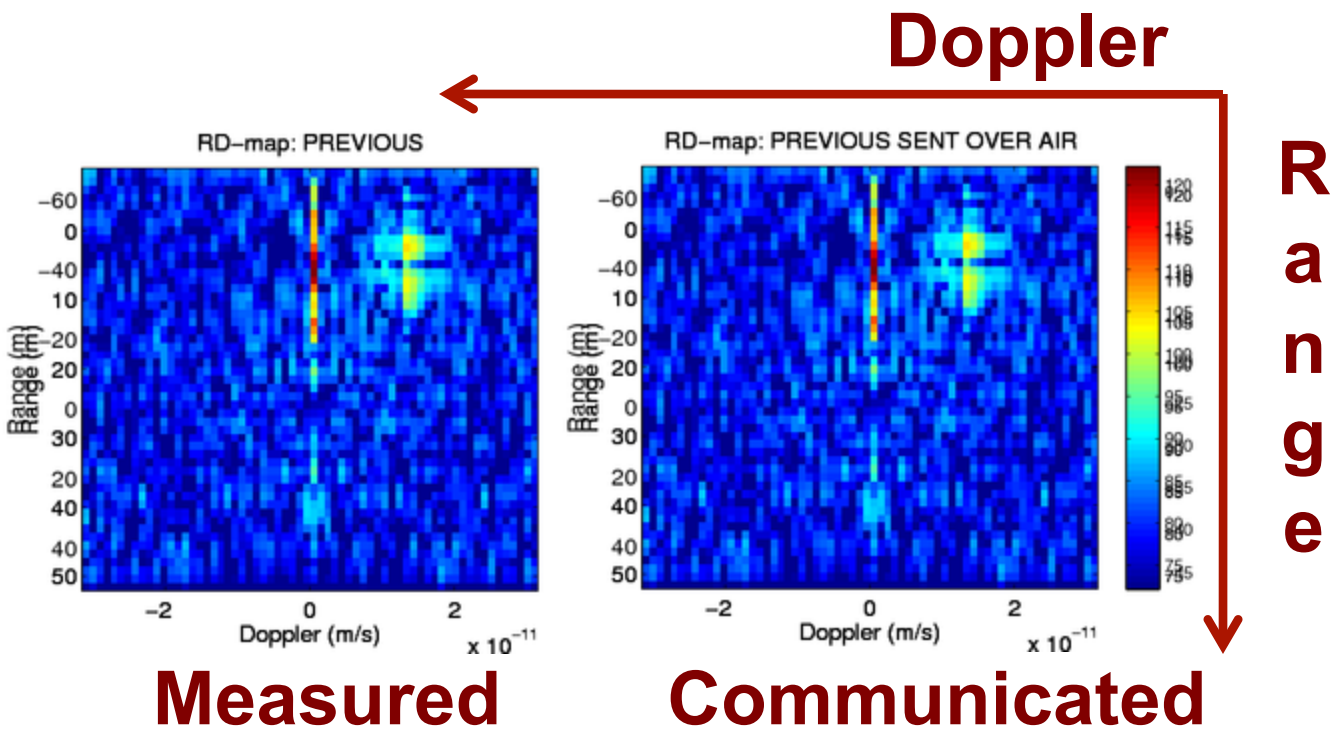
- Compact
- Wide Bandwidth (125 MHz)
- Real-time (DSP + FPGA)



Presented at: the 2012 Statistical Signal Processing Workshop, Ann Arbor

Joint Sensing-Comm Experiment

- Self-adaptive joint radar/communication system
  - PN transmit signal waveform
- Measured and communicated range-Doppler maps
  - n^{th} range-Doppler map used to adapt $(n+1)^{st}$ waveform set.



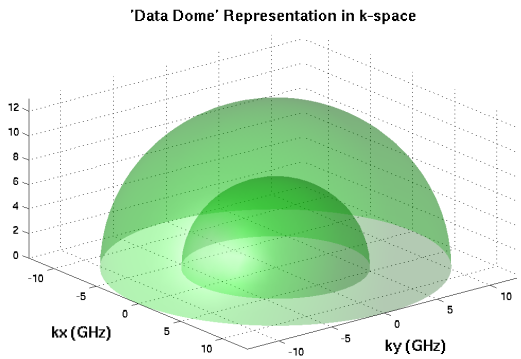
Rossler, Ertin, RLM: *2011*

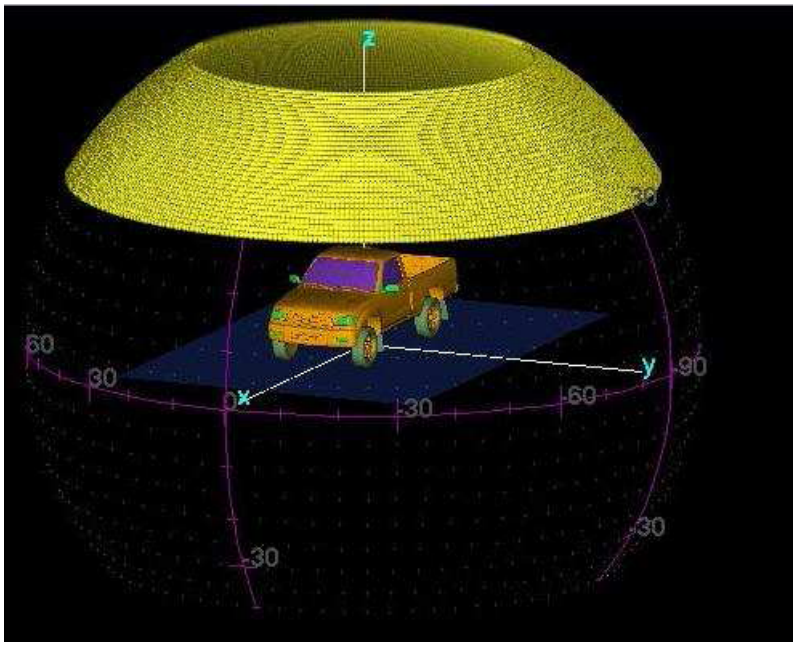
Take-Home Points

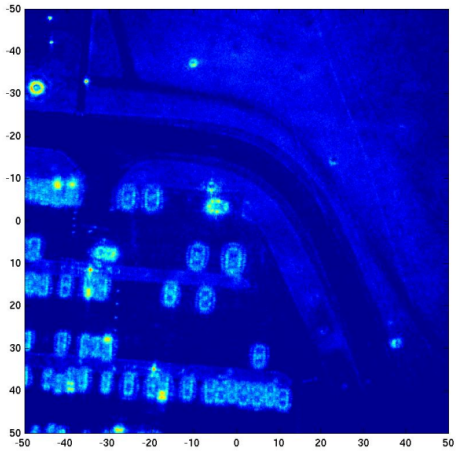
- Advances in sampling and digital processing are moving radar systems more firmly in the digital realm.
- Persistence and wide-angle sensing motivate rethinking the models and algorithms for radar processing.
- Effective 3D reconstruction from sparse apertures is possible
  - Surprising fidelity
  - Huge issues in computation, communication remain
- Huge opportunities for SSPers
  - Modeling; tractable algorithms; adaptation; persistent tracking; classification; performance estimation

Data Resources

- AFRL Sensor Data Management System
  - https://www.sdms.afrl.af.mil
  - Backhoe Volumetric Data (synthetic)
  - Civilian Vehicle Data Domes (synthetic)
  - Gotcha data (measured)
  - SAR-GMTI Challenge Problem







Thank you!