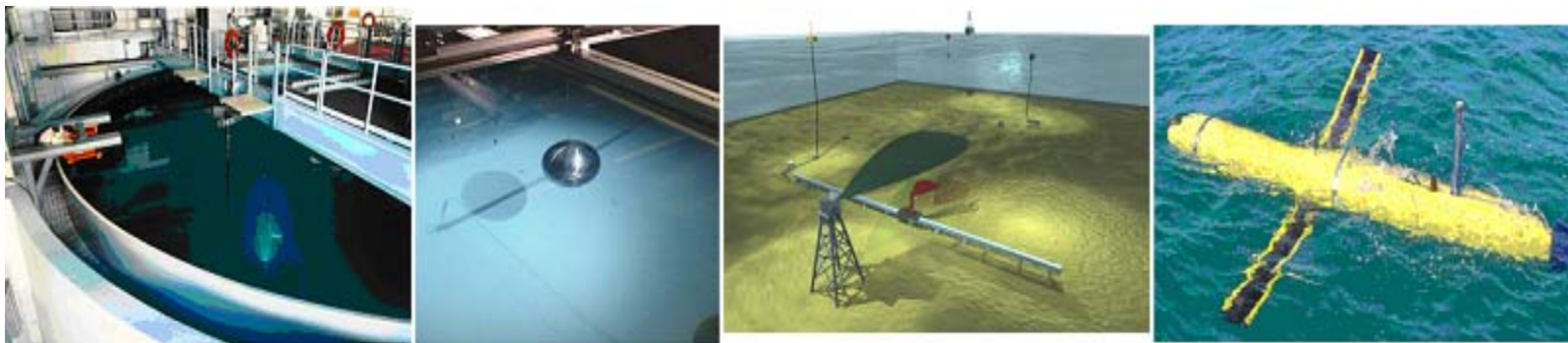


Broadband, Multi-Aspect Scattering from Proud and Buried UXO



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M. Saniga, A. Sarkissian, L. Kraus², and D. Calvo

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² Global Defense Technology & Systems, Inc.

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14. ABSTRACT Sonars which form high resolution images operate at high frequencies where the acoustic wavelengths are short compared to the target dimensions and the waves are scattered predominately from the geometric target boundary. In the structural acoustic regime where acoustic wavelengths are comparable to the target dimensions, sound penetrates the target and the scattered echoes are related to the vibrational dynamics of the object. The time-frequency features in the echoes can then be used to ?fingerprint? the target in addition to examining an image. We have been carrying out studies to evaluate the potential for the detection and identification of unexploded ordnance (UXO) in coastal and inland waters by exploiting their structural acoustic response. We will present and discuss underwater broadband multi-aspect scattering measurements and numerical simulations made on a number of UXO objects and several false targets in the proud and buried condition. The measurements were, for the most part, conducted in the NRL sediment laboratory pool facility. The simulation studies were carried out using two structural acoustic codes ? one time based and the other frequency based ? for treating target, sediment, and acoustic propagation. The UXO scattering data bases include both mono-static and bi-static source/receiver configurations, with both large look-down and near-grazing angle geometries, with the special case of forward scattering included in the latter. These broadband data bases, which can support both standard imaging and structural acoustic feature identification, are being used to train and test relevance vector machine (RVM) and imaging algorithms for identifying the UXO targets and to evaluate how the sediment and associated burial effects impact the identification process.		
15. SUBJECT TERMS		

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BROADBAND, MULTI-ASPECT SCATTERING FROM PROUD AND BURIED UXO

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T. Yoder and L. Kraus (Global Defense Technology & Systems, Inc. [GTEC])

Sonars which form high resolution images operate at high frequencies where the acoustic wavelengths are short compared to the target dimensions and the waves are scattered predominately from the geometric target boundary. In the structural acoustic regime where acoustic wavelengths are comparable to the target dimensions, sound penetrates the target and the scattered echoes are related to the vibrational dynamics of the object. The time-frequency features in the echoes can then be used to “fingerprint” the target in addition to examining an image. We have been carrying out studies to evaluate the potential for the detection and identification of unexploded ordnance (UXO) in coastal and inland waters by exploiting their structural acoustic response. We will present and discuss underwater broadband multi-aspect scattering measurements and numerical simulations made on a number of UXO objects and several false targets in the proud and buried condition. The measurements were, for the most part, conducted in the NRL sediment laboratory pool facility. The simulation studies were carried out using two structural acoustic codes – one time based and the other frequency based – for treating target, sediment, and acoustic propagation. The UXO scattering data bases include both mono-static and bi-static source/receiver configurations, with both large look-down and near-grazing angle geometries, with the special case of forward scattering included in the latter. These broadband data bases, which can support both standard imaging and structural acoustic feature identification, are being used to train and test relevance vector machine (RVM) and imaging algorithms for identifying the UXO targets and to evaluate how the sediment and associated burial effects impact the identification process.



Outline



Background

- Three UXO Search Scenarios
- Imaging and Structural Acoustic ID

Long Range Mono-static Scenario

Bi-static Forward Scattering Scenario

Short-range Down-looking Scenario

- Numerical Simulations for Buried Targets
- Sediment Facility Measurements

Future Plans

The Three UXO SONAR Configurations

Case 1

*Long Range
Monostatic
System*

S, R

Case 3

*Short Range Down-
Looking System*

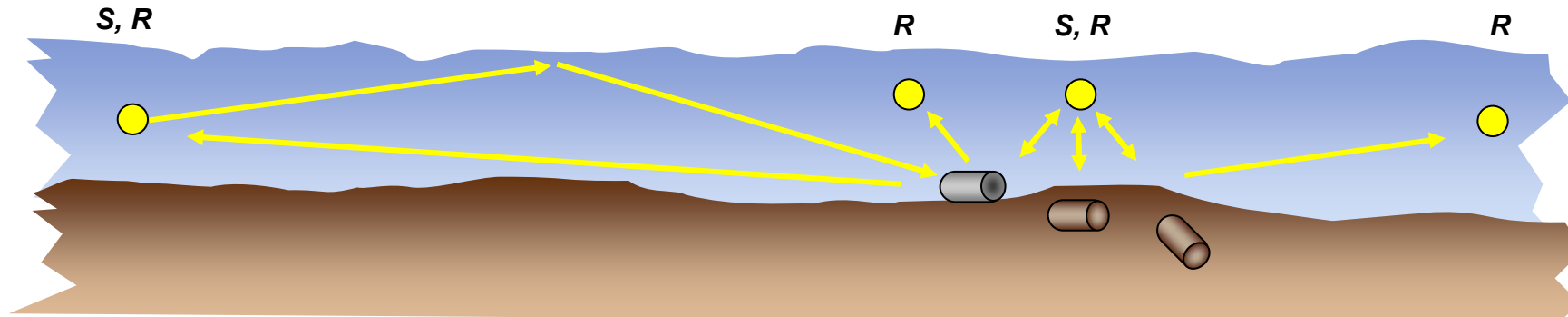
R

S, R

Case 2

*Long Range
Bistatic System*

R



The Three UXO SONAR Configurations

Case 1

*Long Range
Monostatic
System*

S, R

Case 3

*Short Range Down-
Looking System*

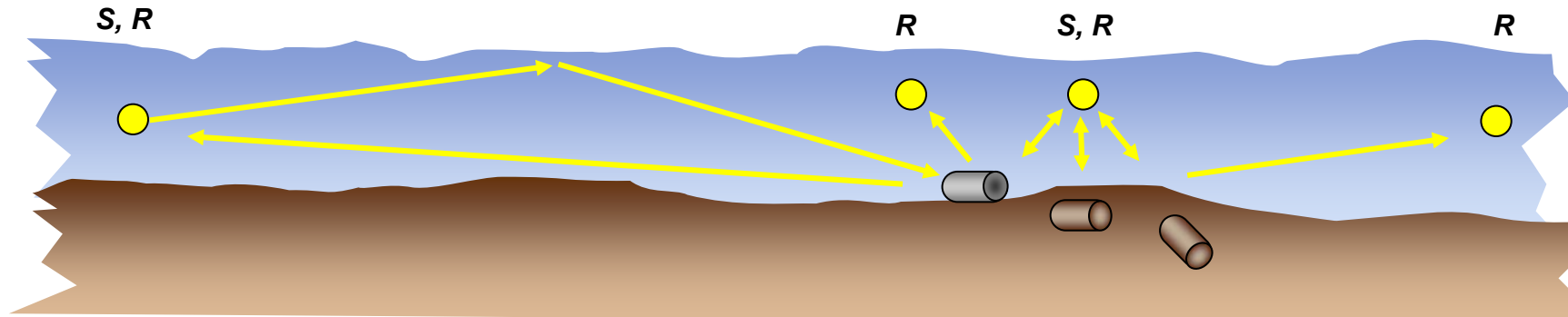
R

S, R

Case 2

*Long Range
Bistatic System*

R

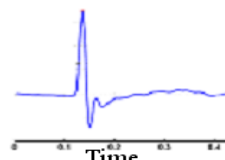
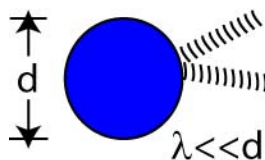


- High Coverage Rates
- Low Sediment Penetration

- Good Sediment Penetration
- Lower Coverage Rates

The Two Target *ID* Paradigms:

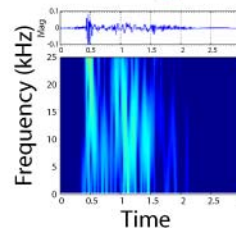
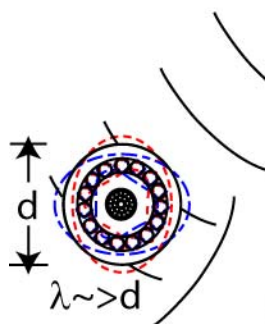
Time-delay in specular echoes processed to form image of target's shape



Acoustic Imaging Regime

Structural Acoustic ID

Echo related to vibrations of casing & internals. Time-frequency features used to "fingerprint" target.

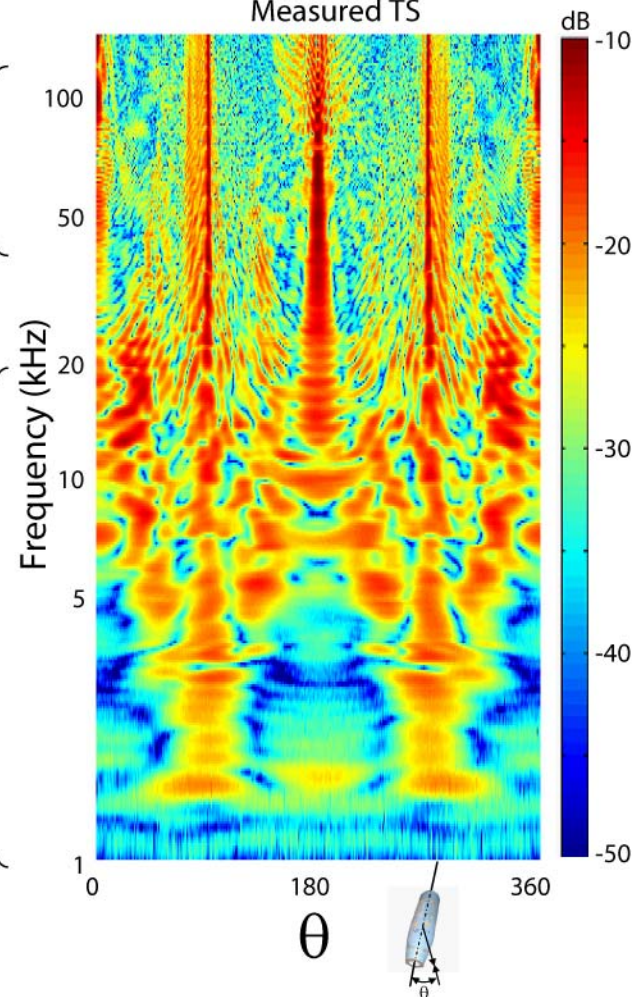


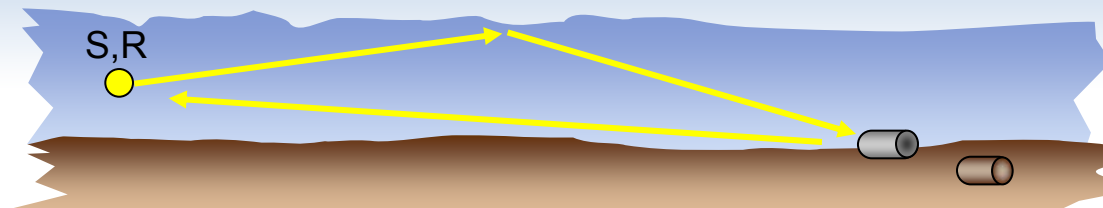
Structural Acoustic Regime

UXO Echo Frequency/Angle Spectrum



Measured TS





Broadband Echo Data on Six UXO and Four False Targets



80 mm Mortar Round



155 mm Artillery Shell



5 in Rocket Warhead



120 mm Mortar Round



105 mm Sabot Round



25 mm Dummy Cartridge



Cinder Block



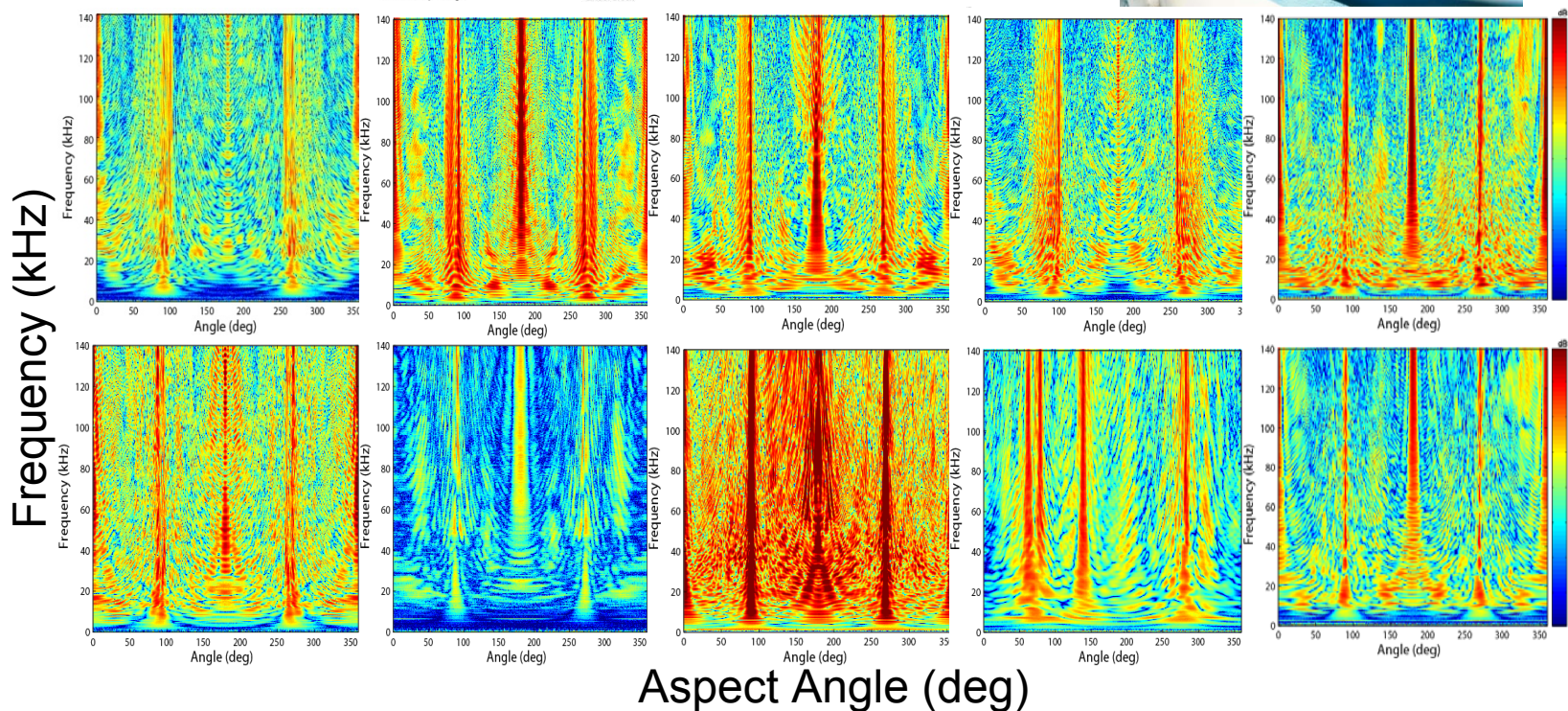
Rock



Concrete-Filled Metal Pipe 1



Concrete-Filled Metal Pipe 2

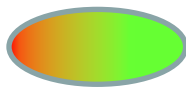


Features Obtained from Measured UXO Echo Frequency/Angle Spectrum

Kernel Classifiers / RVM (KMP)

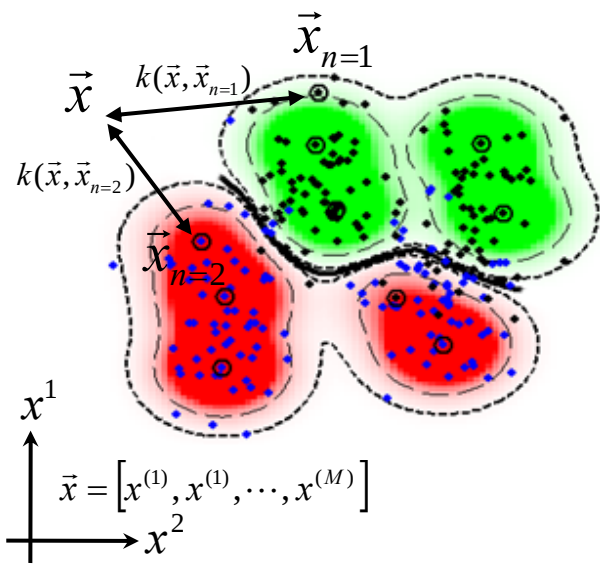
Kernel Classifiers

$$y(\vec{x}) = \sum_{n=1}^N \alpha_n k(\vec{x}, \vec{x}_n) - \alpha_0$$

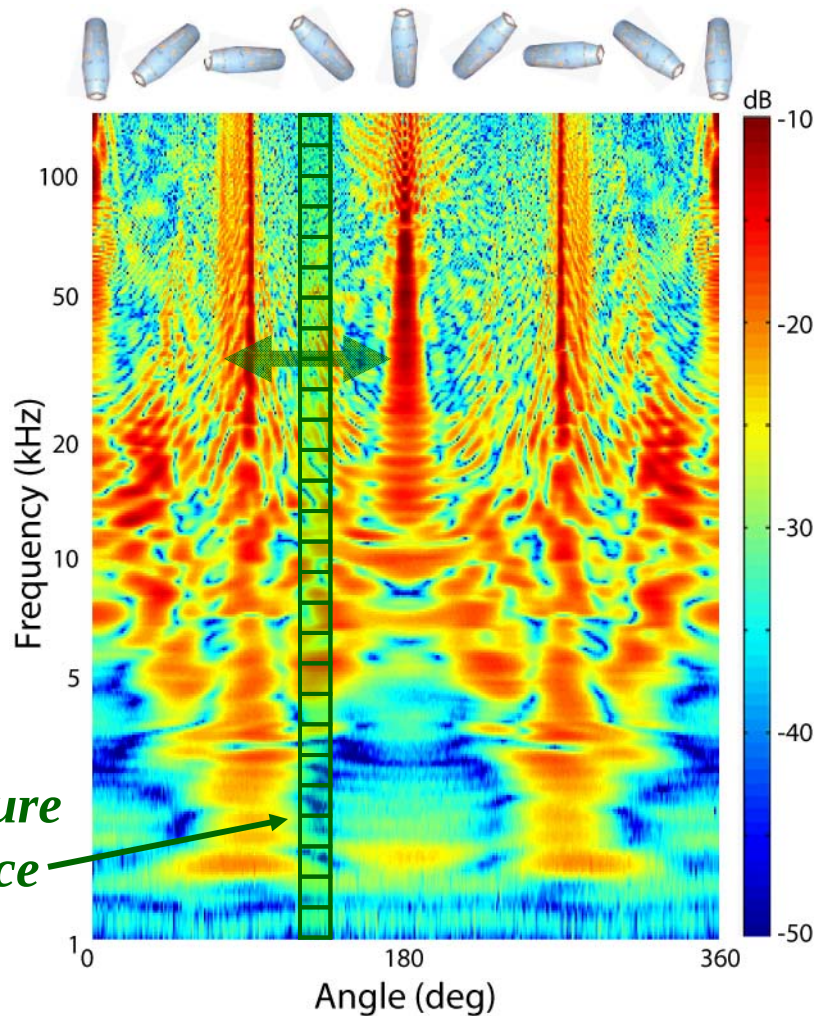


RVM

Minimize the error
Minimize the # of relevant vectors
(force most $\alpha \rightarrow 0$)



Semi-Log Frequency Plot



Feature
Space

ID Algorithm Trained and Tested with Laboratory Data

Grouping # 2	Cinder Block/Rock/Pipes	UXO
-----------------	-------------------------	-----

Clutter

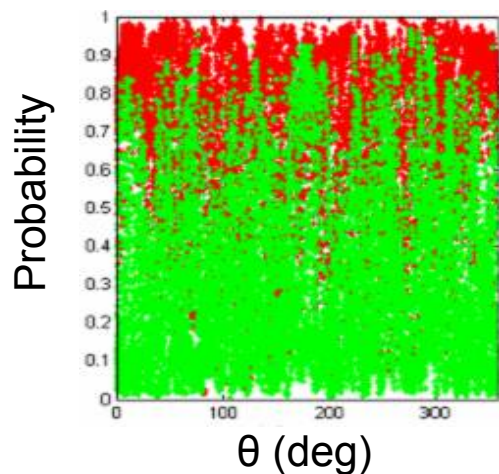


Ordinance

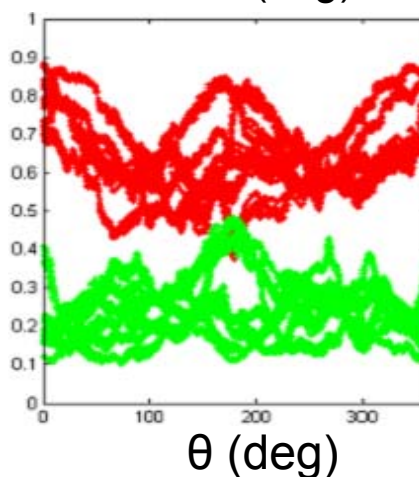


Probability of Correct Identification

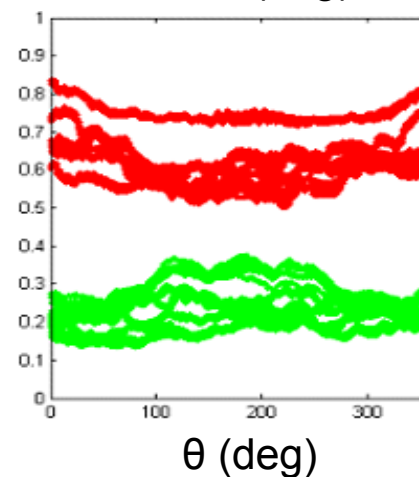
± 0 (deg)



± 30 (deg)



± 75 (deg)





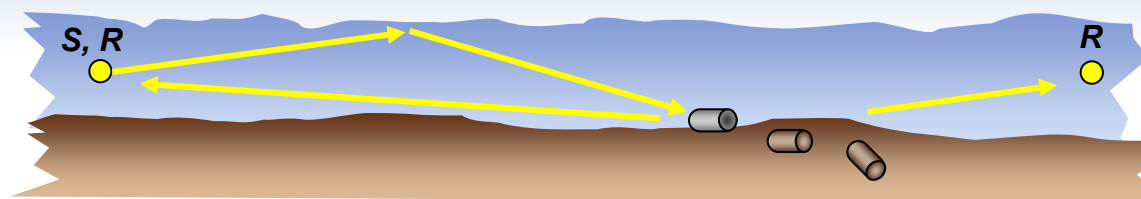
Target ID Using Structural Acoustic Features



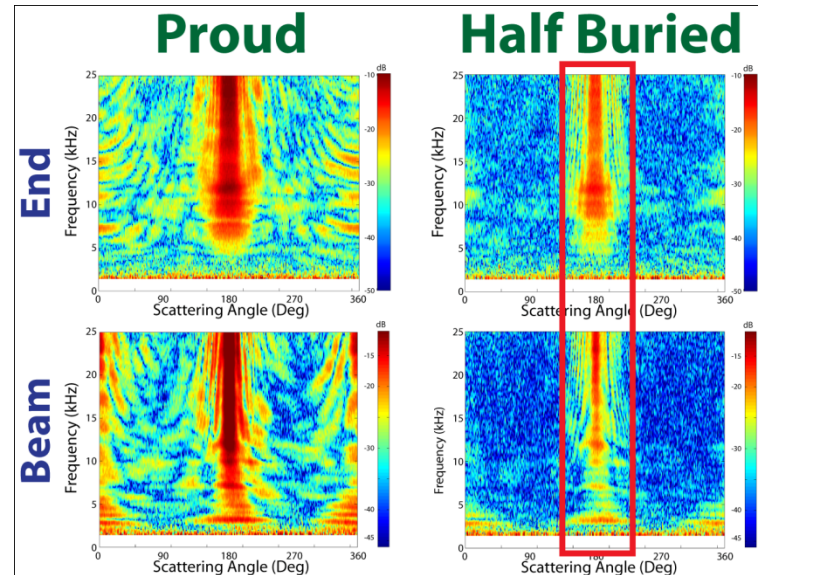
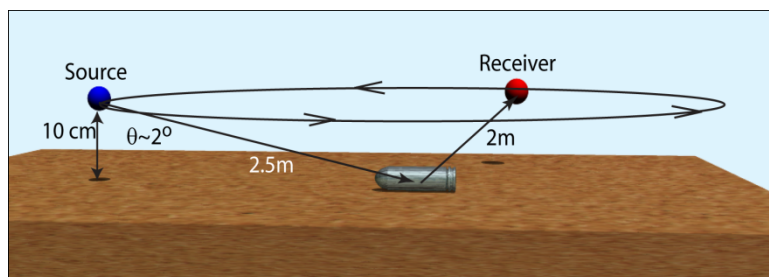
- RVM trained with noise corrupted lab data
- Thirty four cases tested in the lab: all showed good separation

Test #	Target Grouping	False Targets
1	Explosive Simulators	All Others
2	Ordnance Related	Cinder Block/Rock/Pipes
3	Bodies of Revolution	Cinder Block/Rock
4	Mortars	All Others
5	Pseudo-cylinder/Explosive	Cinder Block/Rock/Pipes
6	Mortars	Cinder Block/Rock/Pipes
7	Small Cartridge	Cinder Block/Rock/Pipes
8-14	One Ordnance at a time	Cinder Block/Rock/Pipes
15	Small Cartridge	Cinder Block/Rock
16-26	One Target at a Time	All Others
27	Ordnance Related	Cinder Block/Rock/Noise
28-33	One Ordnance at a Time	All Other Ordnance
34	Wet Mortar	All Other Ordnance

2)



Bi-static echo for source at end & beam in the sediment facility

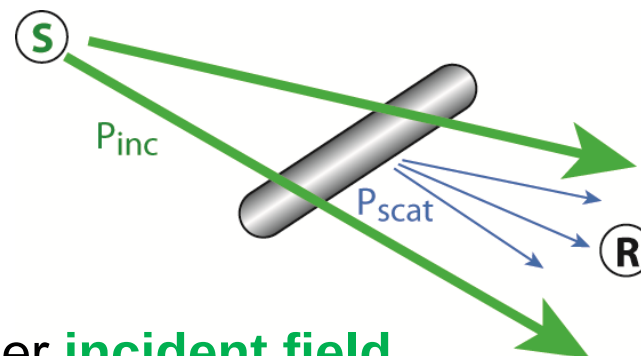


Forward Scatter

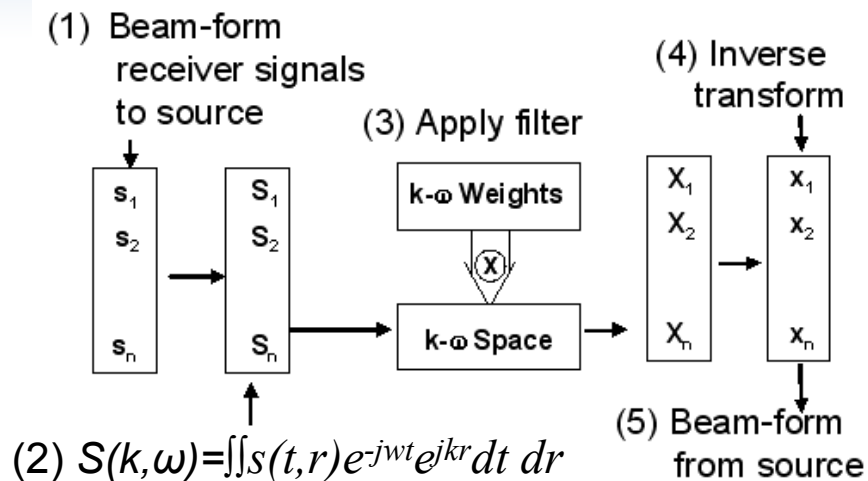
- Highest TS at all θ_{inc}
- Robust upon burial □

But . . .

Echo masked in the much stronger **incident field**.



Extraction of Forward Scatter Echo via Wave-number Filtering



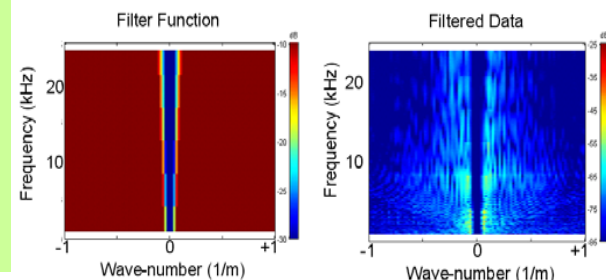
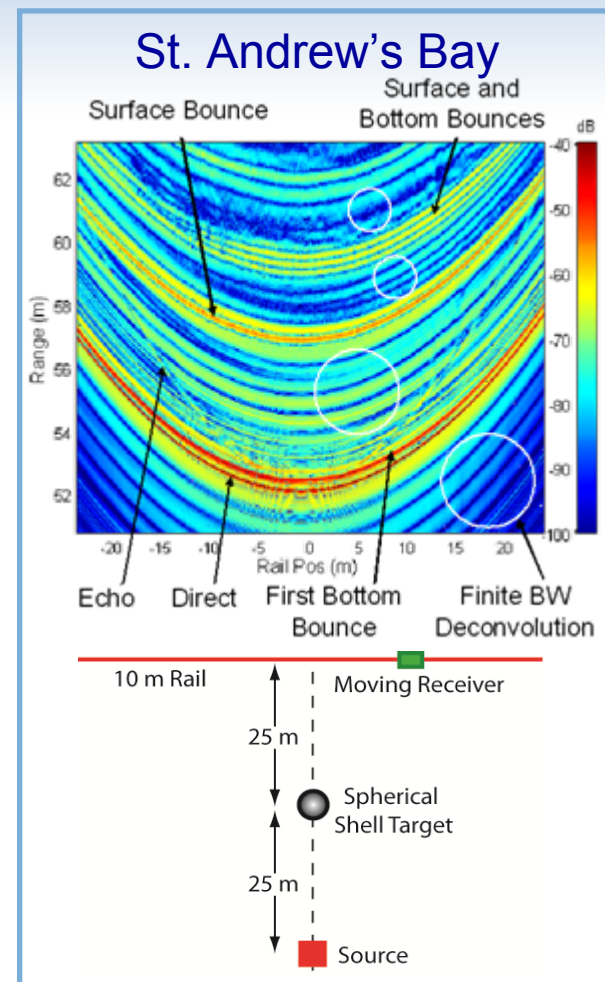
$$P_{INC} \rightarrow P_S r_{sr}^{-1} \exp ik_S (r_{sr} + \Delta r_{sr}(n))$$

$$(1) \rightarrow P_S \exp ik_S \Delta r_{sr}(n)$$

$$(2) \rightarrow \int dr \exp (-ikr) \exp ik_S \Delta r_{sr}(n) \sim \delta(k) + \xi(k)$$

$$(3) \text{ Apply filter } \mathcal{F}(k) = \begin{cases} 0 & \text{for } k \approx 0 \pm \Delta k \\ 1 & \text{elsewhere} \end{cases}$$

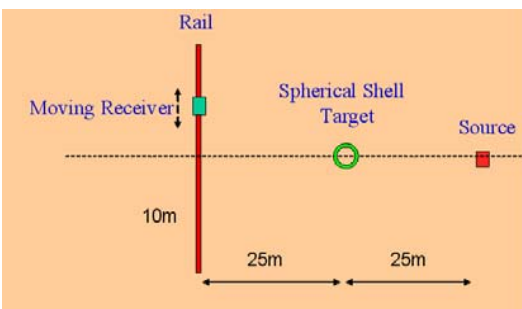
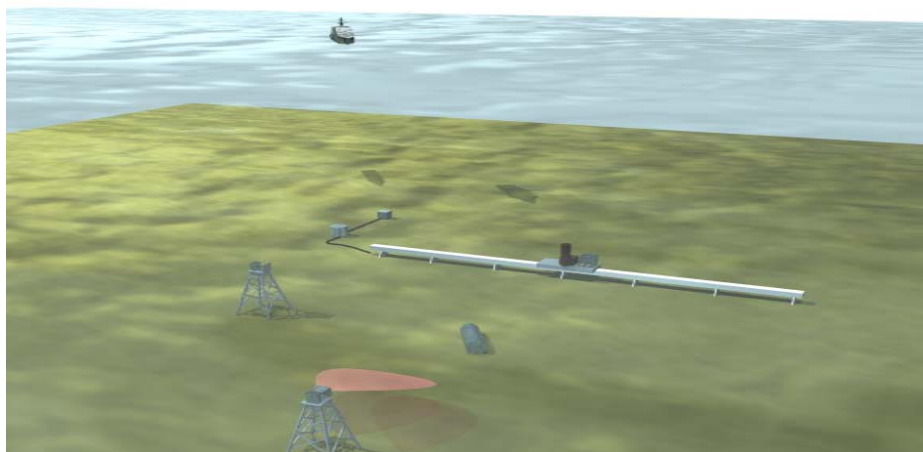
Filter bandwidth $\Delta k = k \Delta r / r$'s $= \omega / C_0 \cdot \Delta r / r$
 Δr 's $\sim 0.05\text{m} \rightarrow \Delta k(20 \text{ kHz}) \sim 0.1\text{m}^{-1}$



Prosecuting Forward Scattering in a Marine Environment (Case

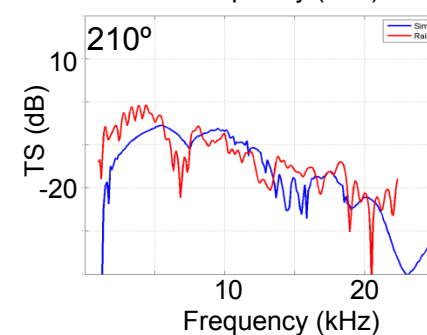
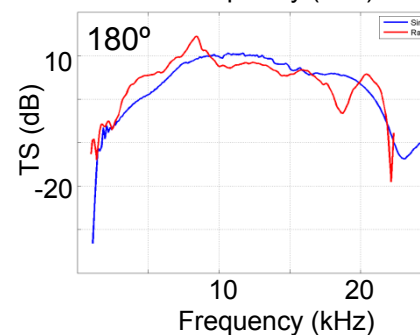
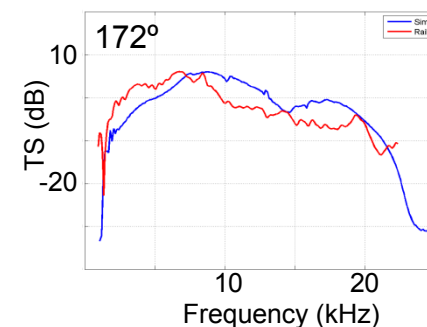
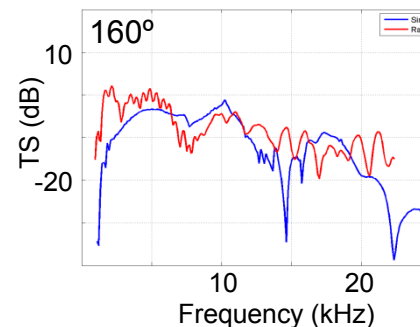
- Gulf of Mexico with ~ 40 ft water depth
- Forward scatter of proud spherical shell (12" radius)

St. Andrew's Bay



Extraction of Forward Echo via Wavenumber Filtering

Gulf Rail Measurements vs Simulation using Free-Field



- Extraction technique also applicable to backscattered echo/clutter

The Look-Down SONAR Configuration

Case 1

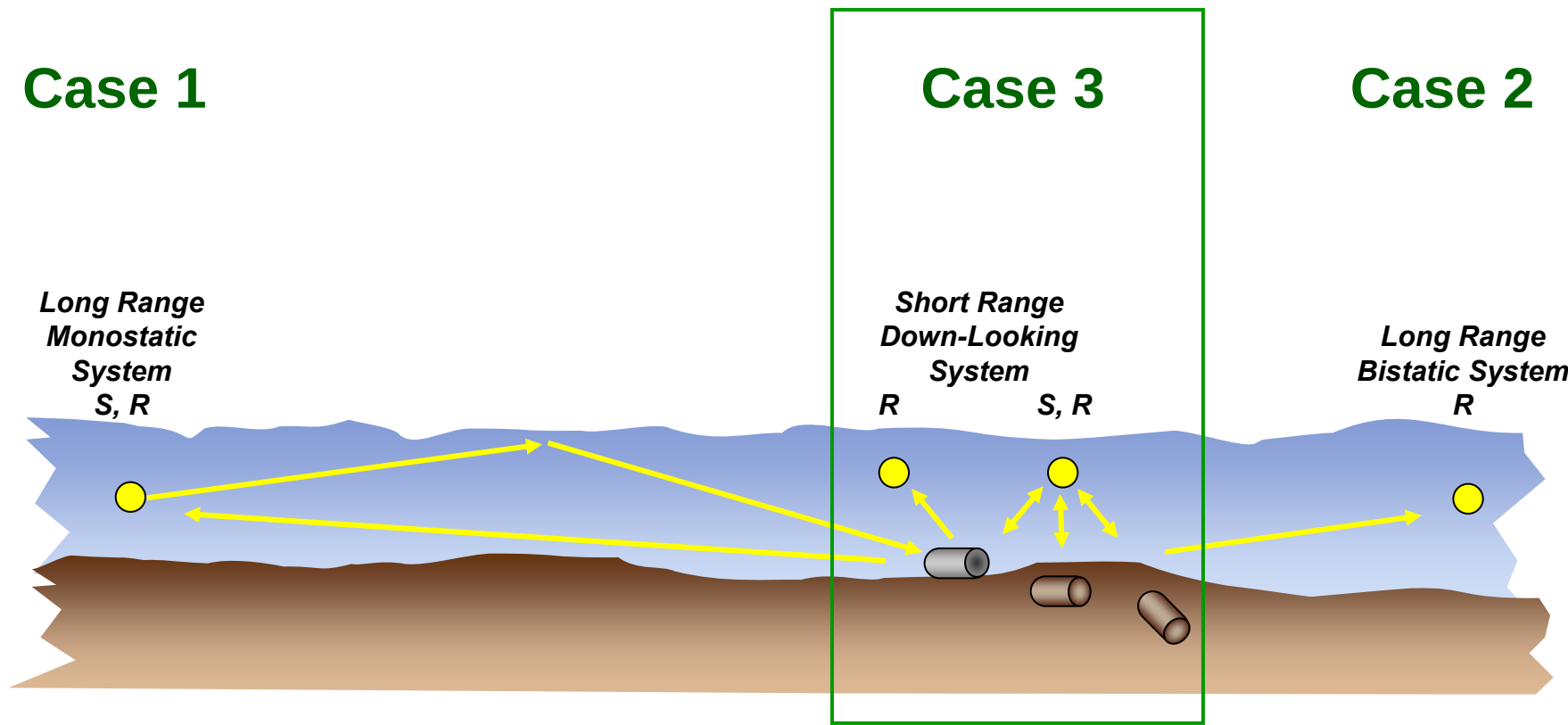
*Long Range
Monostatic
System
S, R*

Case 3

*Short Range
Down-Looking
System
R S, R*

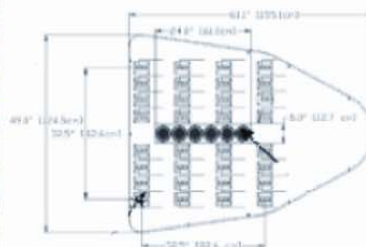
Case 2

*Long Range
Bistatic System
R*

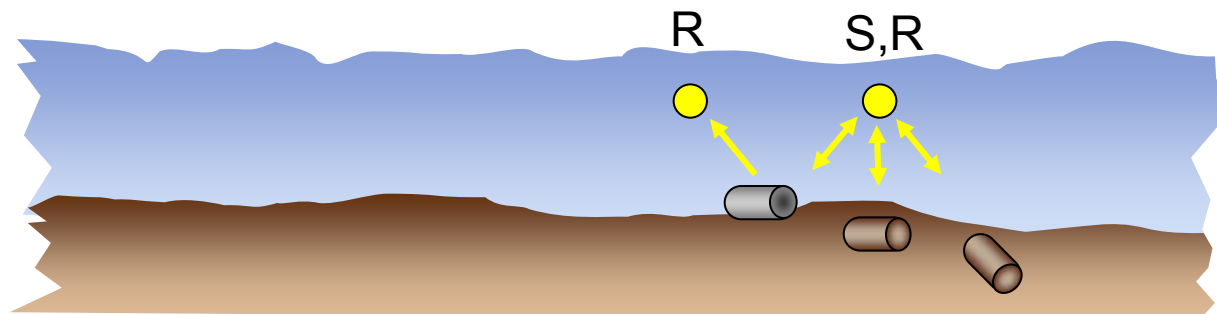


A down-looking, limited angle bi-static structural acoustic sonar could be implemented with the Bottom Object Sonar System (BOSS) developed by S. Schock

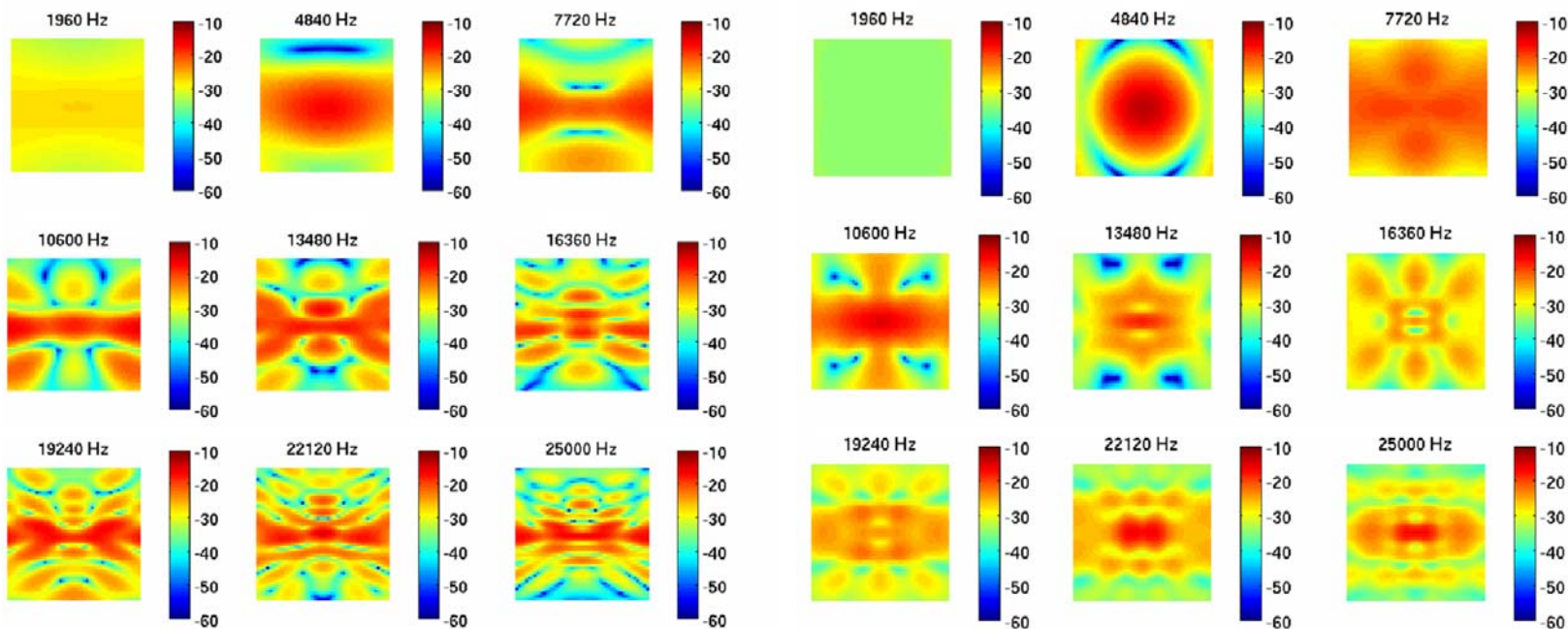
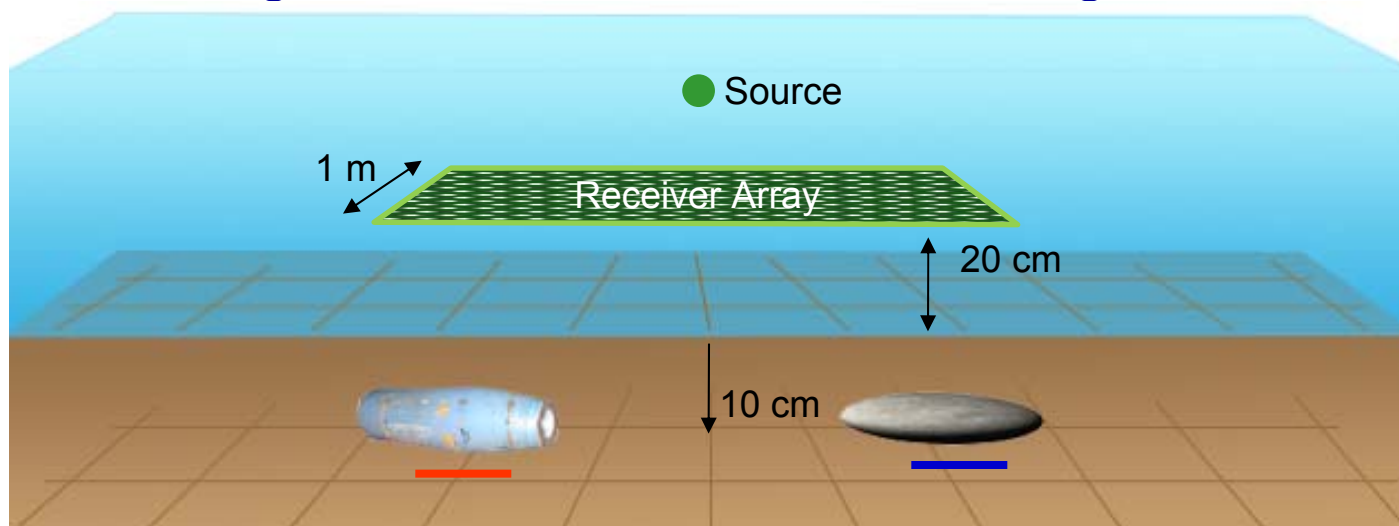
Towed BOSS Configuration with Bottom Sources/Receivers



AUV-based BOSS with Extended Receiver Arrays



Looking down at buried 5-inch rocket & large rock

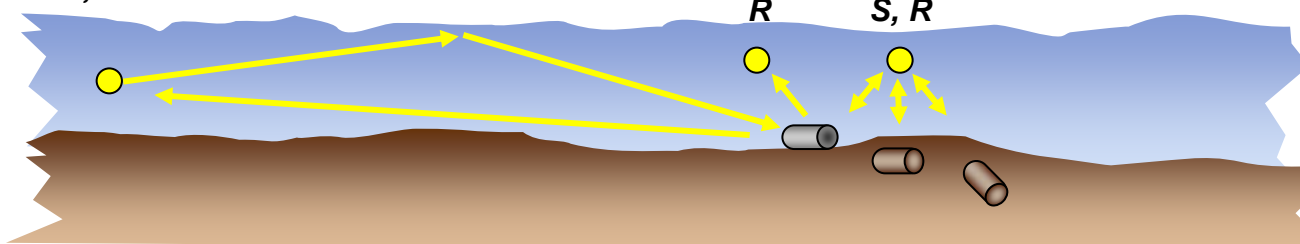


Extension of 2D ID Algorithm

Look-Down Case

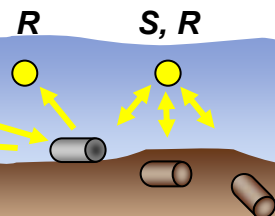
Case 1

Long Range
Monostatic System
S, R

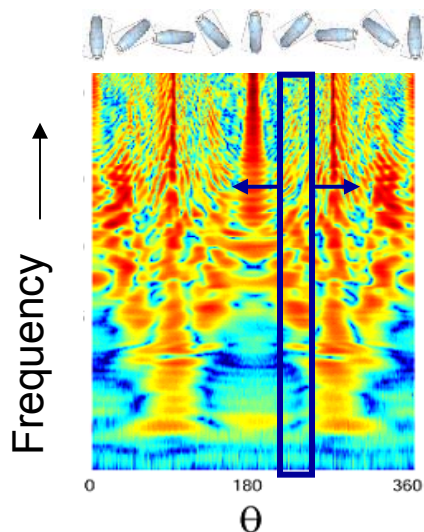


Case 3

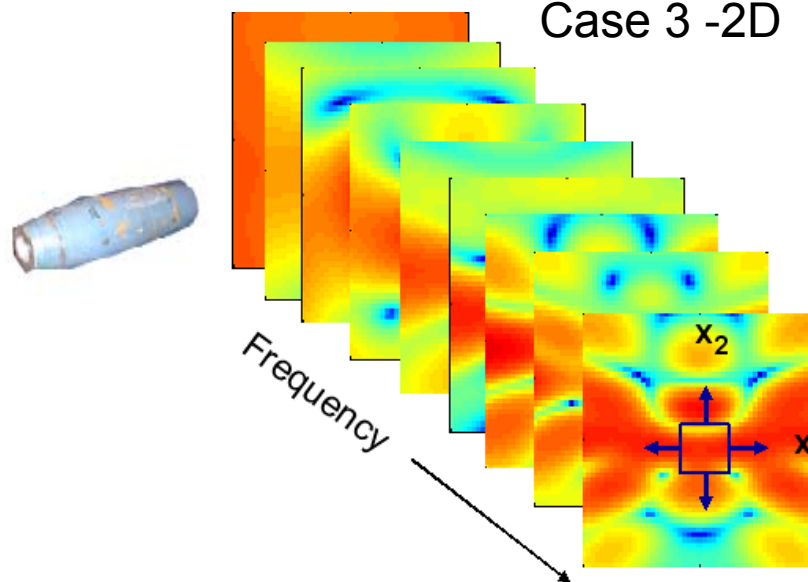
Short Range Down-
Looking System
R S, R



Our Present RVM
Case 1 – 1D

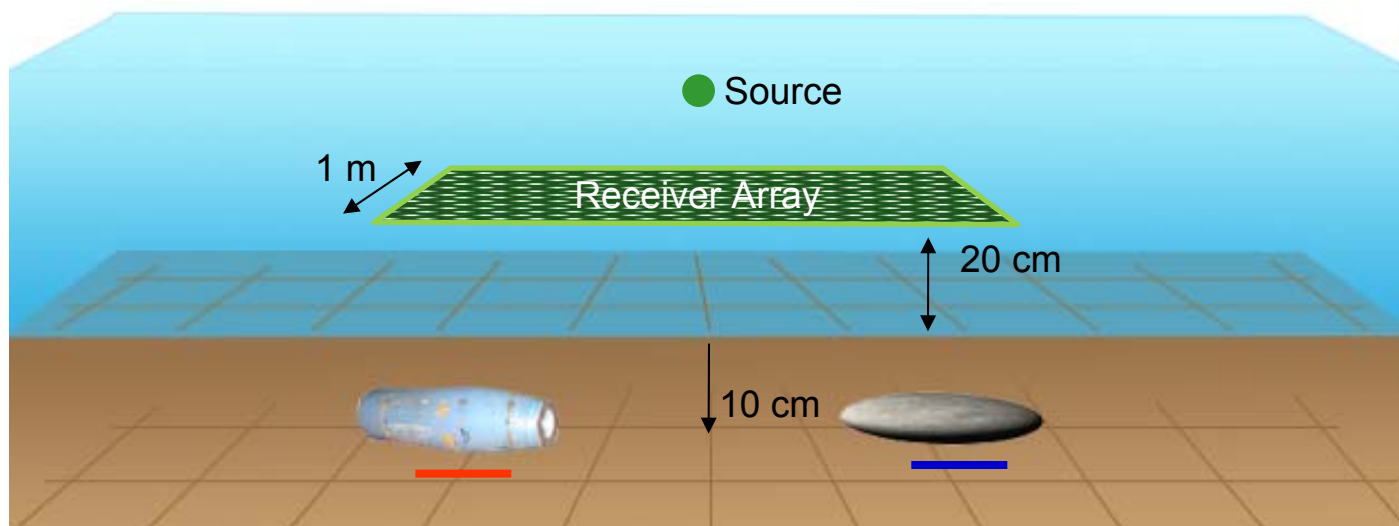


Case 3 -2D

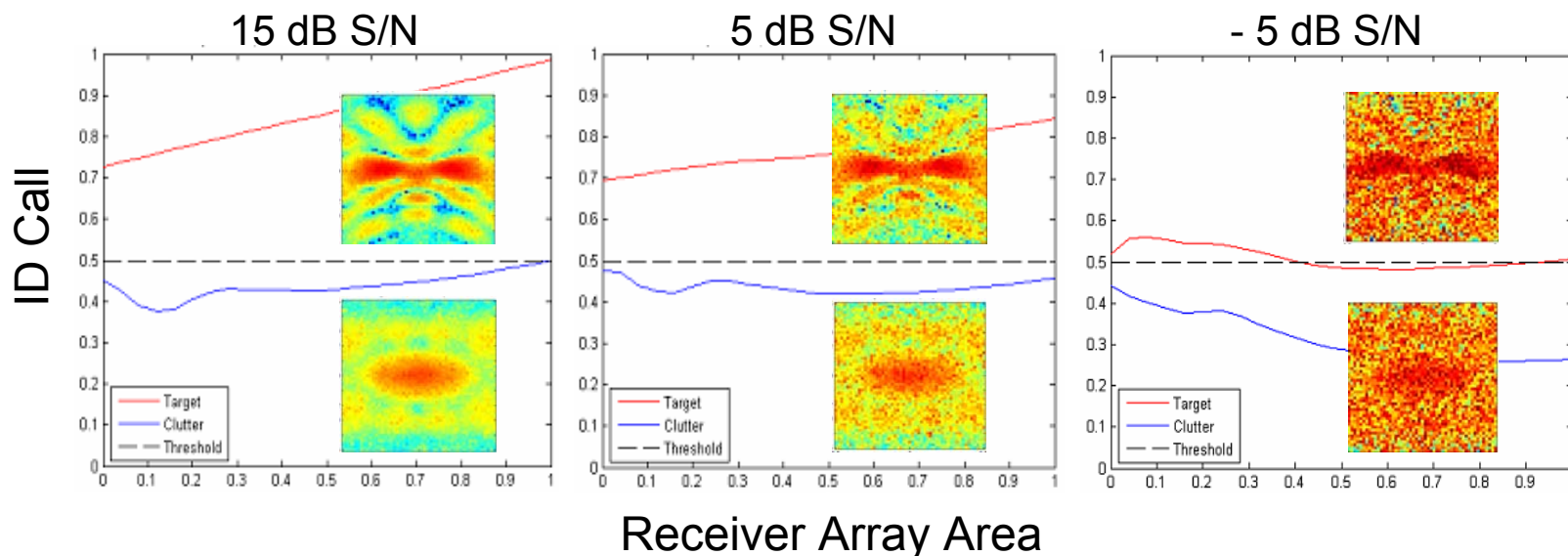


RVM Identification Algorithm Feature Spaces

STARS3D Simulation



Simulations predict encouraging performance for initial 2-D RVM

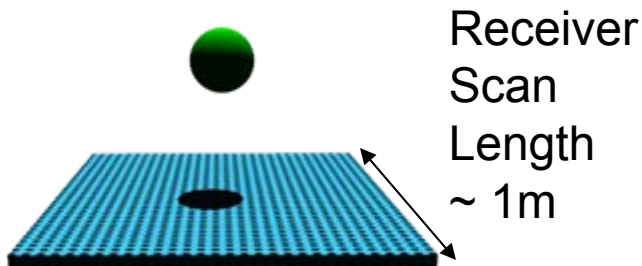




New NAH Measurement Capability to Support Look-Down Search Scenario

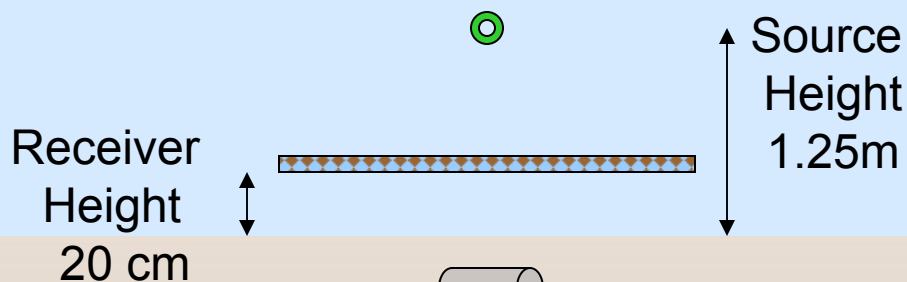
Synthetic Array

Receiver
Spacing
(Virtual)
3 cm
 $\lambda / 2 @ 25\text{kHz}$



Receiver
Scan
Length
 $\sim 1\text{m}$

Cylindrical Line/
Spherical Source



Buried UXO



NRL Sediment Pool Facility

New NAH Measurement Capability for Look-Down Search Scenario

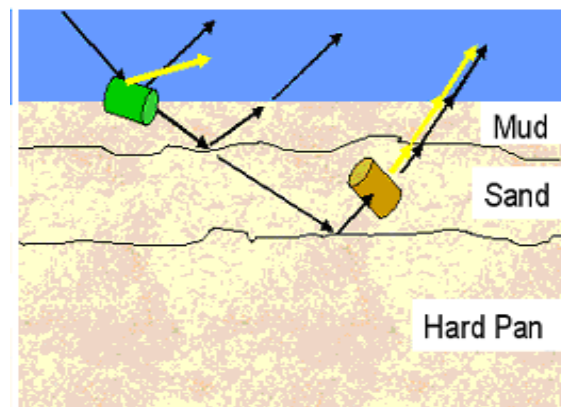
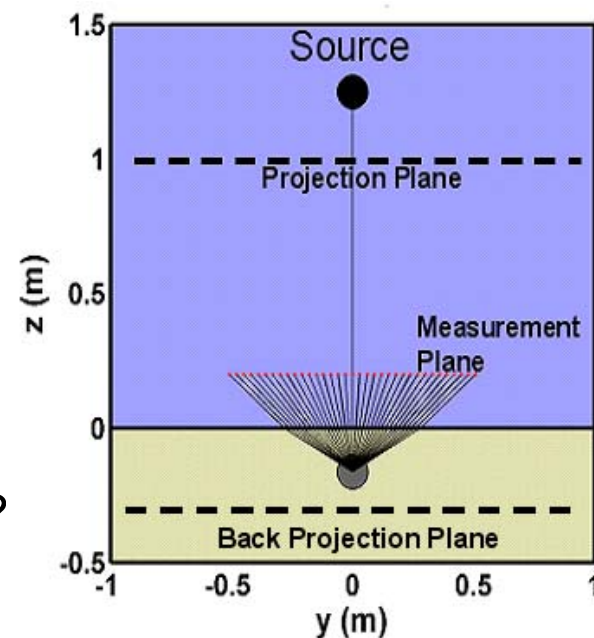
Data easily propagated up to higher positions

For lower part of the SA band, receiver distance $\ll \lambda$: nearfield hologram (NAH)

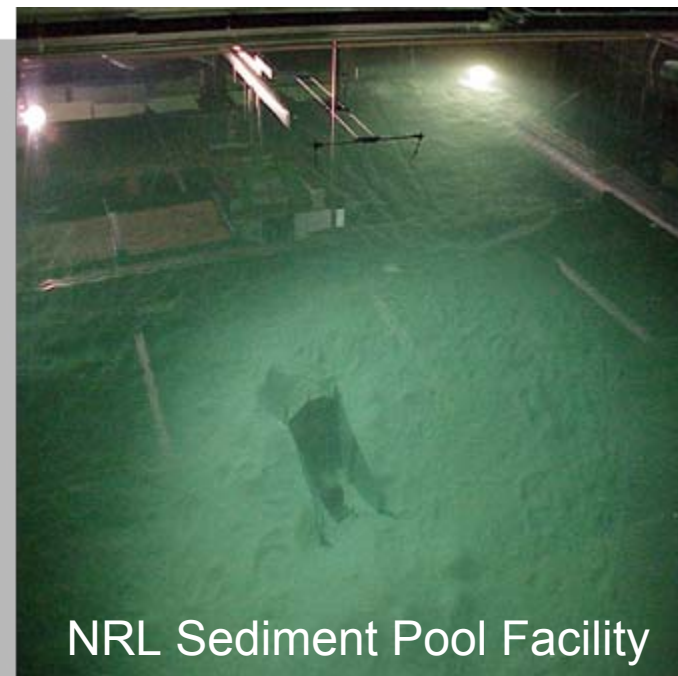
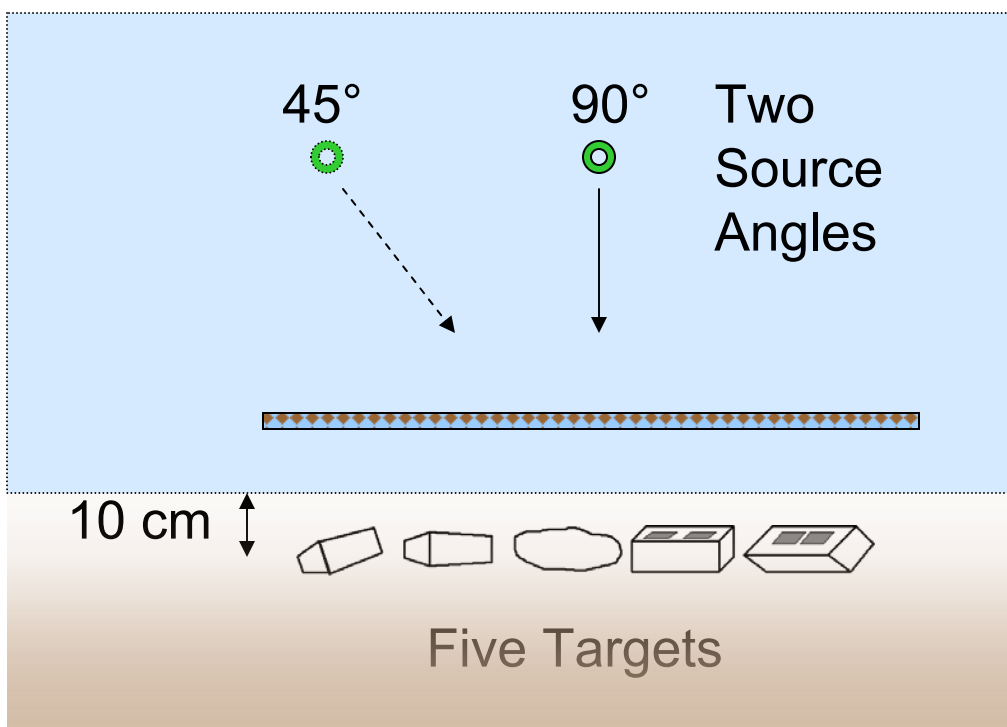
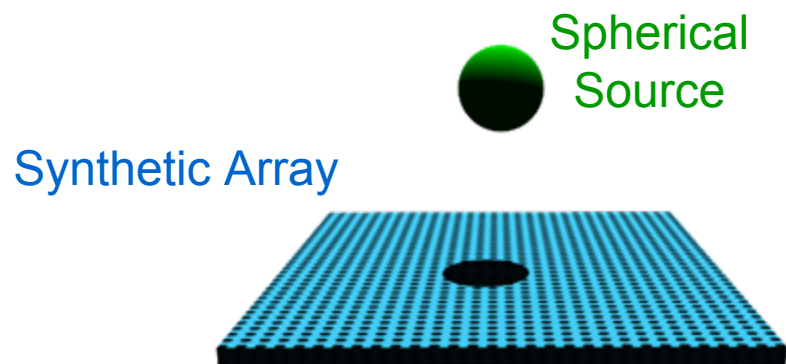
- *Do evanescent waves matter?*
- *Can we project to water/ sediment interface?*
- *Can we project to planes below interface?*

Construct velocity and intensity maps

- *Are the latter more effective for target ID?*

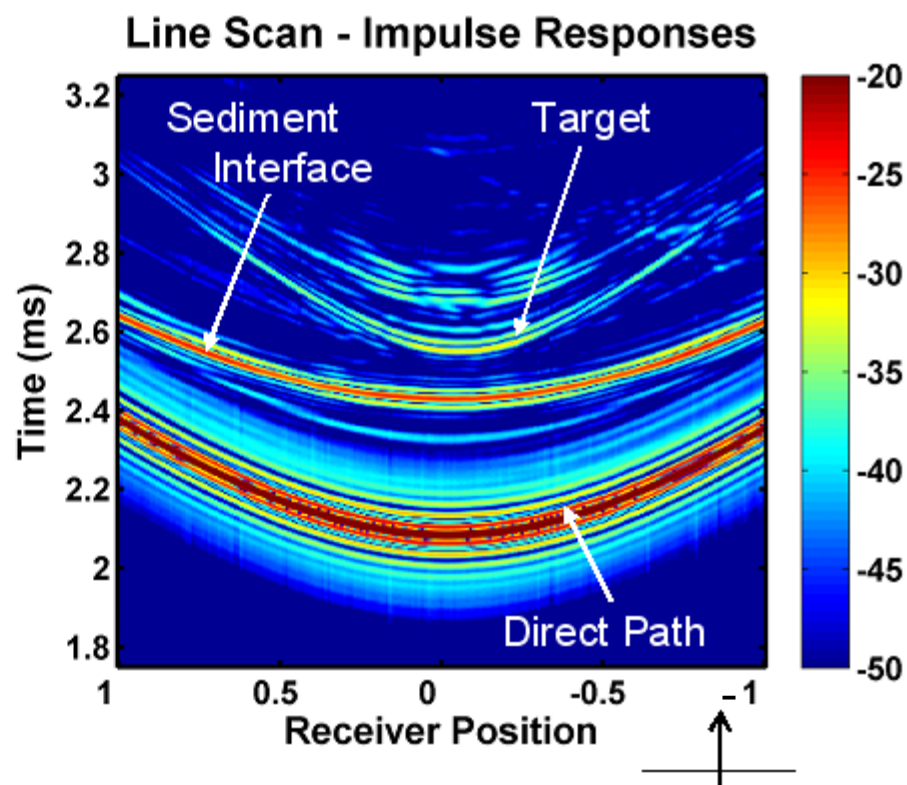
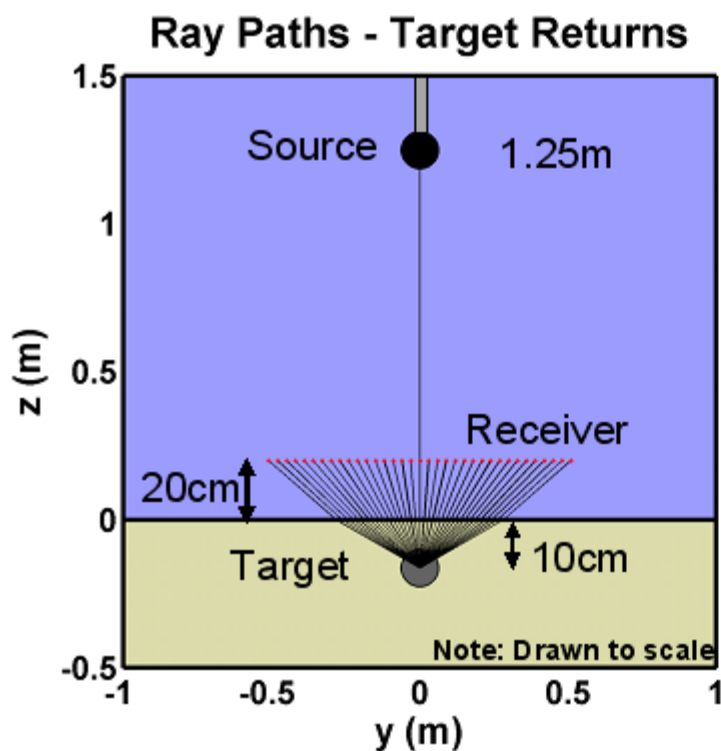
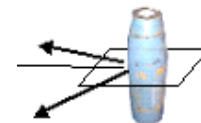


Buried Target Measurements in the NRL Sediment Facility

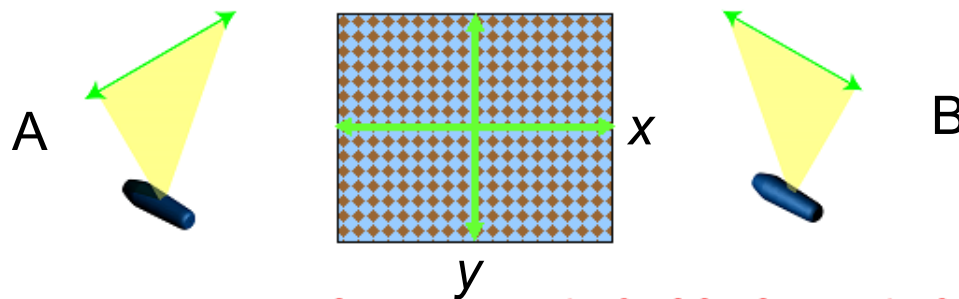


Preliminary measurements in NAH sediment facility

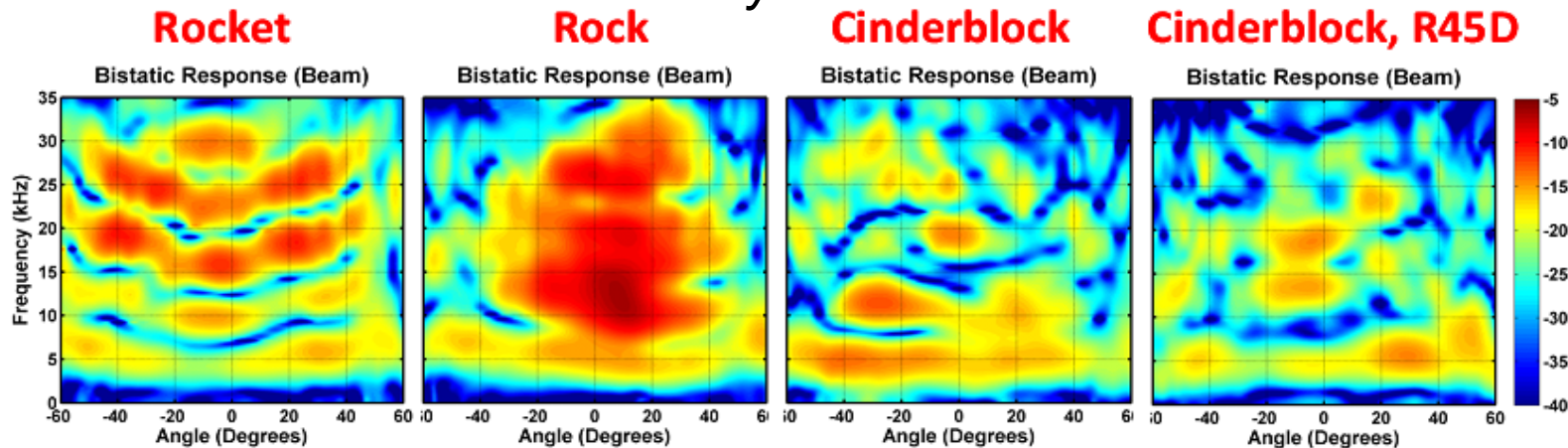
- **Geometry is known due to high precision robotic system**
- **Target returns are isolated by temporal windowing:**
 - ~ Use a ray-approximation to estimate time of flight values



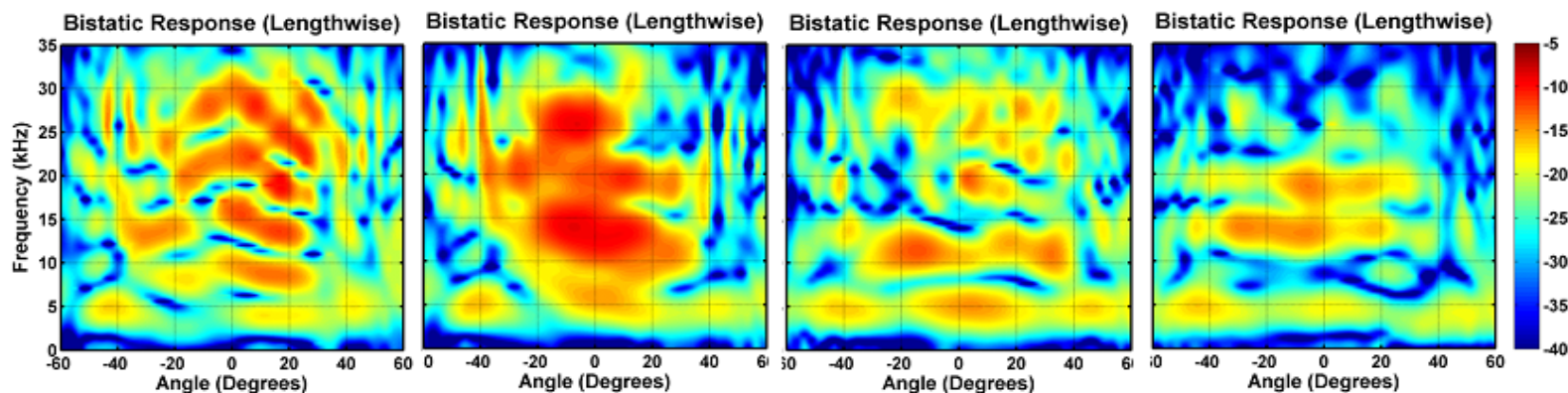
Target Strength vs Frequency / Angle Measured Along x and y Axis of Array

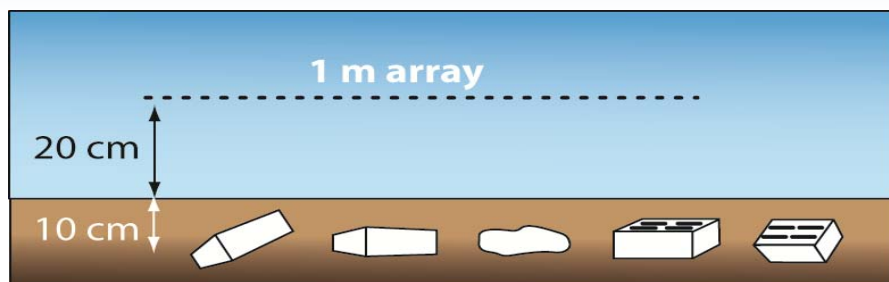


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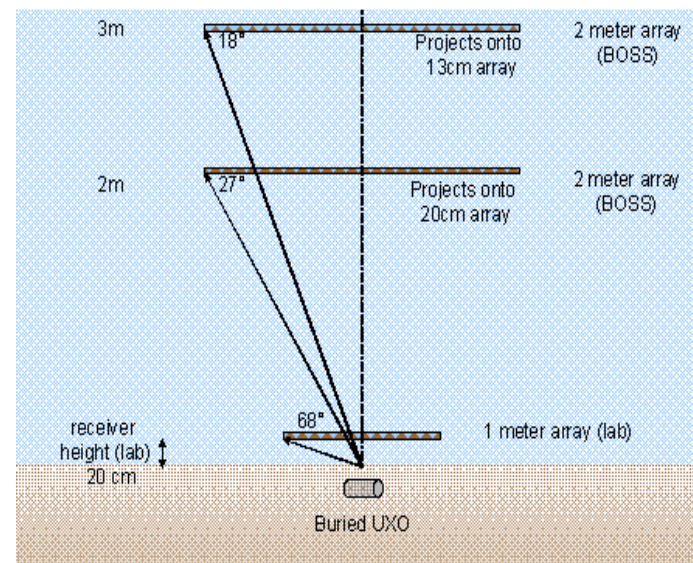
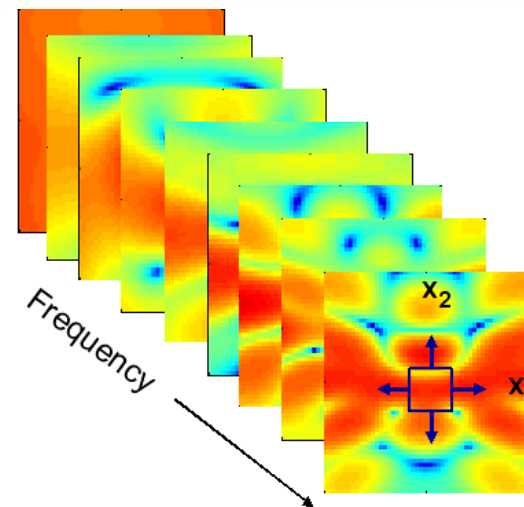
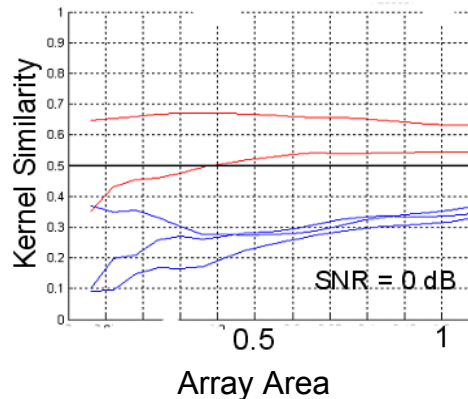
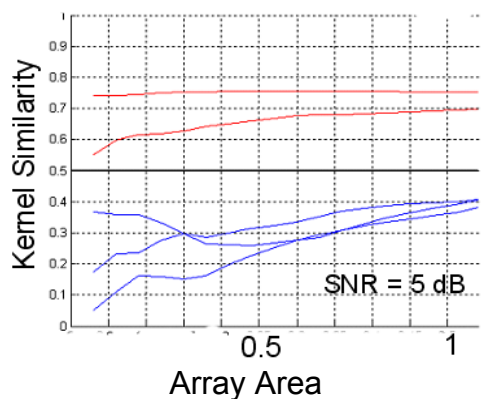
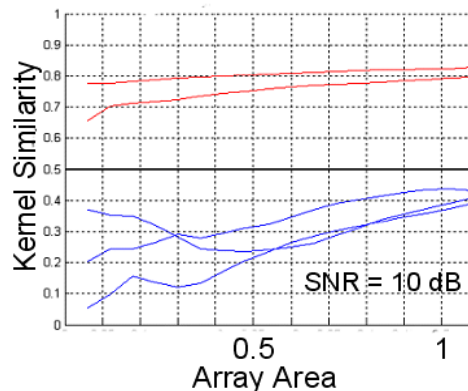
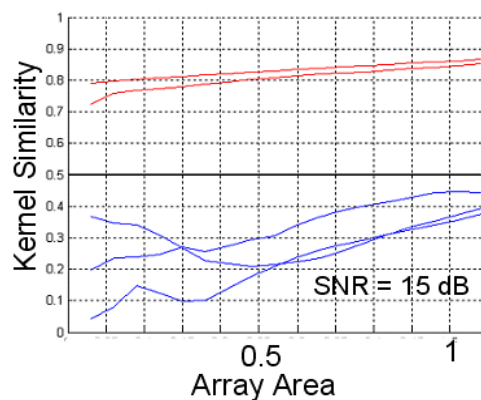


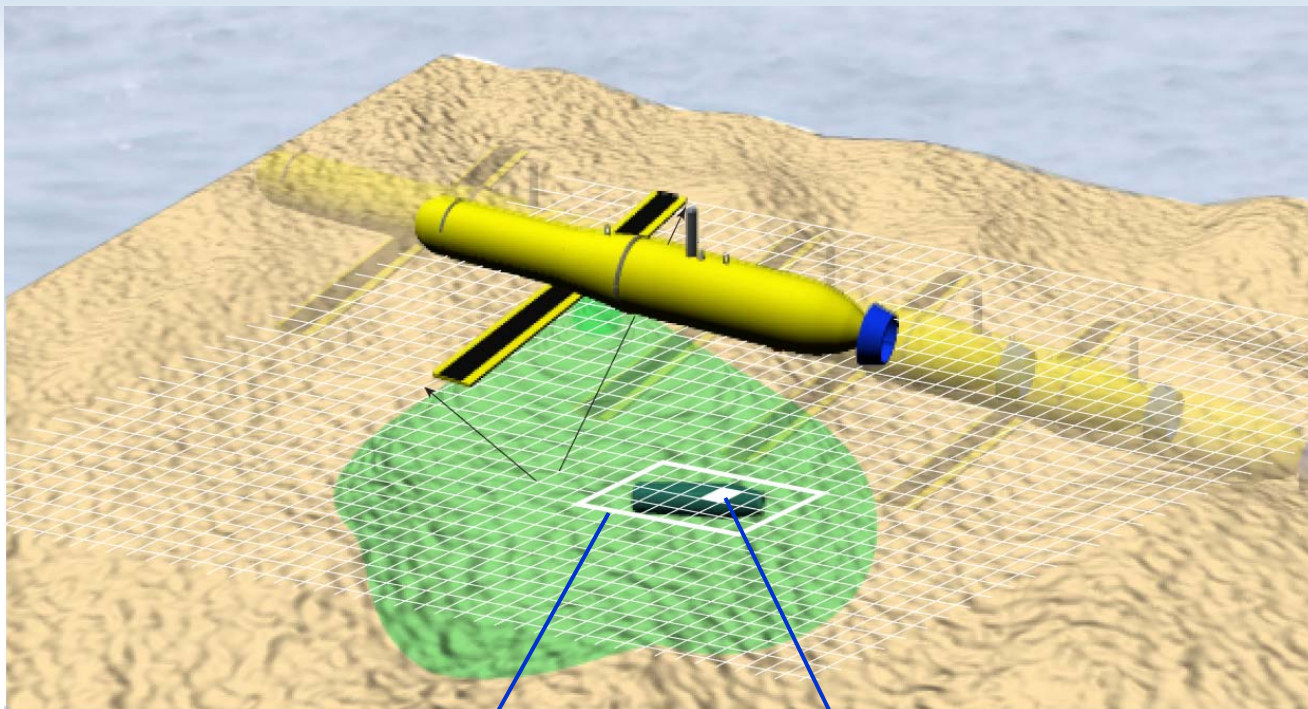
B



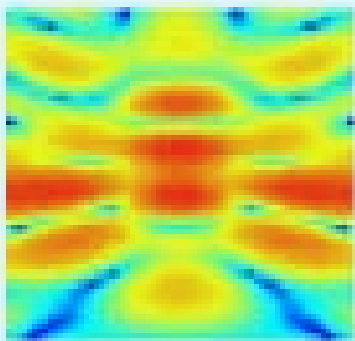


Rocket/False Target Feature Separation





Feature -
Based ID



Acoustic Image



The pressure at receiver point r_n generated by a point scatterer located at r_i can be written as:

$$P_n(\bar{r}_n | \bar{r}_i, \omega) = -i\rho_0 kc Q_s(\omega) G(\bar{r}_n | \bar{r}_i, \omega)$$

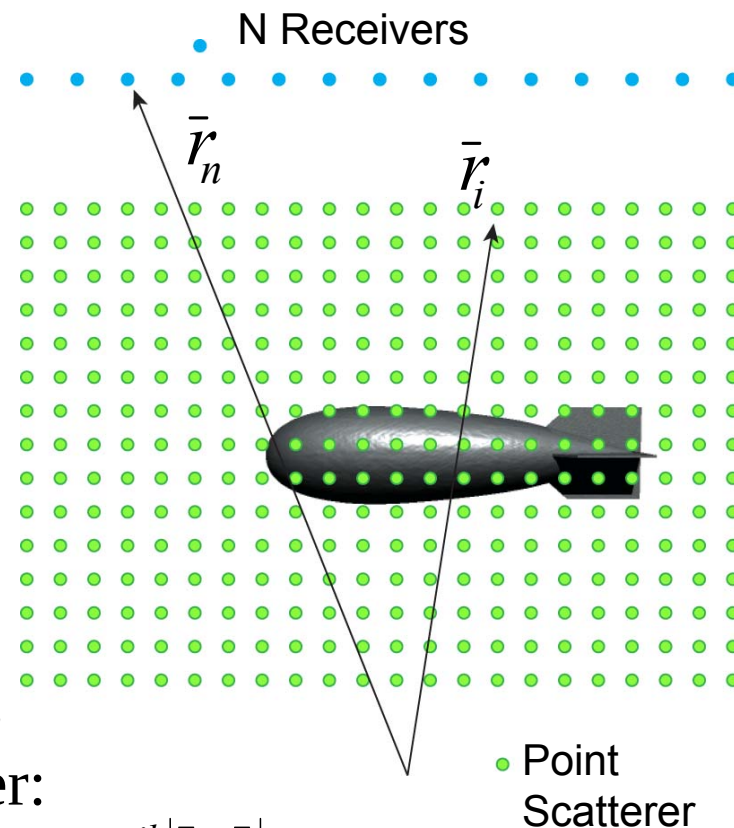
$$\text{where, } G(\bar{r}_n | \bar{r}_i, \omega) = \frac{e^{ik|\bar{r}_n - \bar{r}_i|}}{4\pi|\bar{r}_n - \bar{r}_i|}$$

and Q_s is the volume velocity at $\bar{r}_i$ in response to the incident field.

We collect the source strength terms into a “scattering strength” parameter:

$$P_n(\bar{r}_n | \bar{r}_i, \omega) = \underbrace{\sigma_i(\bar{r}_i, \omega)}_{\text{Scattering Strength}} \underbrace{V(\omega)}_{\text{Input Pressure Waveform}} \frac{e^{ik|\bar{r}_n - \bar{r}_i|}}{4\pi|\bar{r}_n - \bar{r}_i|}$$

Pressure at n^{th} Receiver
Scattering Strength
Input Pressure Waveform



The scattered pressure is then normalized by the incident signal,

$$D_n(\bar{r}_n | \bar{r}_i, \omega) = \frac{P_n(\bar{r}_n | \bar{r}_i, \omega)}{V(\omega)} = \sigma_i(\bar{r}_i, \omega) \frac{e^{ik|\bar{r}_n - \bar{r}_i|}}{4\pi|\bar{r}_n - \bar{r}_i|}$$

Solving for the scattering strength,

$$\sigma_i(\bar{r}_i, \omega) = 4\pi|\bar{r}_n - \bar{r}_i| D_n(\bar{r}_n | \bar{r}_i, \omega) e^{-ik|\bar{r}_n - \bar{r}_i|}$$

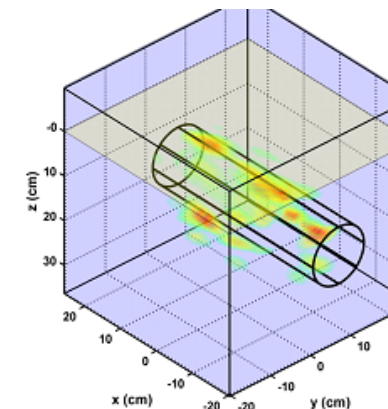
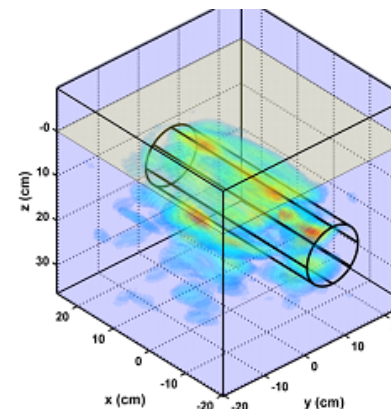
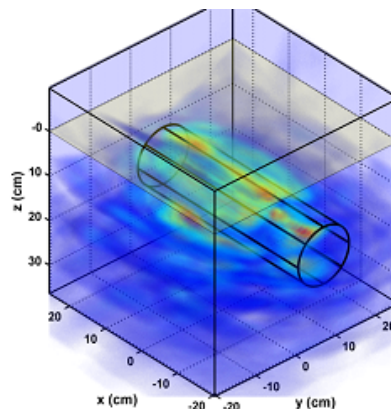
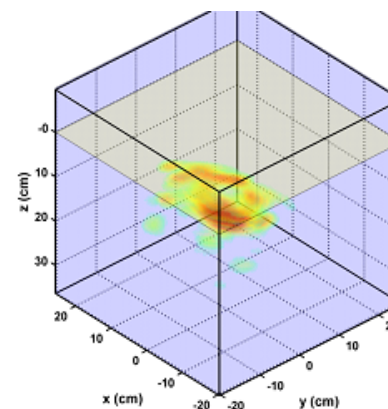
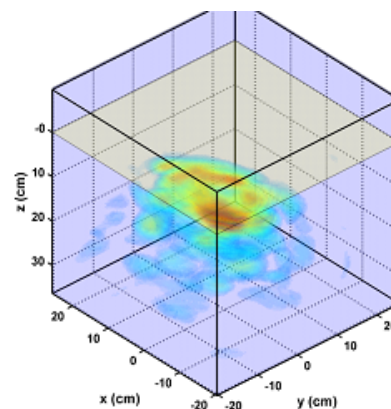
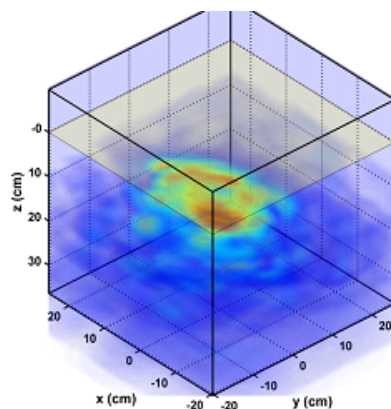
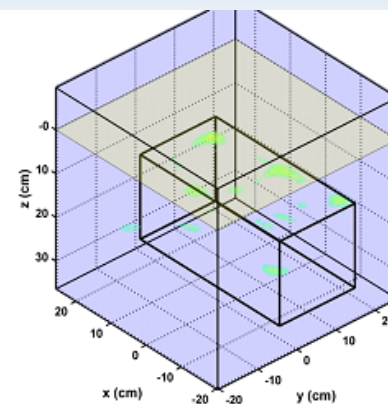
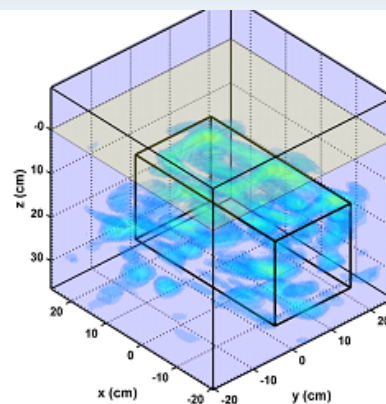
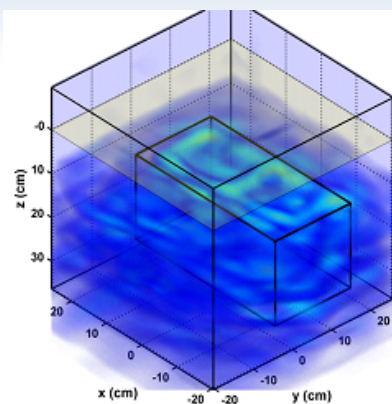
Taking the inverse Fourier transform, and assuming a perfectly reflecting point scatterer, *i.e.* $\sigma_i(\bar{r}_i, \omega) = \sigma_i = \text{Constant}$

$$\sigma_i(\bar{r}_i) \delta(t) = 4\pi|\bar{r}_n - \bar{r}_i| d_n(\bar{r}_n | \bar{r}_i, t - |\bar{r}_n - \bar{r}_i|/c)$$

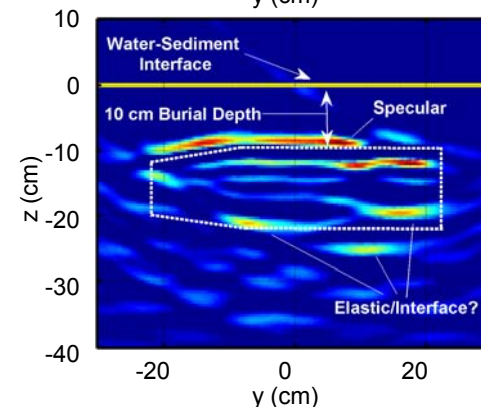
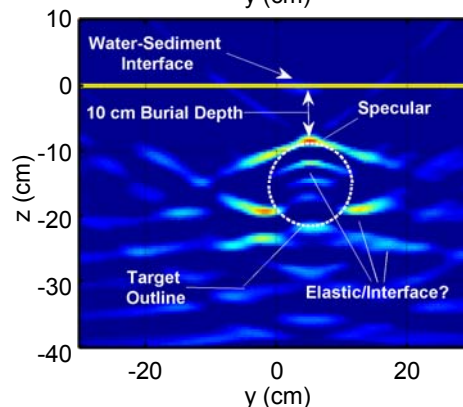
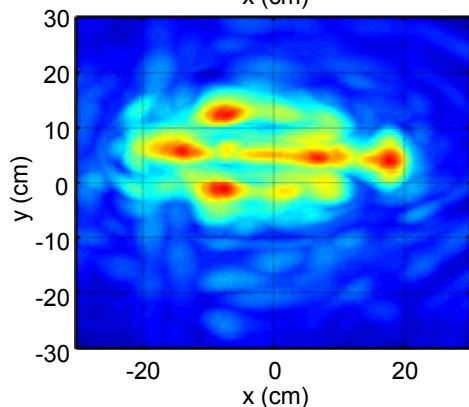
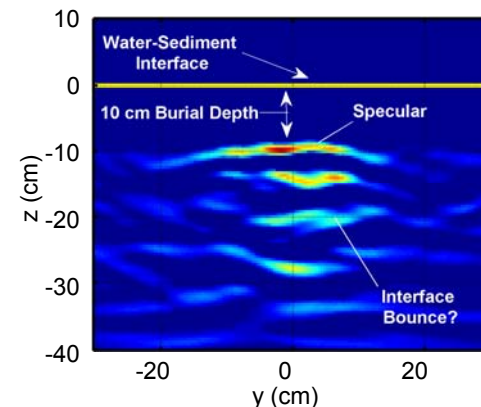
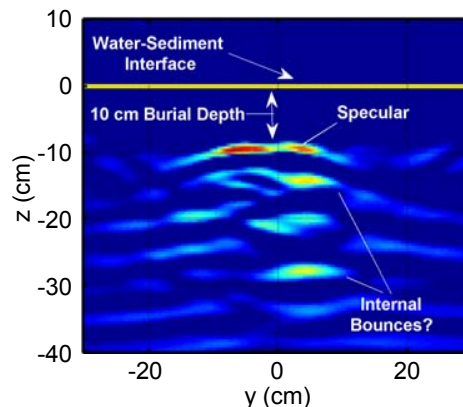
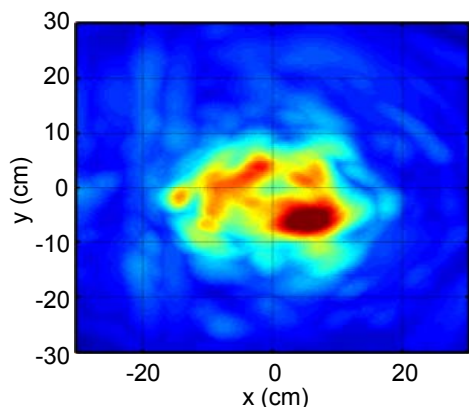
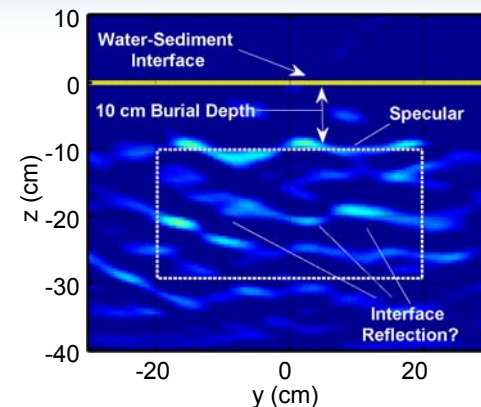
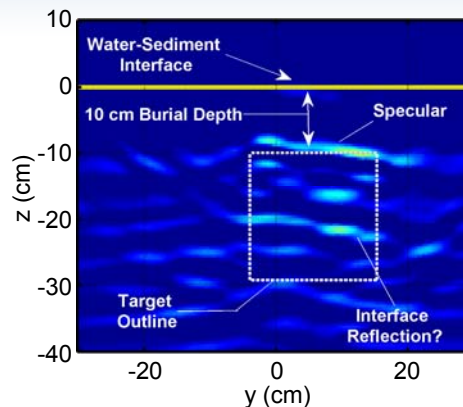
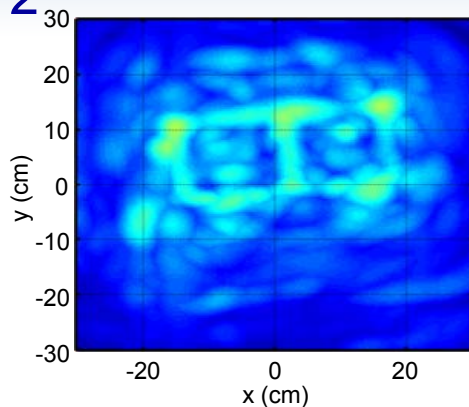
Multiply by $\delta(t)$, integrate over time, and average over all channels:

$$\text{Image Strength at } \bar{r}_i \equiv \sigma_i(\bar{r}_i) = \frac{1}{N} \sum_{n=1}^N 4\pi|\bar{r}_n - \bar{r}_i| d_n(\bar{r}_n | \bar{r}_i, |\bar{r}_n - \bar{r}_i|/c)$$

Imaging Band 12 – 25 kHz



Imaging Band 12 – 25 kHz

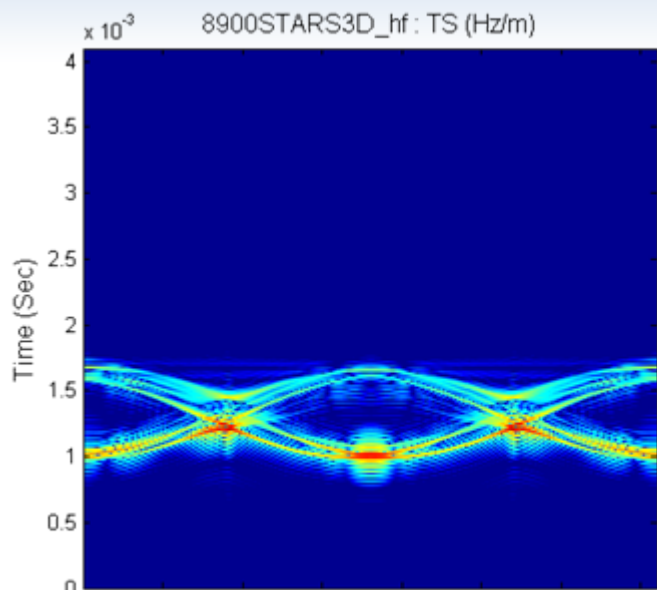




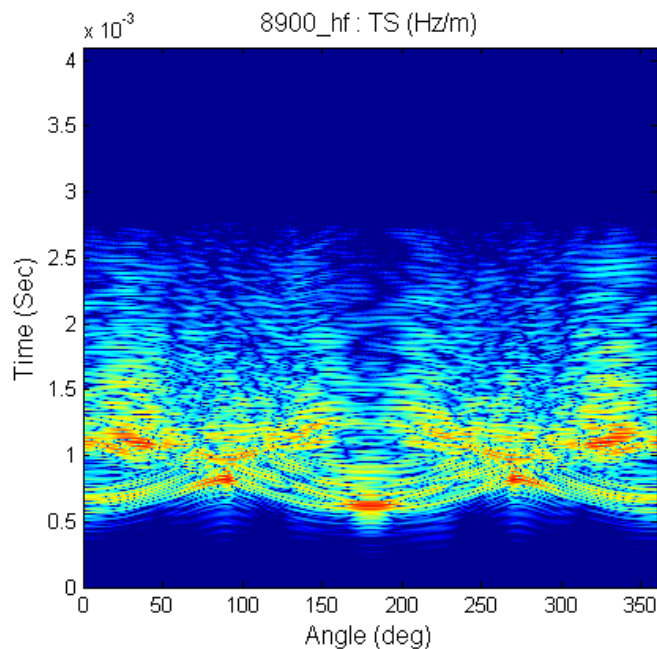
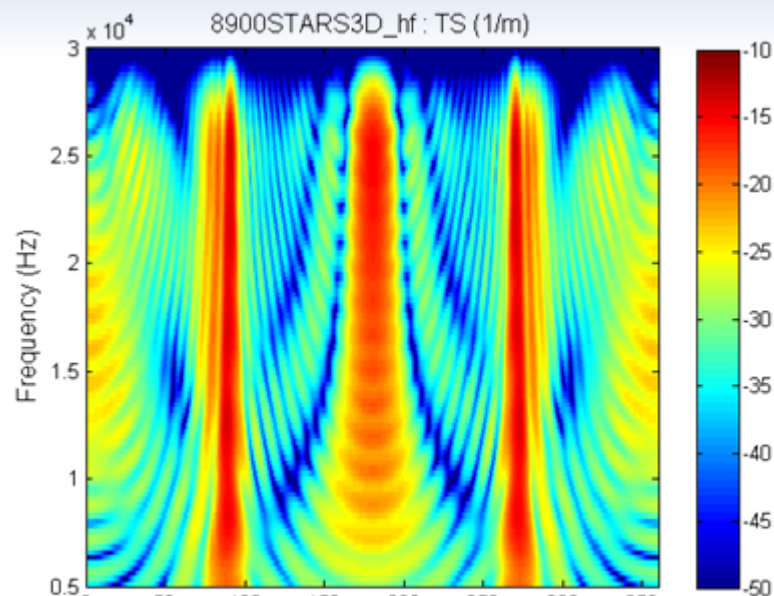
Time / Angle Plots for Rocket

Time Domain

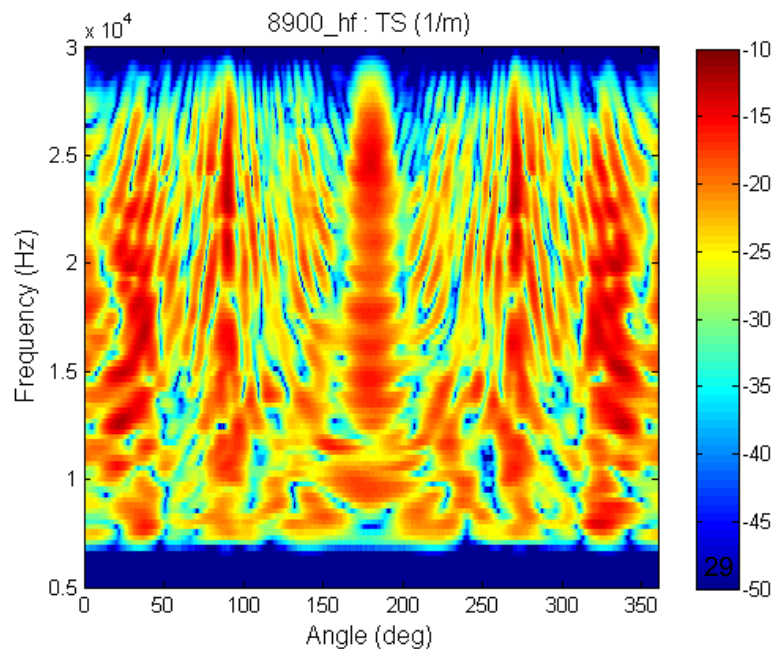
Frequency Domain



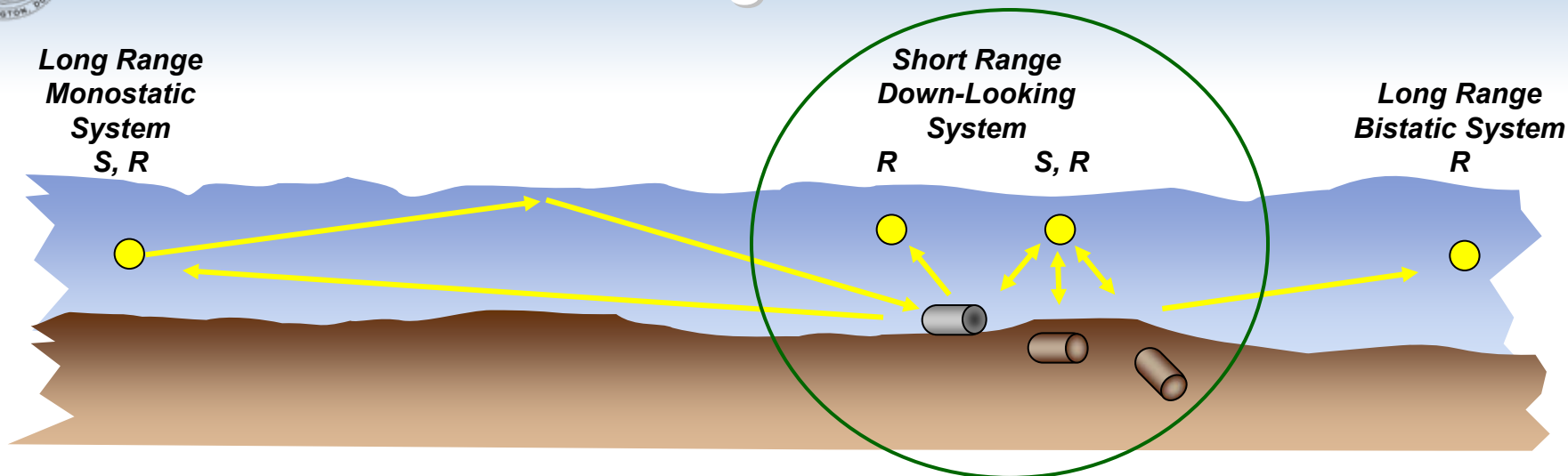
Only
Specular



Full
Response
(Elastic)



Concluding Remarks



In our new focus on the short range down-looking scenario our plans are to :

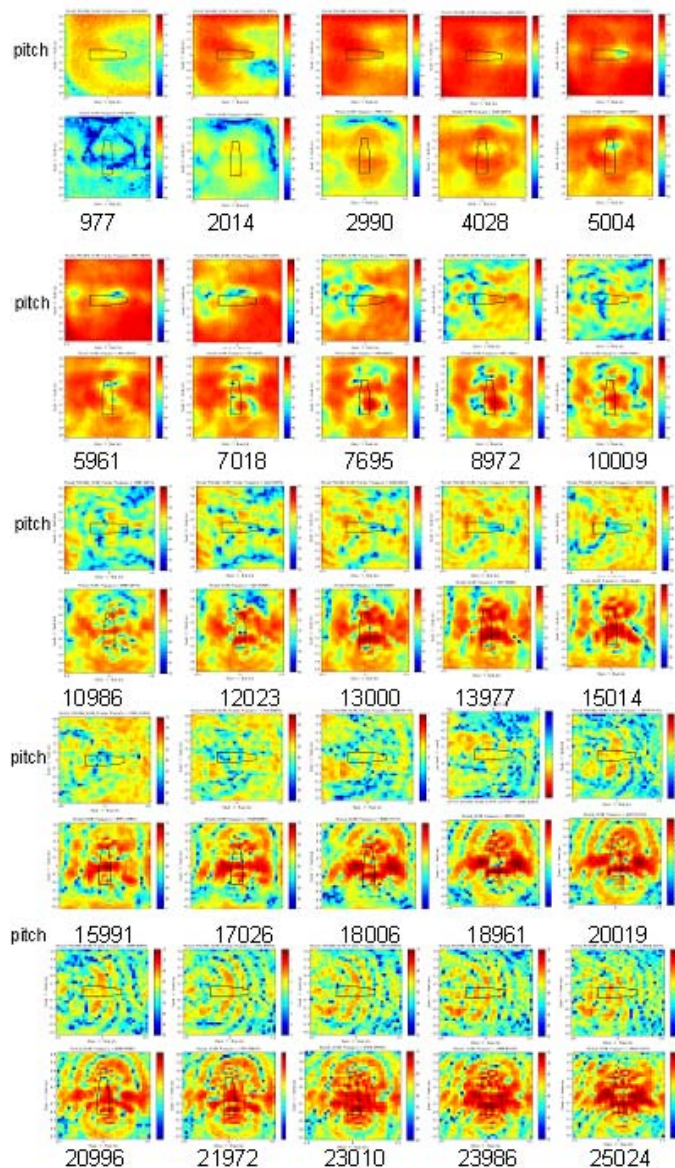
- Develop a RVM structural acoustic ID algorithm methodology which includes burial effects and target “pitch” angles in the training
- Fuse structural acoustic and image ID algorithms, perhaps in an interactive manner
- Move to marine environments and naturally occurring clutter



Backup Slides



Scattered pressure over receiver array
for 5 inch rocket buried at 30° downward
pitch angle for frequencies in Hz



Free-field mono-static TS
30° downward nose pitch

Semi-Log Frequency Plot

