Underwater Acoustics: understanding the environment to increase autonomy

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What's the problem?

- More than 70% of the earth's surface is covered by water…

  …but we know less about it than we do about the surface of Mars!

- Infrastructure on seabed >1000m below surface
  - Deep; dark; dangerous

Oil flowing from BP well Gulf of Mexico, May 2010
Depth: 1500m

What is this talk about?

- focus on active sonar
- high frequency sonar

- other disciplines:
  - very low freq: seismic
  - low freq: ASW
  - high freq: MCM, imaging
  - very high freq: ultrasound monitoring, cell manipulation, medical applications

The sensing problem

Sensing is the link between the physical world and signal processing.

Two different methodologies:

- use a priori knowledge of the physical world to extract useful information
- build the sensor(s) around a specific problem

Underwater acoustics: a very exciting field!

- at the meeting point of various scientific disciplines
- place for creativity

Overview

- **A bit of history**
- **Underwater basics: the sonar equation**
- **Sidescan sonar: simulator and applications**
- **SAS**
- **BioSonar: the power of wideband**
- **MIMO**

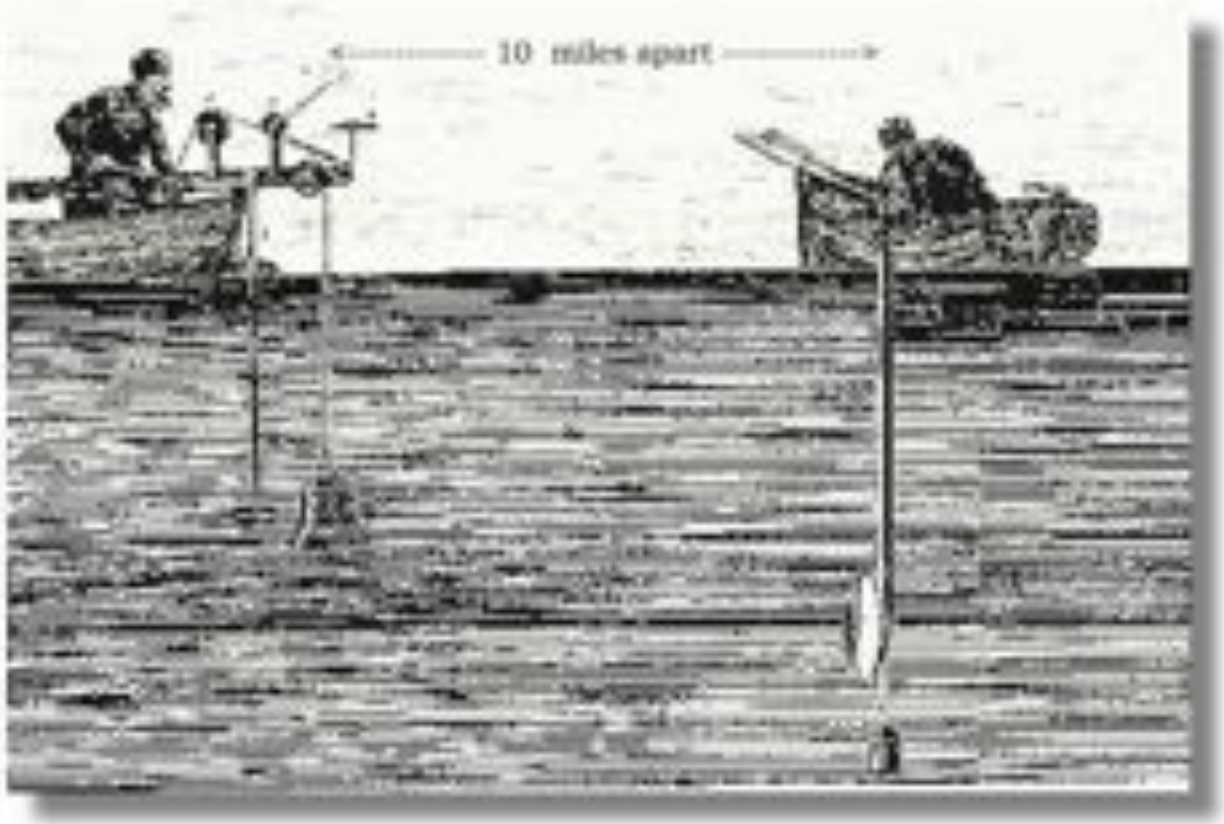
A bit of history

"If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you."
Leonardo da Vinci (1490)

A bit of history

The first issue to solve to develop active sonars was to generate sound in water. The high impedance of water compared to air (about 3500 times higher).

Daniel Colladon and Charles Sturm in an experiment in Lake Geneva in Switzerland in 1827 managed to estimate the velocity of sound in water using an underwater bell as a pulse generator.



1435 meters per second

A bit of history

First breakthrough: discovery of piezoelectricity by Pierre and Jacques Curie in 1880.

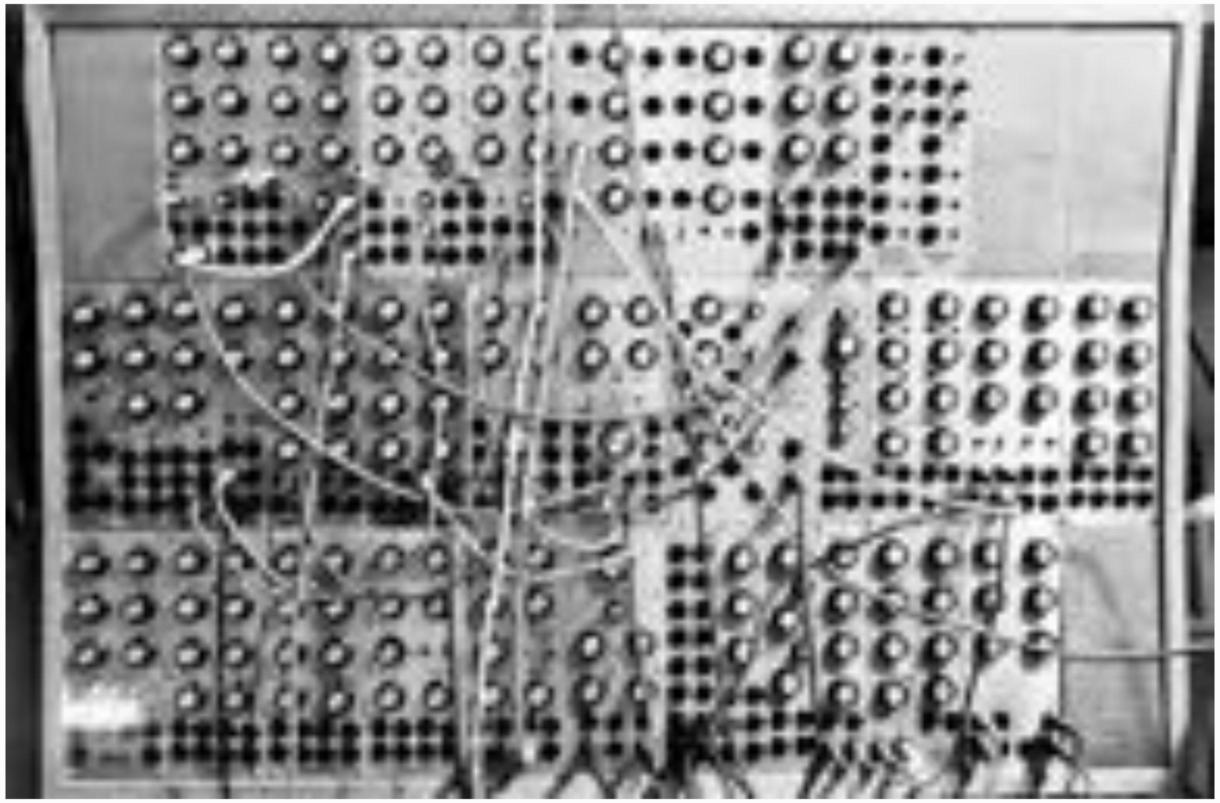
In 1917 Charles Langevin and Constantin Chilowsky used the piezoelectric effect of quartz to build the first active sonar.

First electrometer

A bit of history

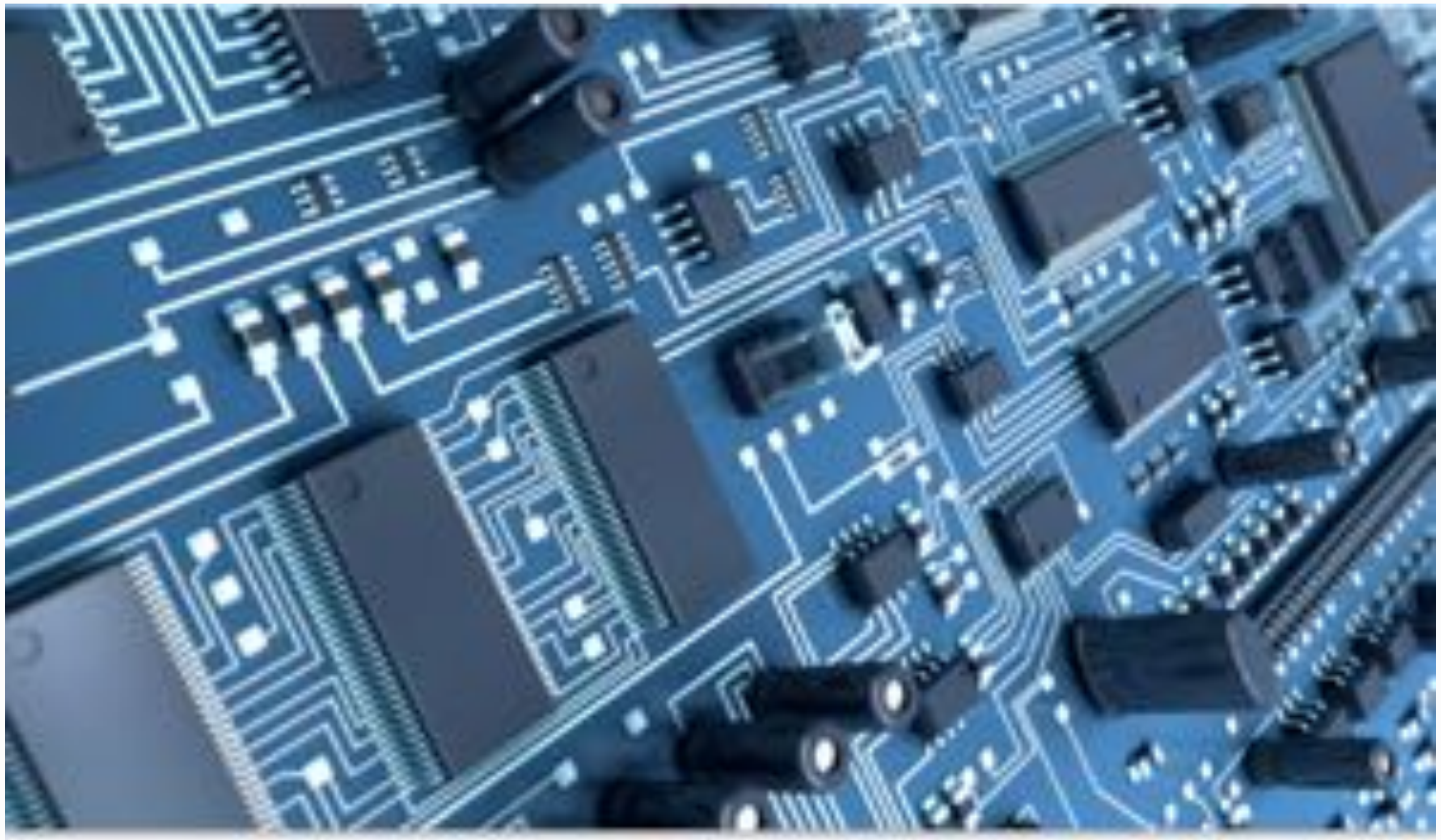
<u>Second breakthrough:</u> Analog electronics

filtering, amplification and processing were integrated into sonar systems increasing drastically the SNR



A bit of history

<u>Third breakthrough:</u> Digital electronics



performance

portability

versatility

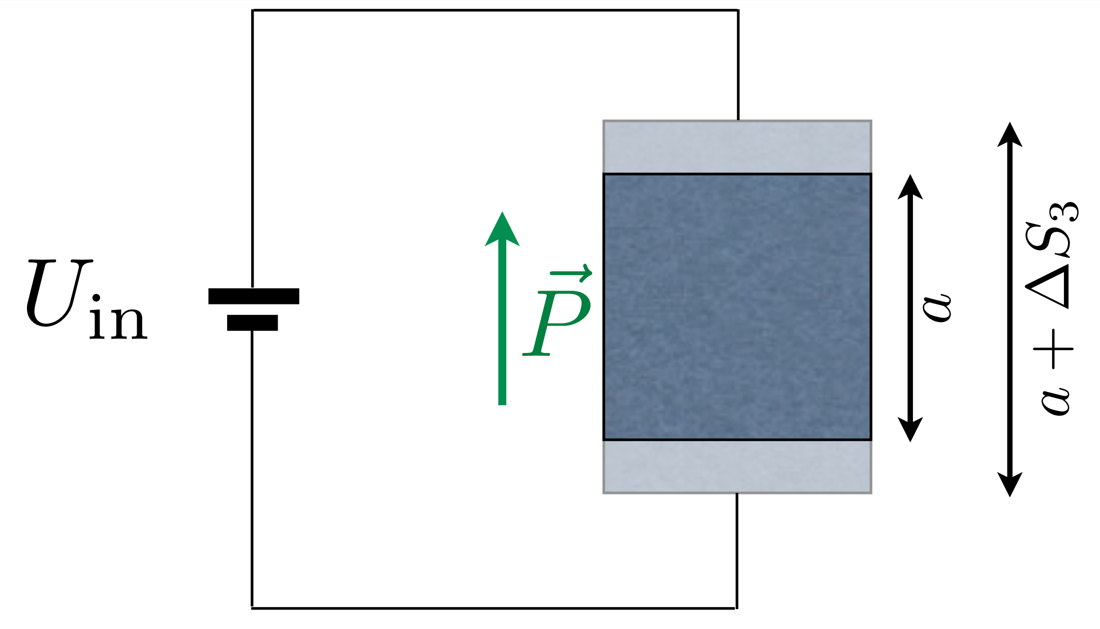
The piezoelectric effect

Principles of piezoelectricity (Lippman, 1881)

$$S = s^E T + d^t E$$

$$D = d T + \epsilon^T E$$

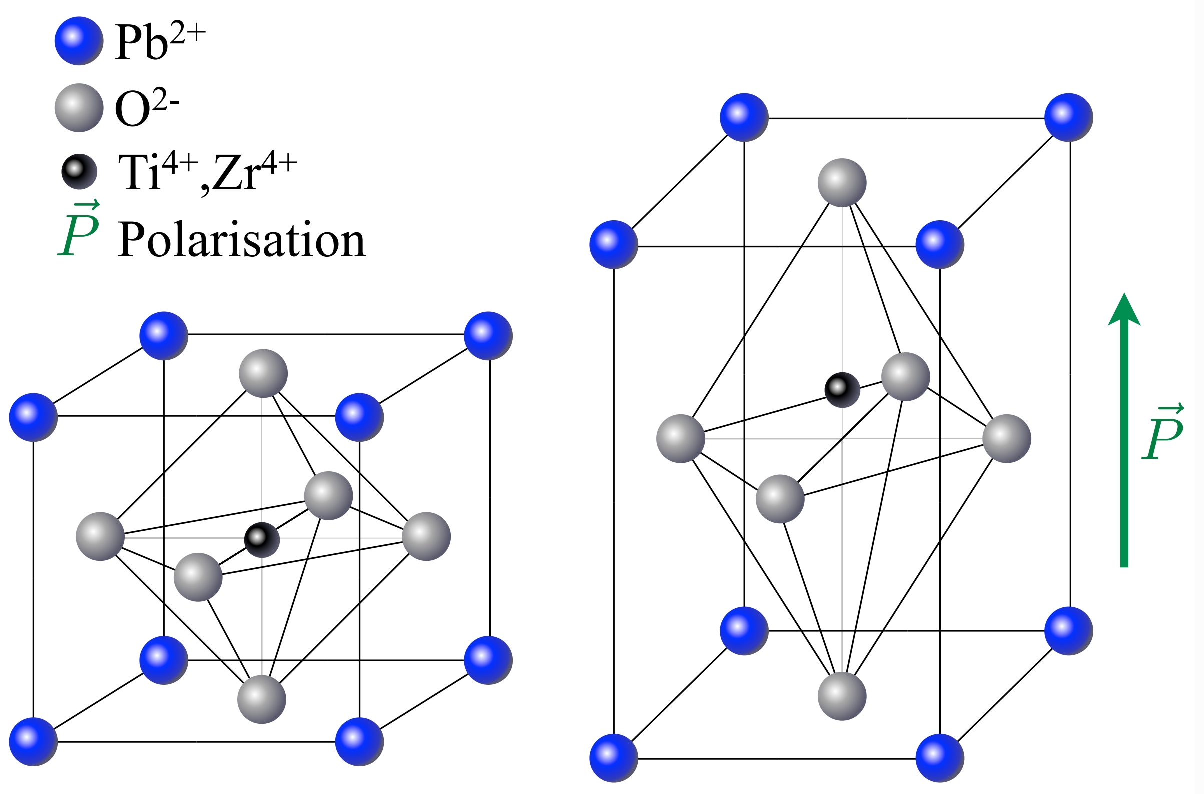
$$\Delta S_3 = d_{33}\, U_{\text{in}}$$



The piezoelectric effect

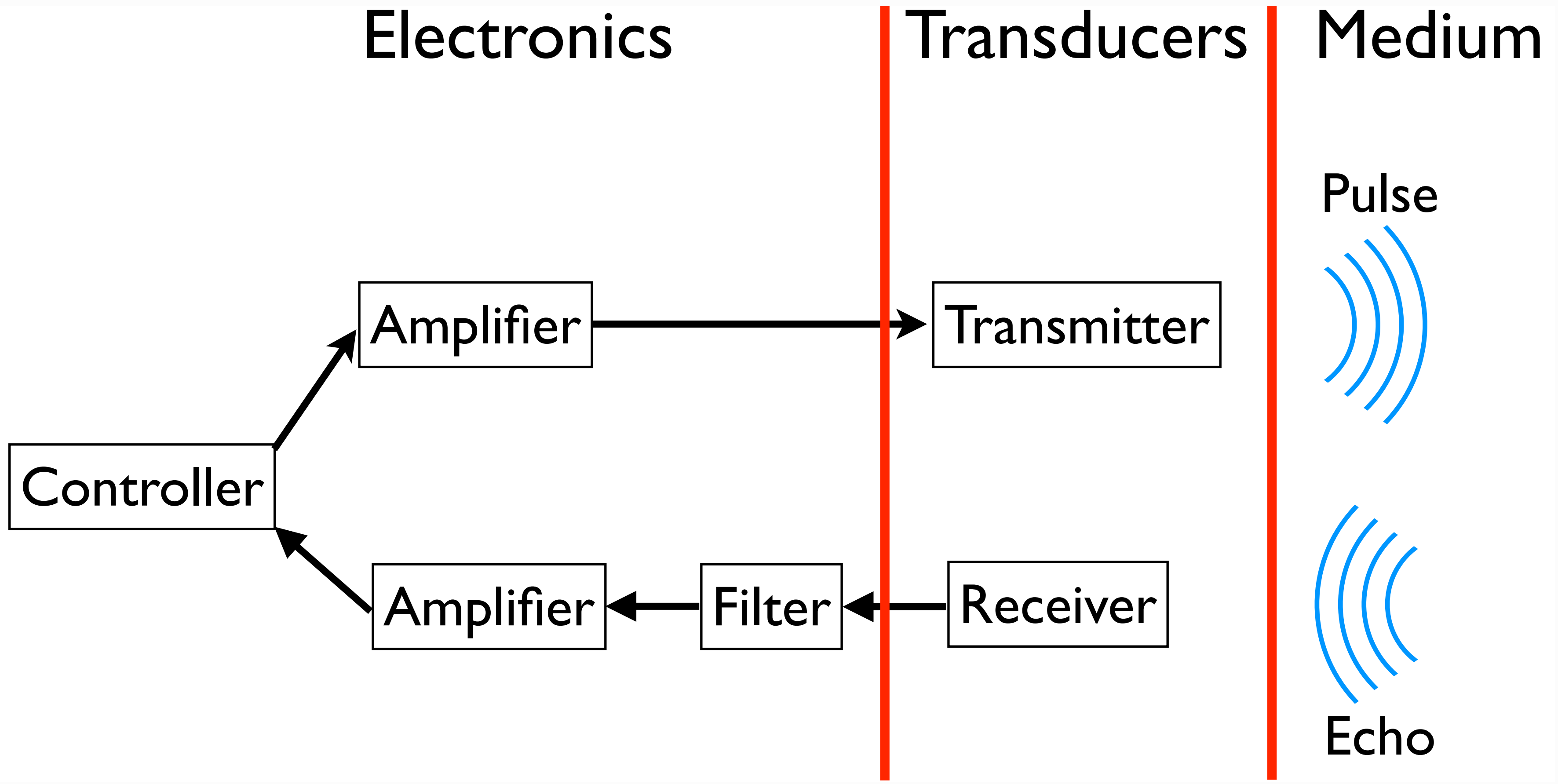
Synthetic piezocrystals present higher piezoelectric effects than the natural ones. In particular the direct piezoelectric term d33 which links linearly the displacement to the electric charge is much higher (around 10 times higher). This property induces a much higher electromechanical efficiency.

The metals are mixed at high temperature (higher than the Curie temperature). A voltage field is then applied to polarise the crystal in one specific direction. A remnant polarisation is then recorded into the intrinsic nature of the piezoceramic.



Crystal configuration of PZT above Curie temperature (left) and below the Curie temperature (right).

Sonar electronics



The sonar equation

The sonar equation formulated by Urick describes in a simple manner and from an energetic point of view the basic sonar principles. It relates the energy sent into the water by the transmitter to the energy received by the receiver.

$$SL - 2TL + TS = NL - DI + RL + DT$$

Similarity with the radar equation $$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R^4}$$

The sonar equation

The sonar equation despite its simplicity is a powerful tool in order to predict and evaluate the performances of a given sonar. One of the main applications of sonars developed during the 2nd World War was the detection of submarines. For ASW (anti-submarine warfare) detection range is a critical parameter.

The sonar equation

Sound speed in seawater is given by the Mackenzie's equation (1981)

$$\begin{aligned} c =& 1448.96 + 4.591T - 5.304.10^{-2}T^2 + 2.374.10^{-4}T^3 \\ &+ 1.340(S-35) + 1.630.10^{-2}D + 1.675.10^{-7}D^2 \\ &- 1.025.10^{-2}T(S-35) - 7.139.10^{-13}TD^3 \end{aligned}$$

The sound speed in fresh water is given by the empirical equation of Grosso and Mader [1972]:

$$\begin{aligned} c =& 1402.388 + 5.03711T - 0.0580852T^2 \\ &+ 3.342.10^{-4}T^3 - 1.478.10^{-6}T^4 + 3.15.10^{-8}T^5 \end{aligned}$$

The sonar equation

The Source Level

	Sonar	Frequency (in kHz)	Source Level (in dB)
Manmade Sonars	Tritech SeaKing Obstacle Avoidance Sonar	325; 675	235
	Reson SeaBat 8101 Multibeam	240	217
	GeoAcoustics Dual Frequency Sidescan	114; 410	223
	Didson Detection Sonar Acoustic Camera	1100; 1800	205
	HWU Biosonar (prototype)	30 → 150	200
Biological Sonars	Bottlenose dolphin (Turiops truncatus)	30 →130	228
	False killer whale (Pseudorca crassidens)	100 → 130	228
	Harbour porpoise (Phocoena phocoena)	120 →140	162

The sonar equation

The Transmission Loss

$$TL = 20 \log r + \alpha r$$

Absorption (Francois and Garisson)

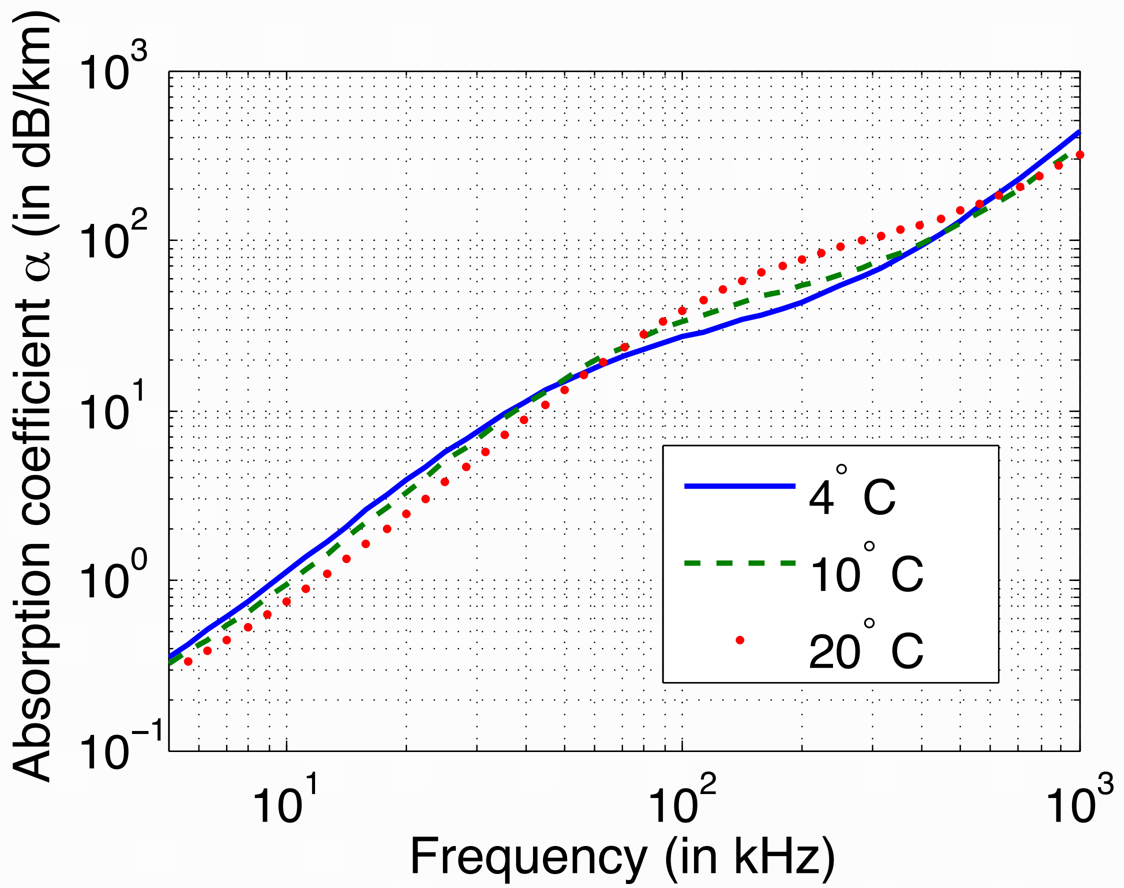
$$\begin{matrix}\text{Total} \\ \text{Absorption}\end{matrix} = \begin{matrix}\text{BoricAcid} \\ \text{Contribution}\end{matrix} + \begin{matrix}\text{MgSO4} \\ \text{Contribution}\end{matrix} + \begin{matrix}\text{PureWater} \\ \text{Contribution}\end{matrix}$$

The formula is given by:

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2$$

The sonar equation

The Transmission Loss

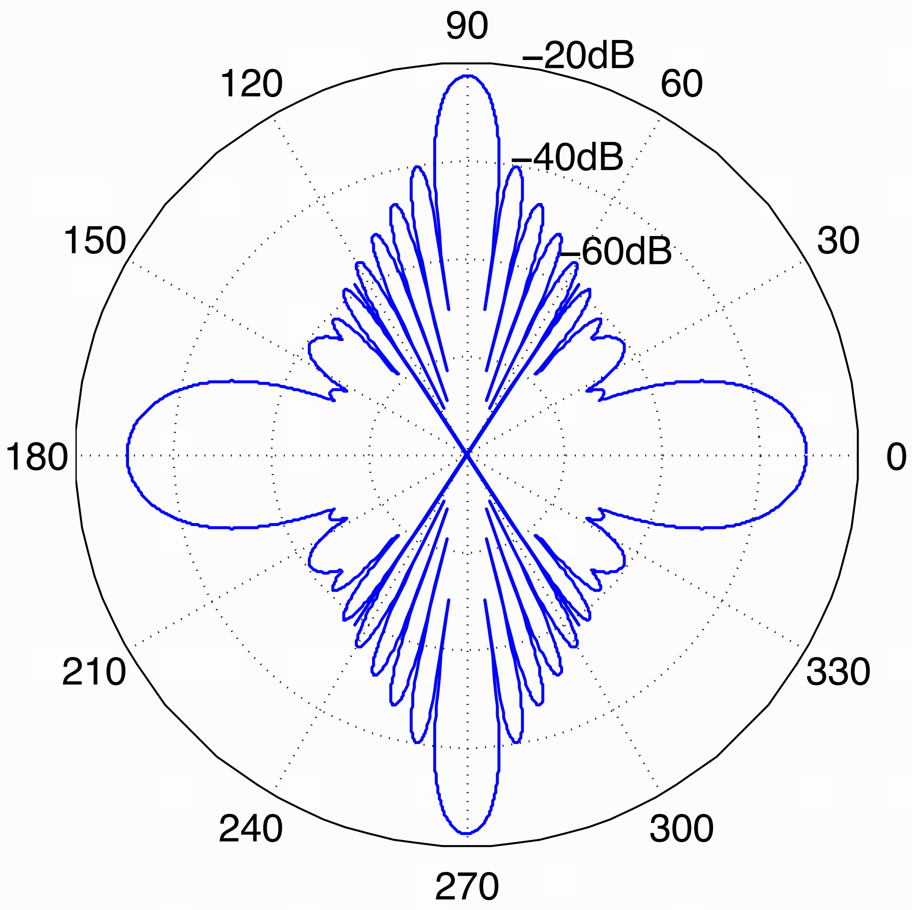


The sonar equation

The Target Strength

$$TS = 10 \log \left(\frac{I_r}{I_i} \right)$$

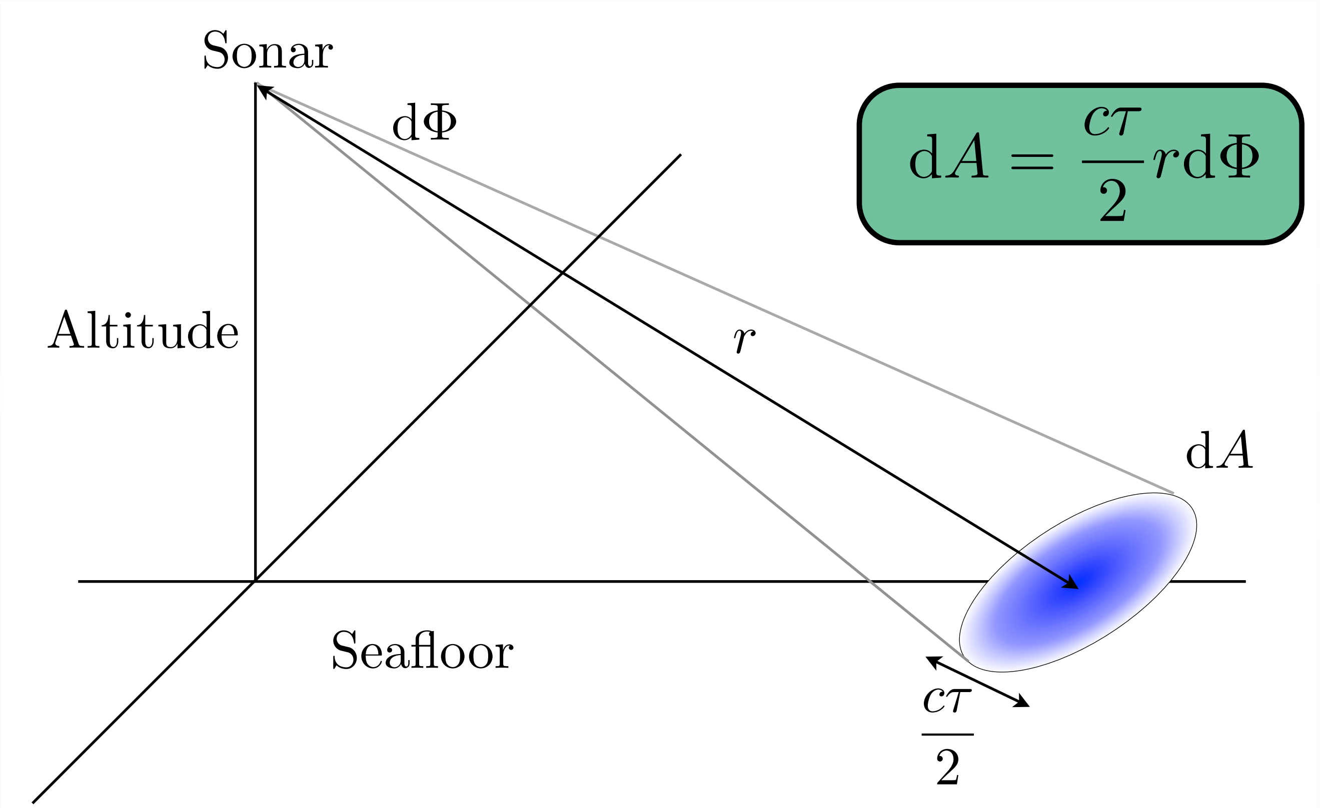
Finite cylinder

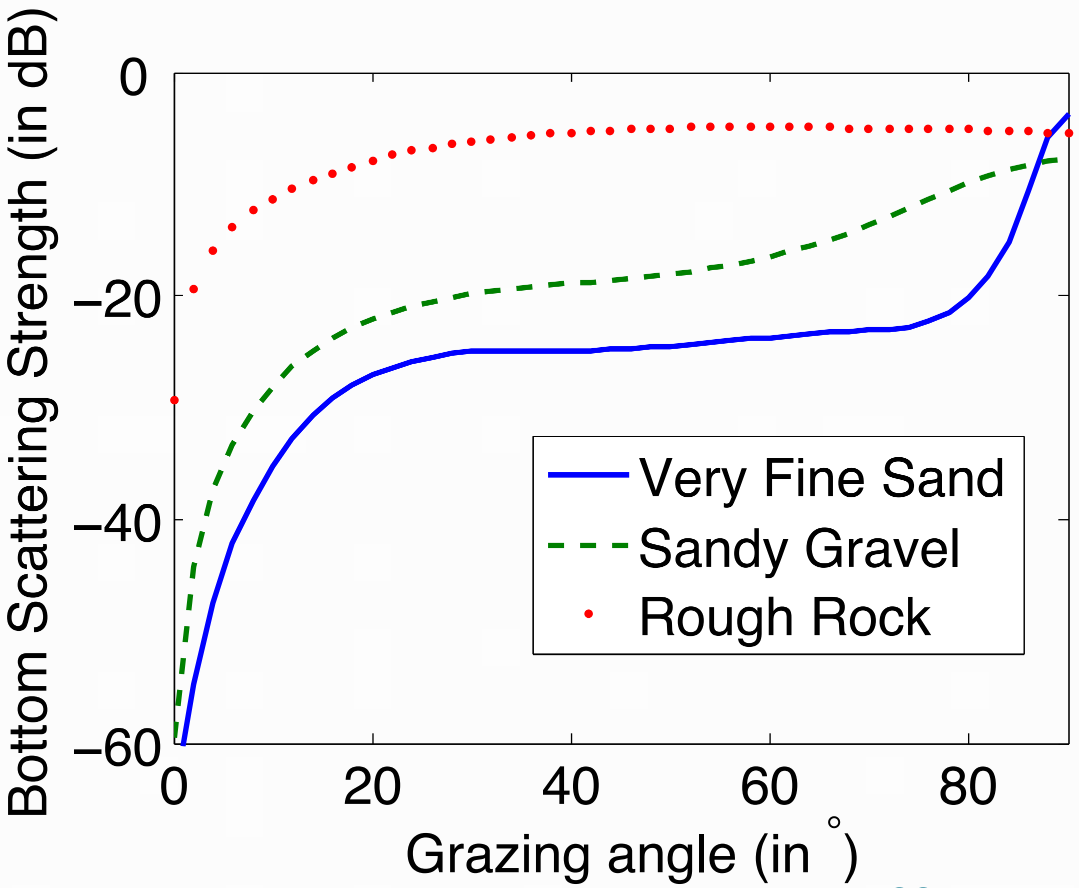


The sonar equation

The Reverberation Level

$$RL = SL - 2TL + S_s + 10\log \frac{c\tau}{2}\phi r$$

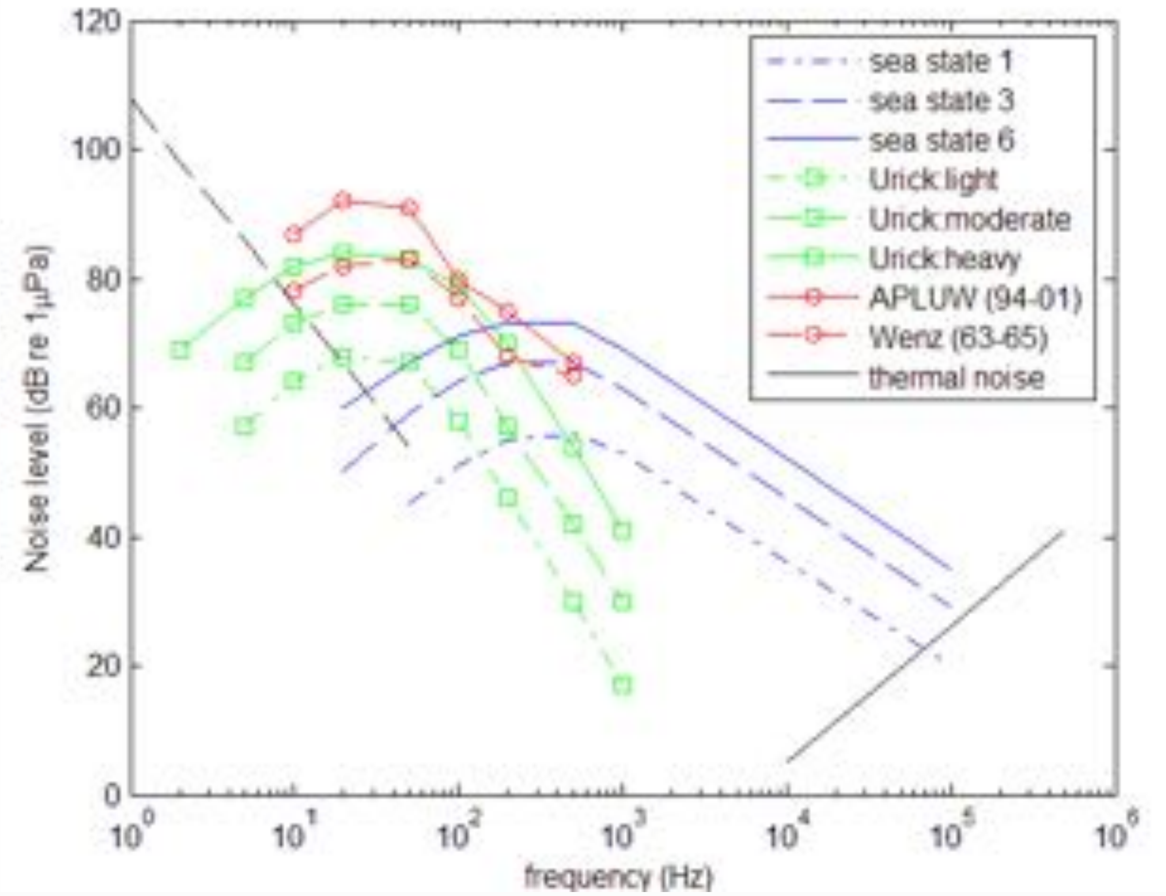




The sonar equation

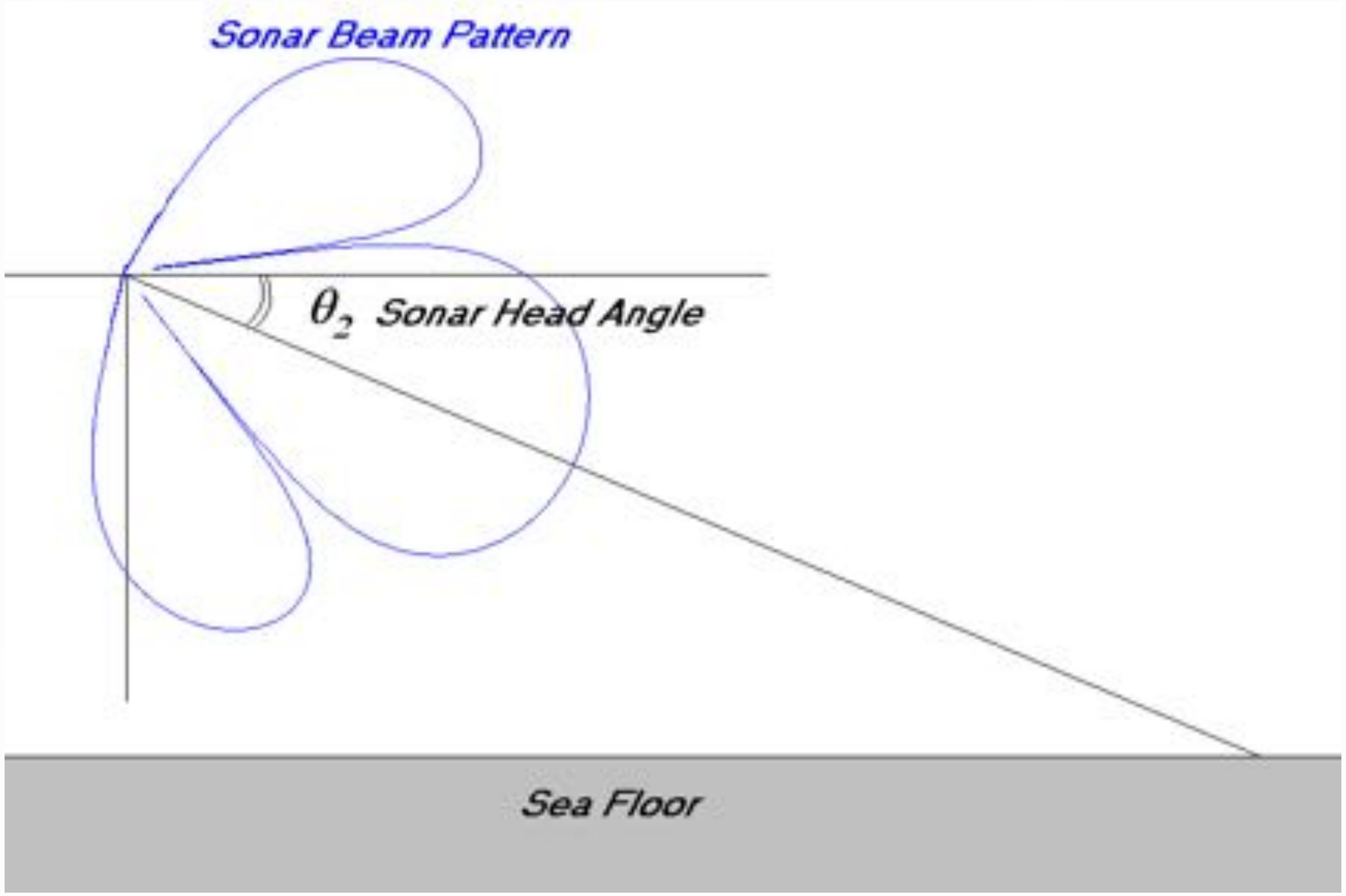
The Noise Level

Deep water noise spectra: below 10Hz ocean turbulence predominant; 10-150Hz shipping noise is major contributor; 0.1-10kHz dominated by the Knudsen spectra mainly due to wind and wave action; 10-100kHz thermal noise is significant.

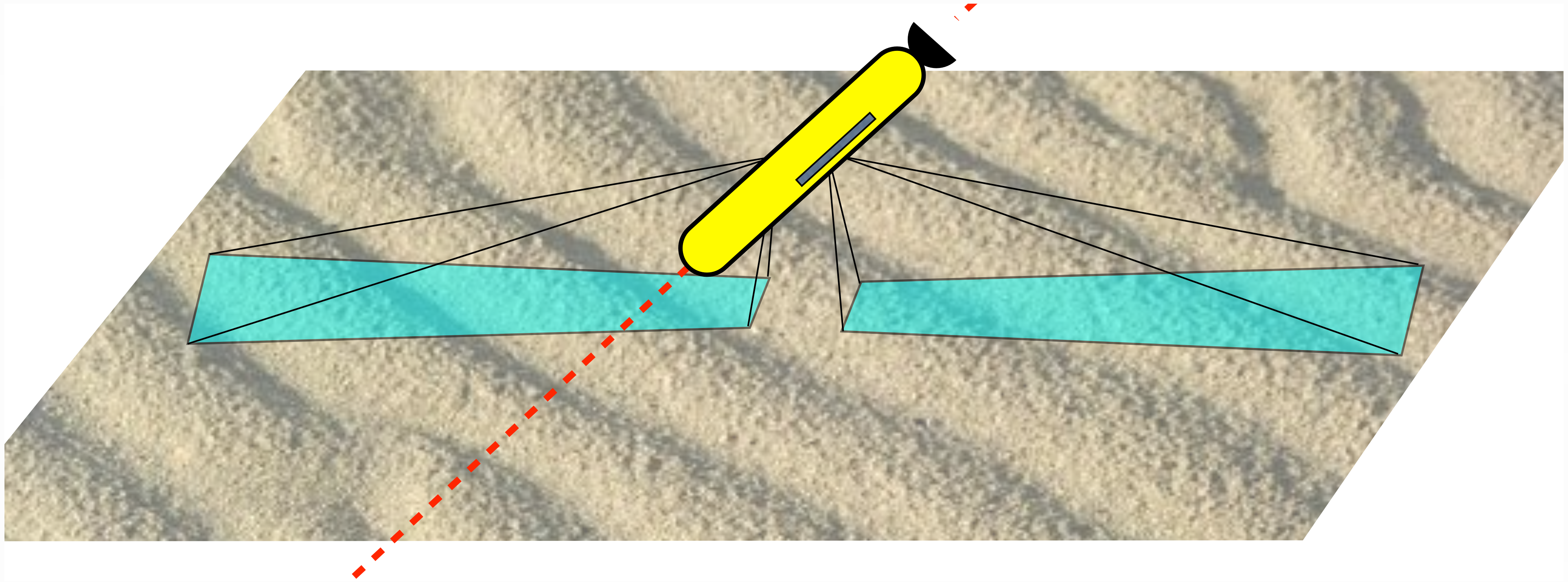


The sonar equation

The Beam Pattern and the Directivity Index



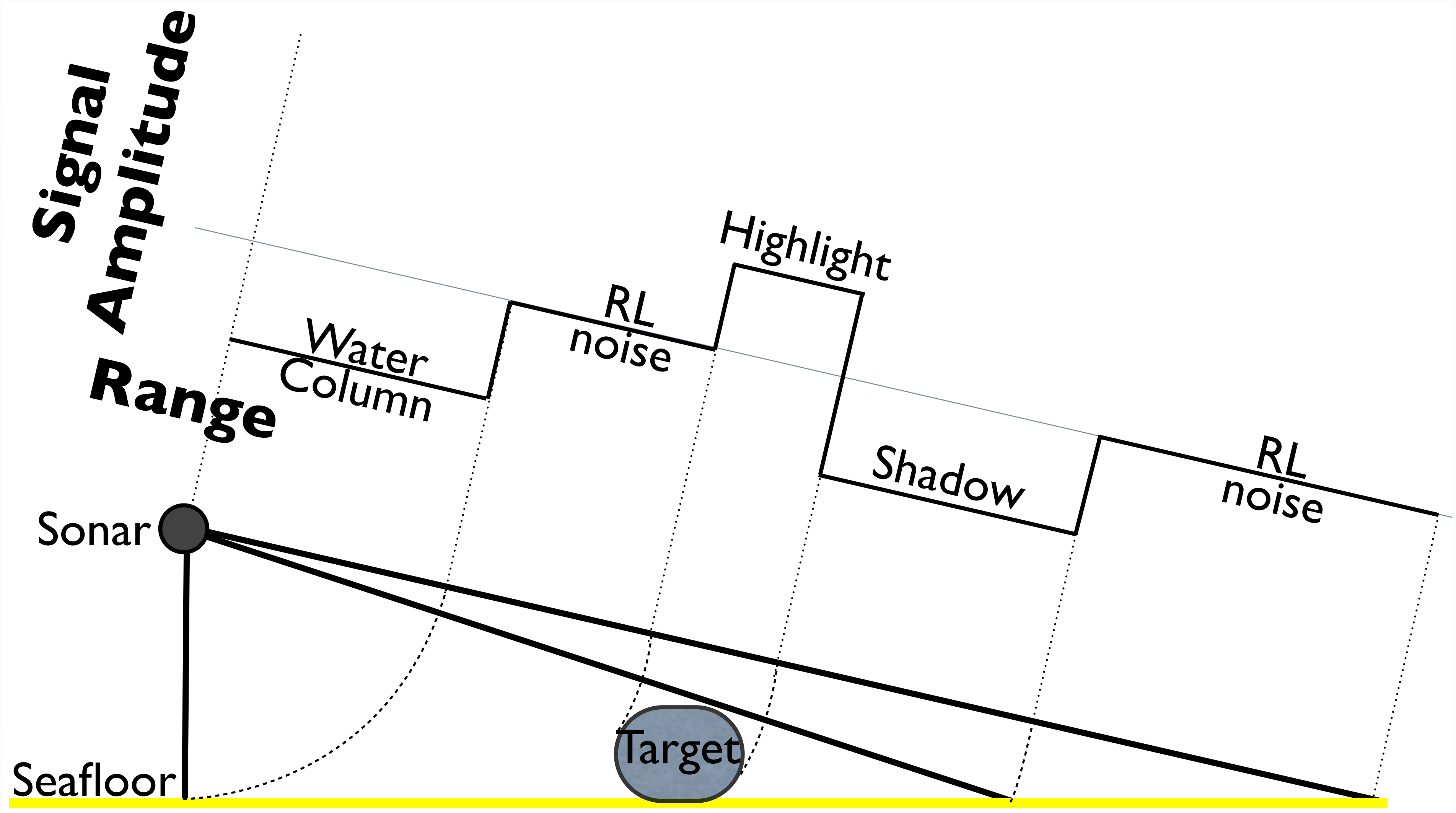
Sidescan Sonars



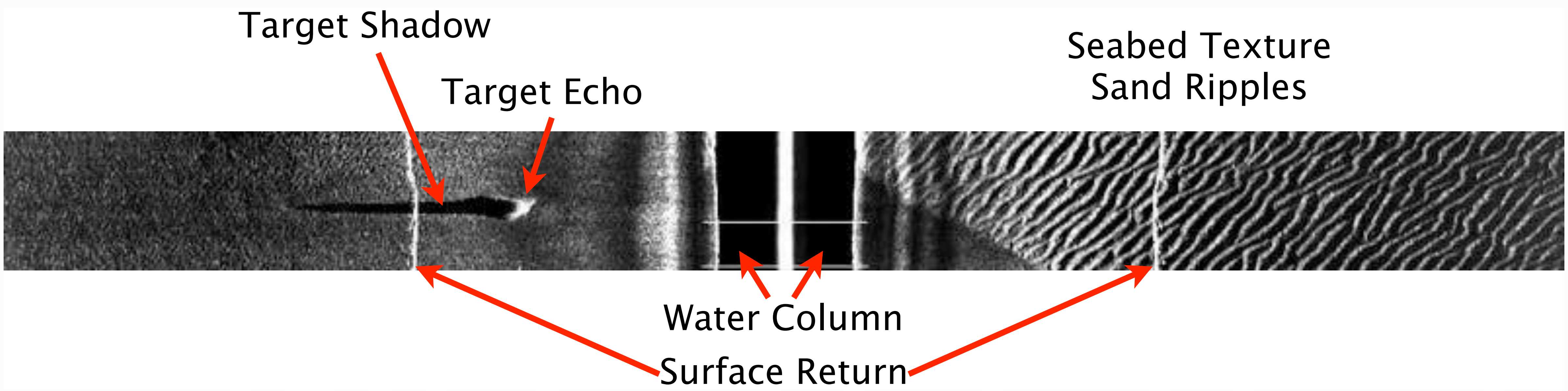
Sidescan configuration

Sidescan Sonars

Sonar gives you a range information.

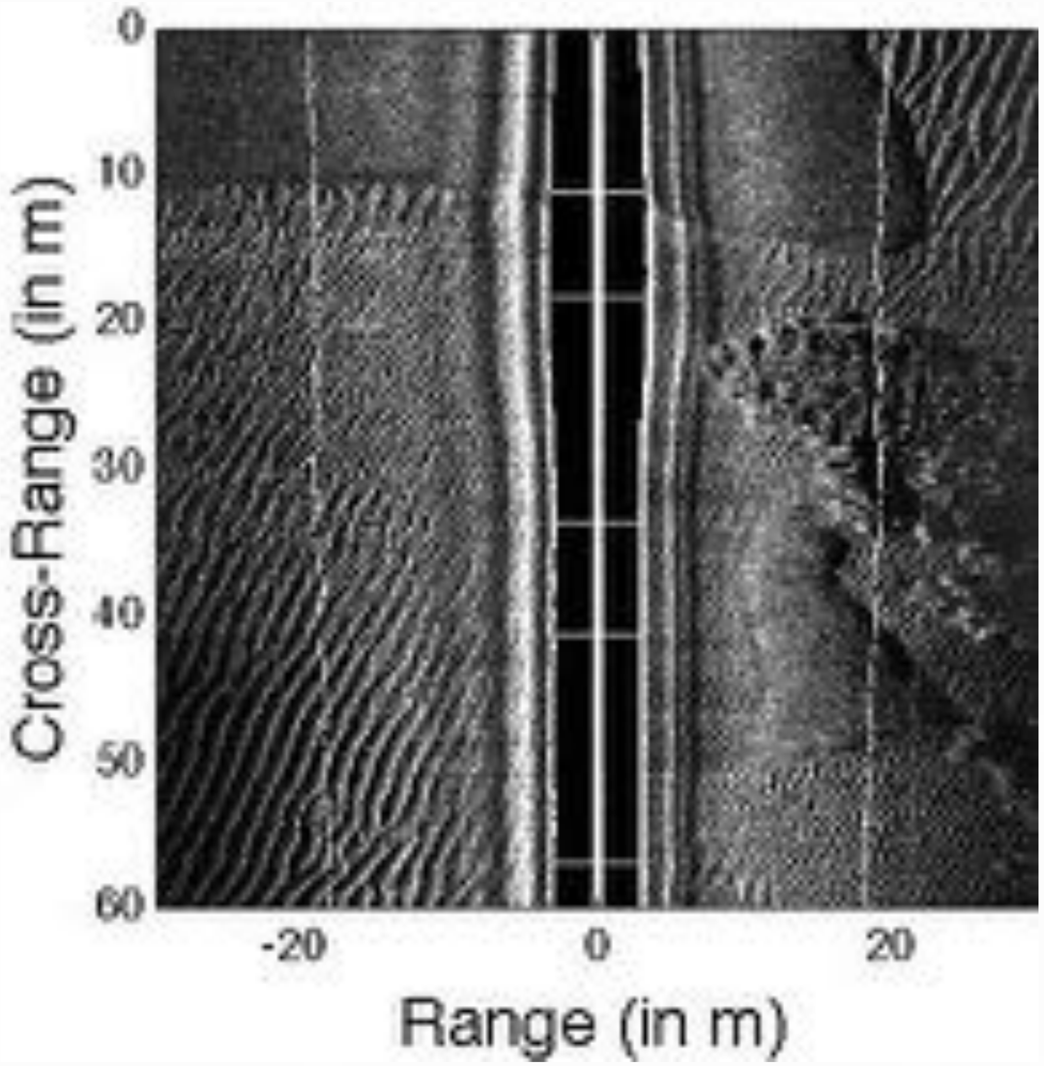


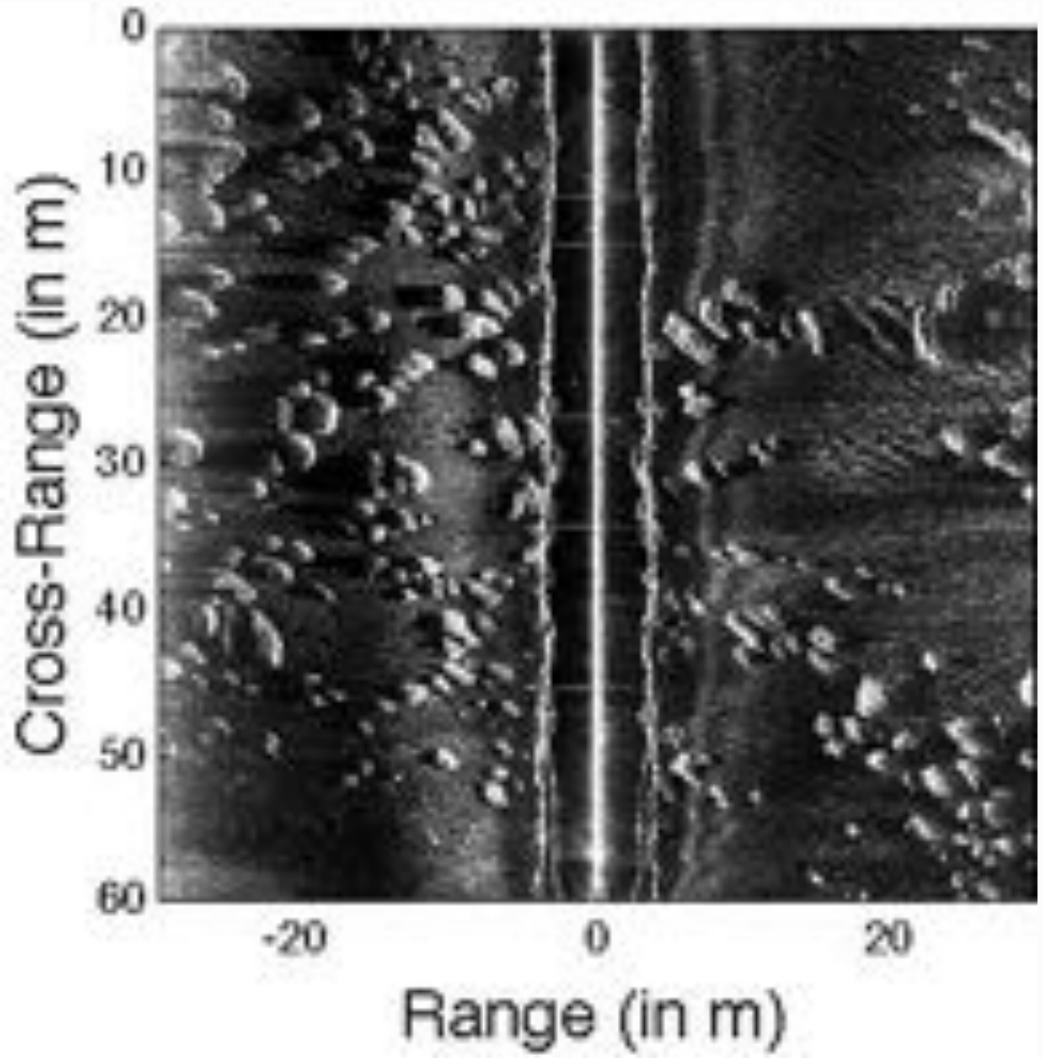
Sidescan Sonars



Sidescan Sonars

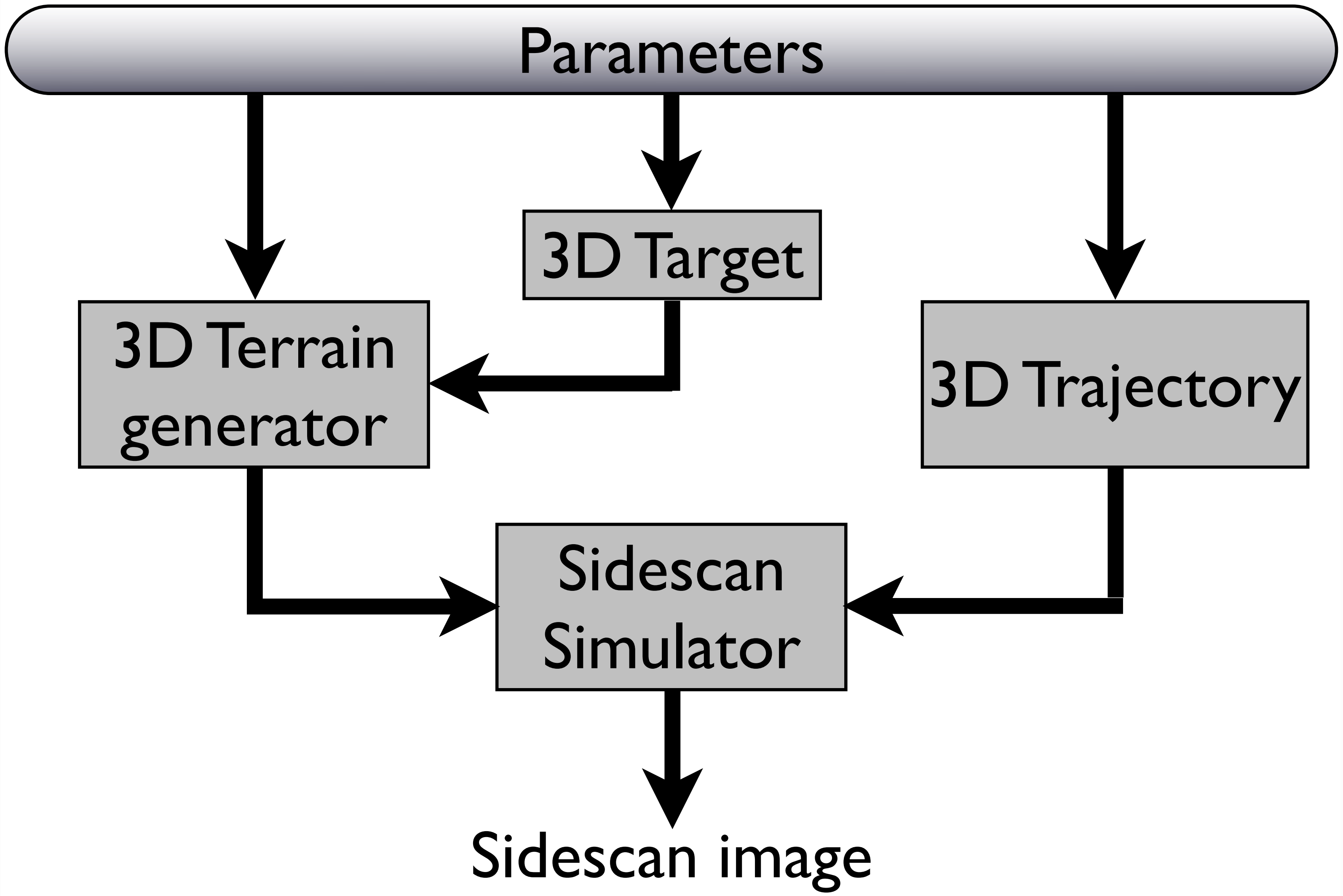
Examples of sidescan images





Sidescan Simulator

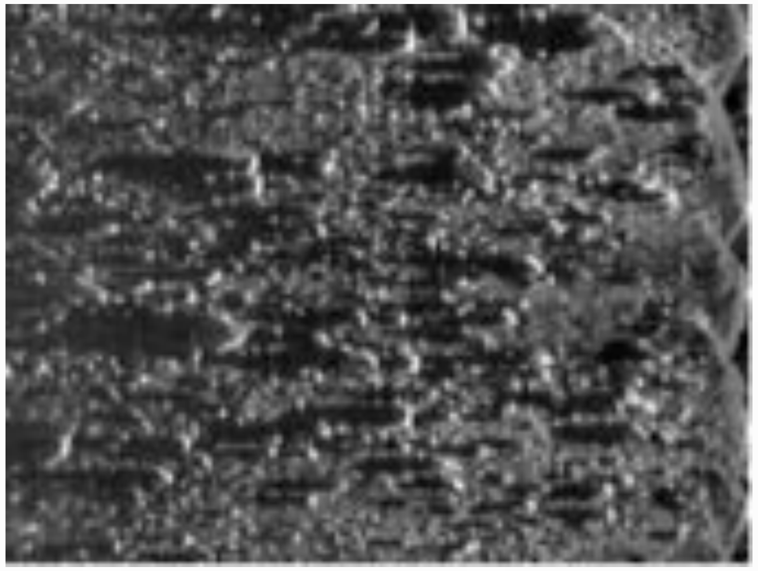
Motivation: collecting real data is expensive

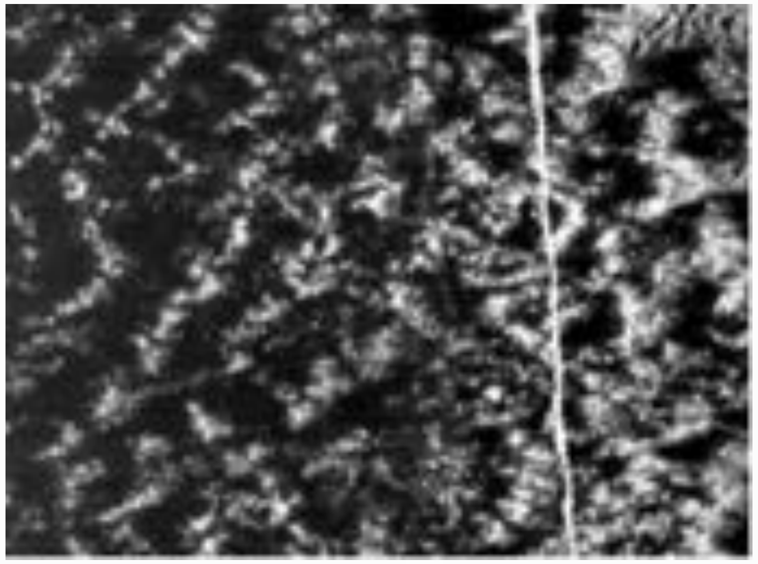


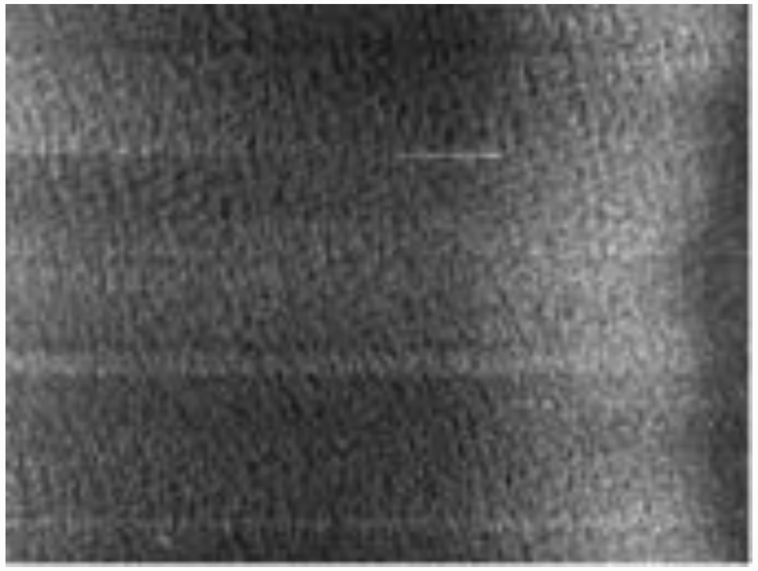
Sidescan Simulator

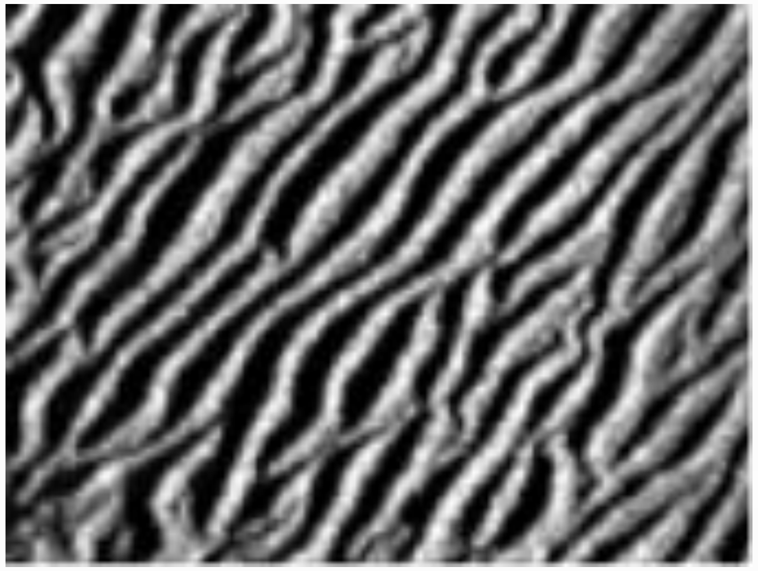
Seabed variety

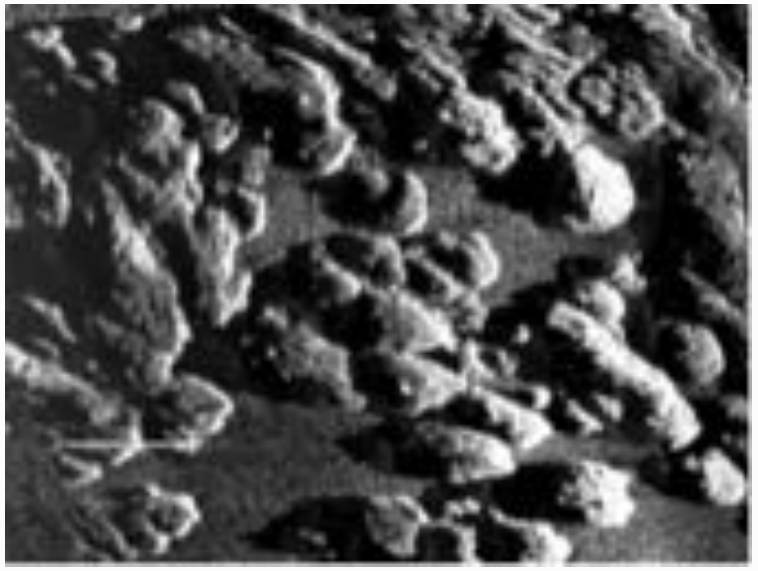
generate realistic 3D seabed environments







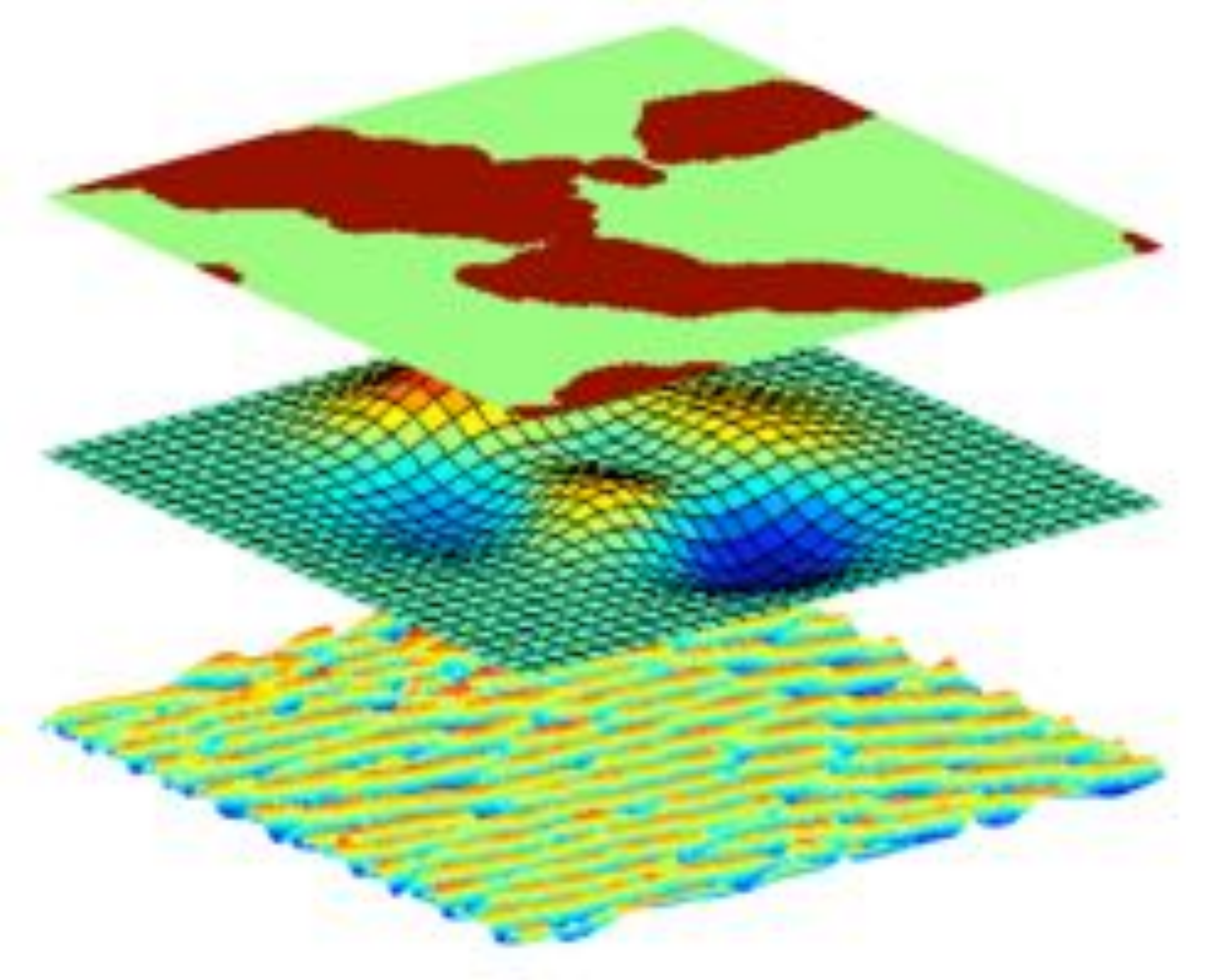




Sidescan Simulator

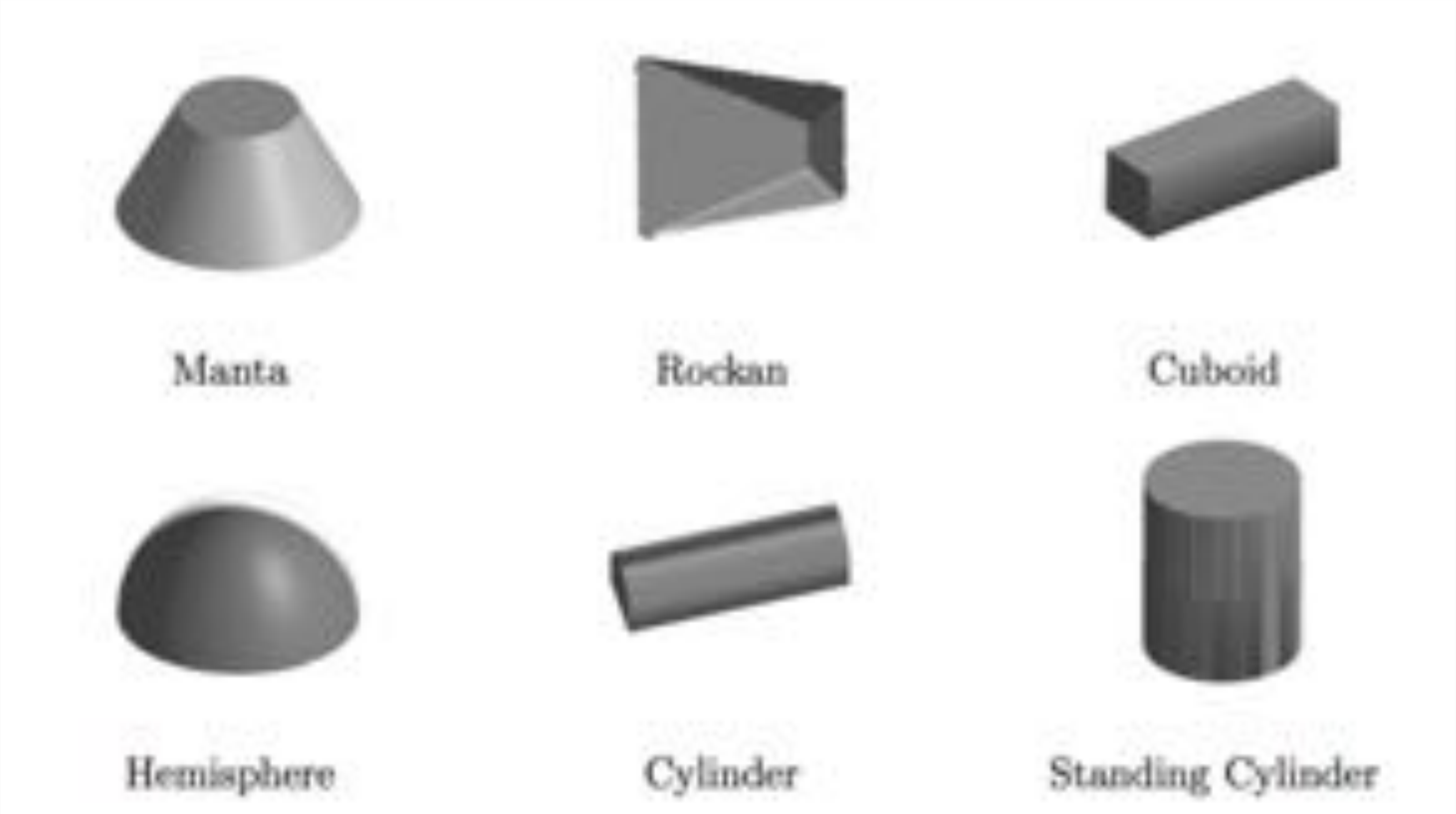
Decomposition of the 3D representation of the seafloor in 3 layers: partition between the different types of seabed, global elevation, roughness and texture.

In the late seventies, mathematicians such as Mandelbrot [1982] linked the symmetry patterns and self-similarity found in nature to mathematical objects called fractals



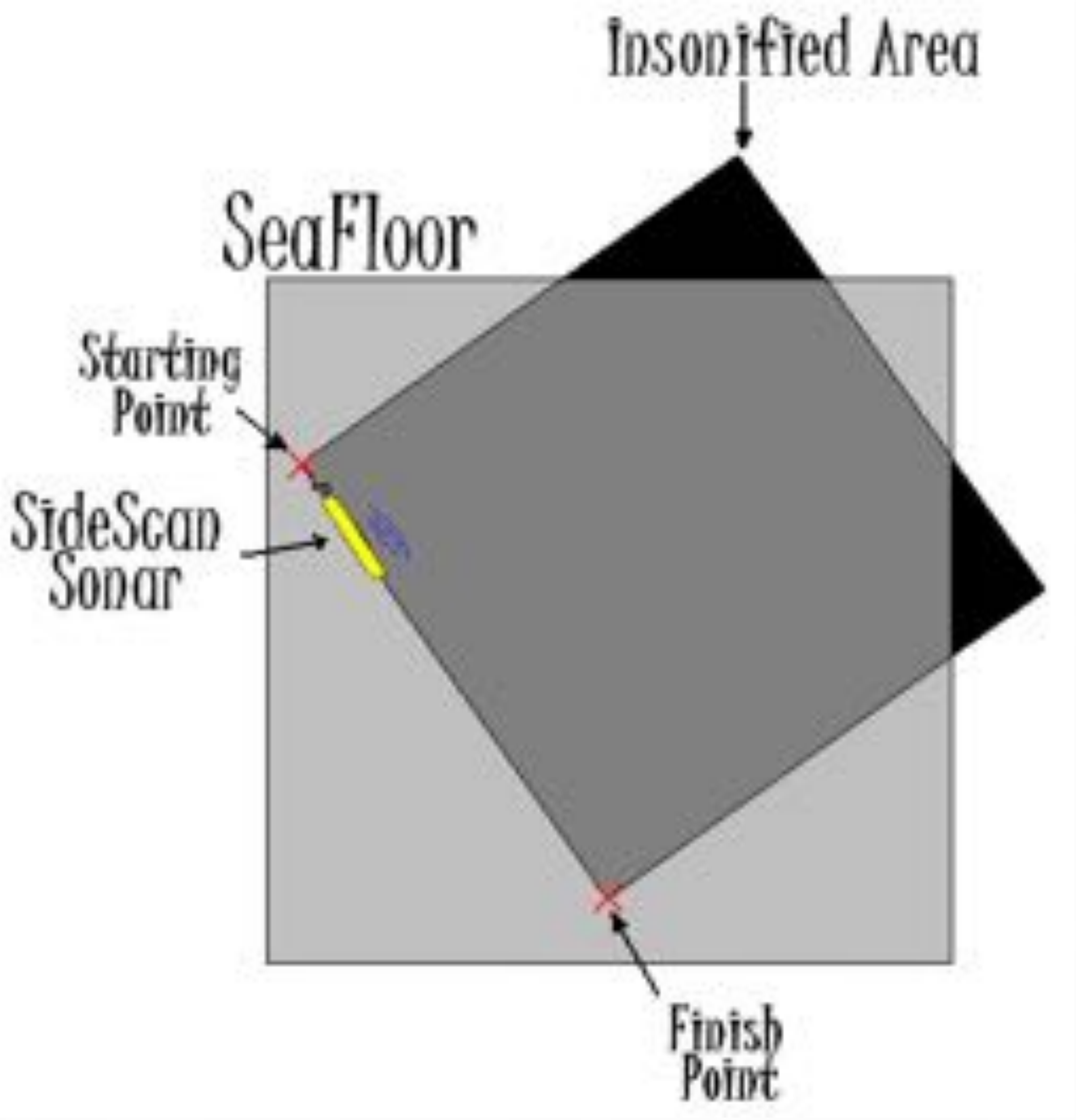
Sidescan Simulator

3D Targets Generation



Sidescan Simulator

Plan view of the trajectory of the sonar platform can be placed into the 3D environment.



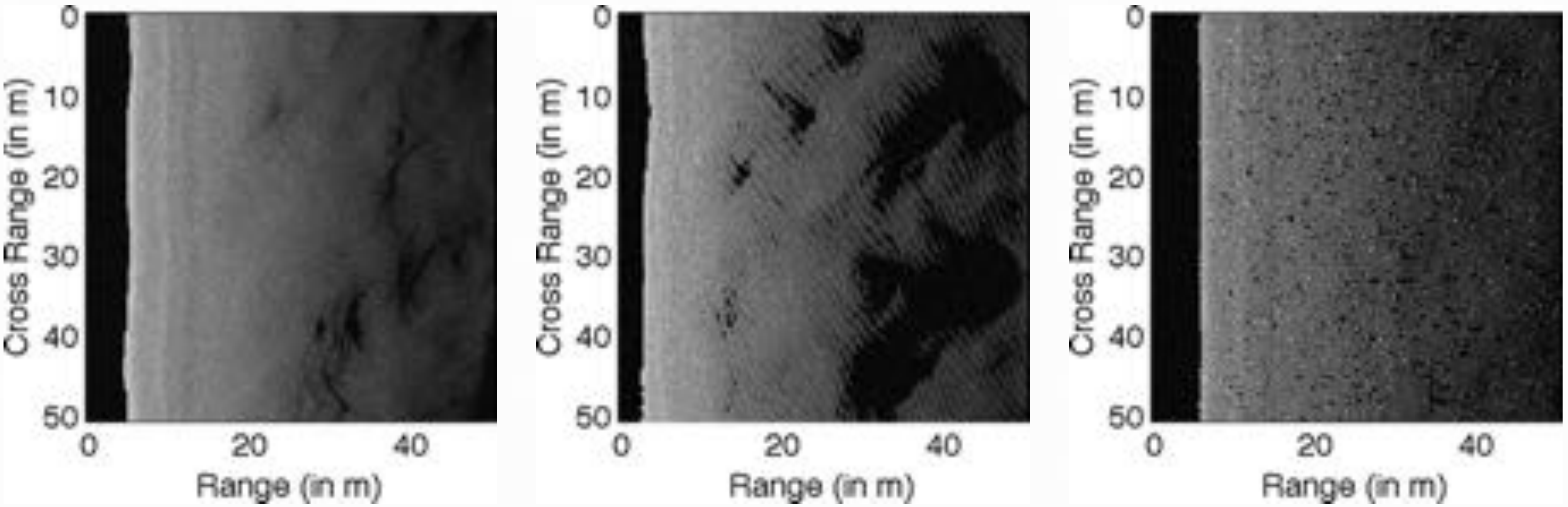
Sidescan Simulator

Solving the excess level equation:

$$XS = SL - 2TL + TS + DI - NL - RL$$

Sidescan Simulator

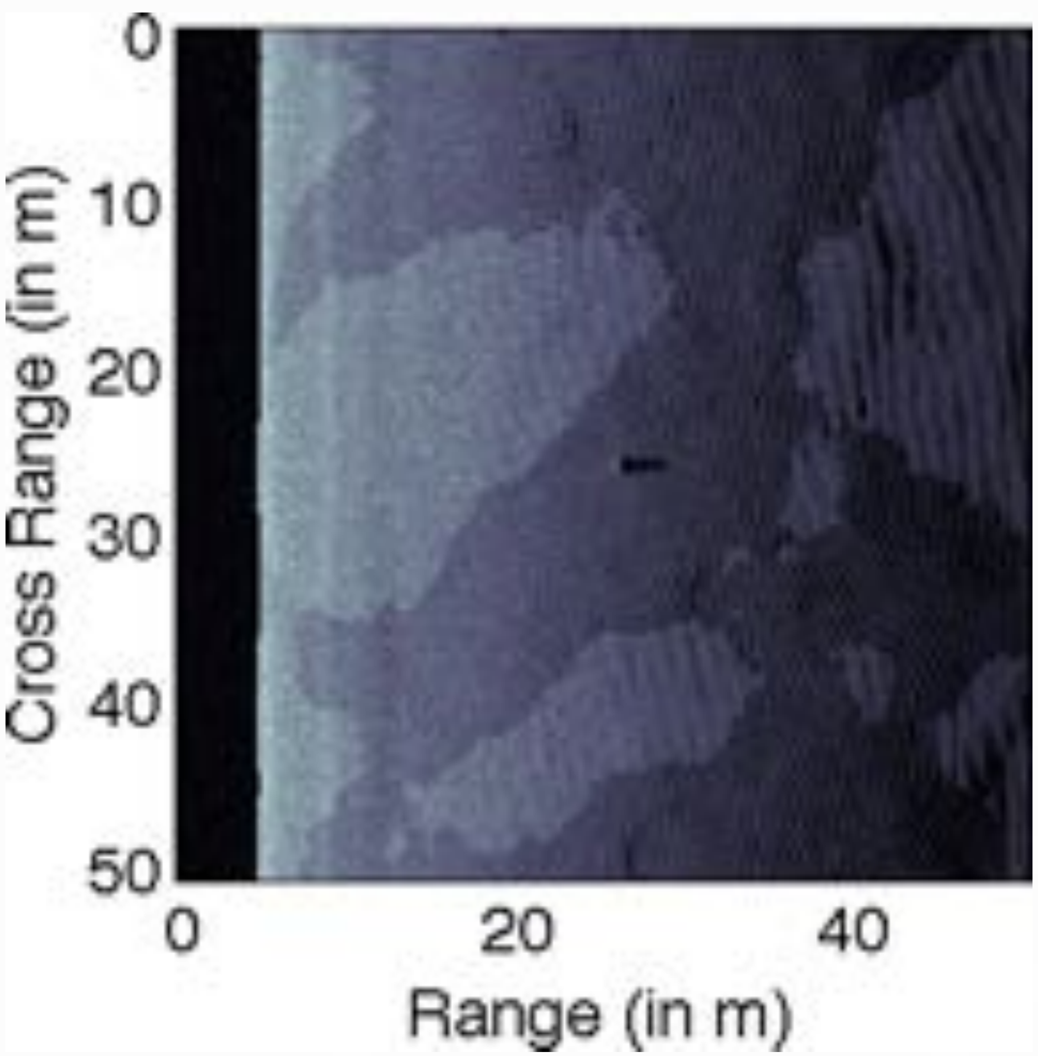
Examples of simulated sonar images for different seabed types (clutter, flat, ripples), 3D elevation and scattering strength. (a) represents a smooth seabed with some small variations, (b) represents a mixture of flat and cluttered seabed and (c) represents a rippled seabed

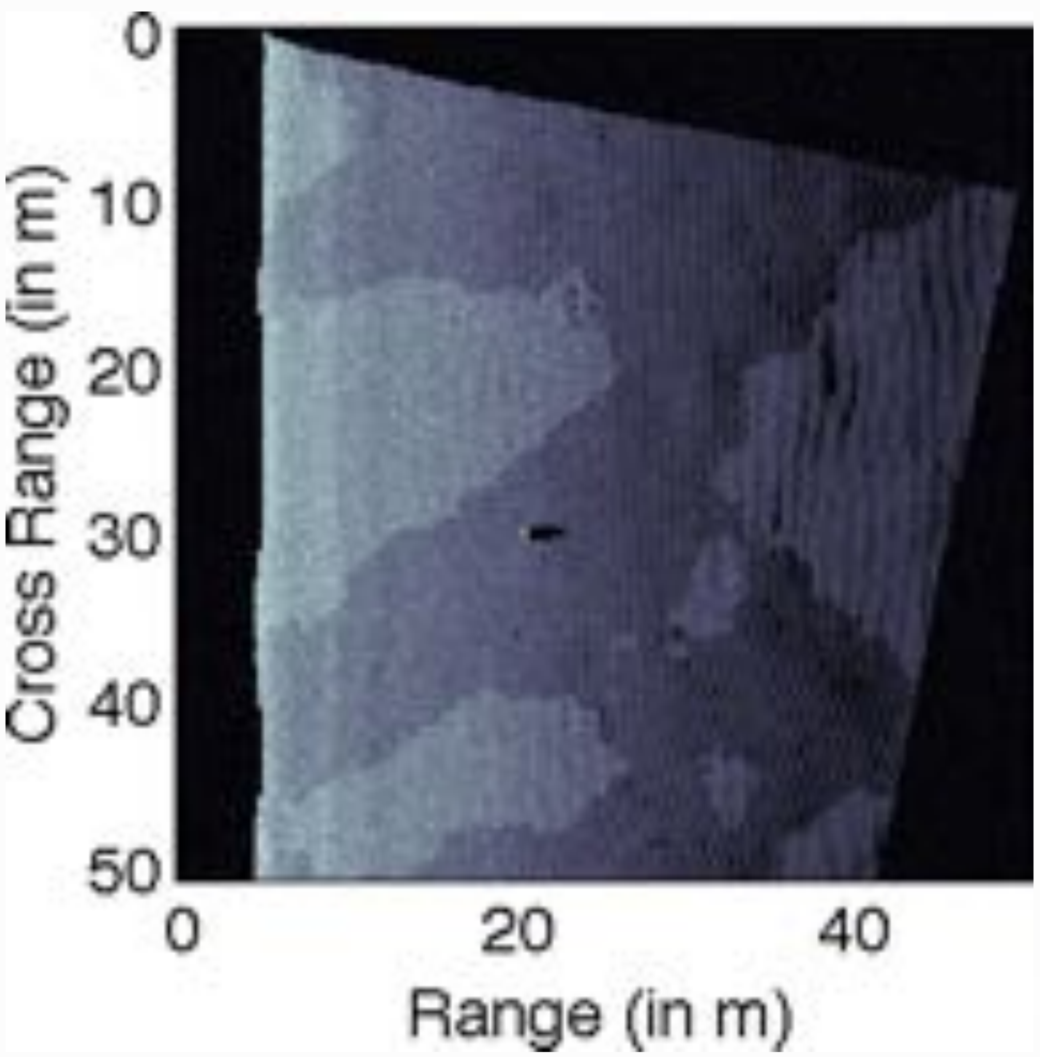


(a) (b) (c)

Sidescan Simulator

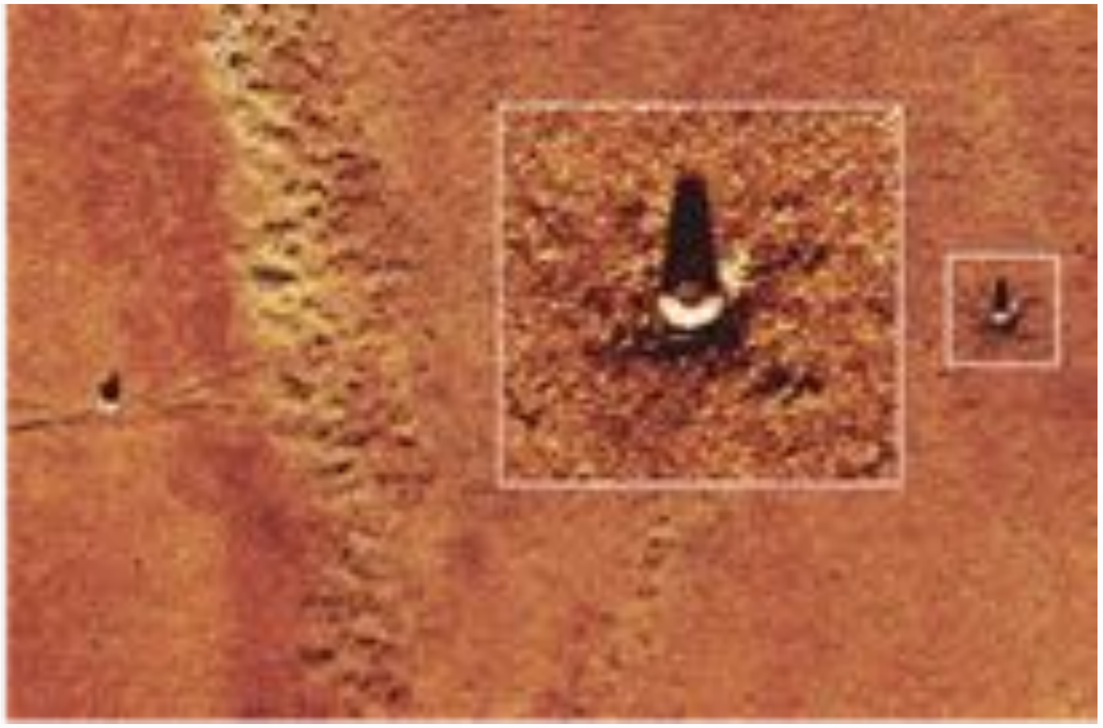
Mine like objects at different view angles

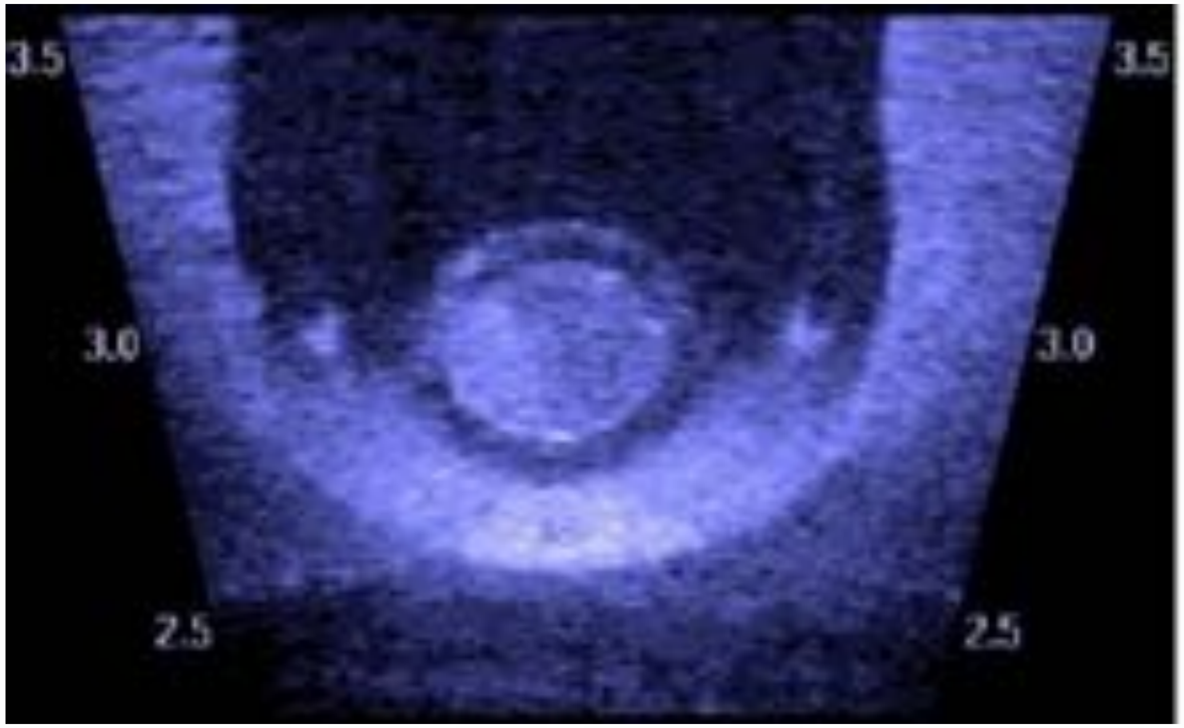




Sidescan Simulator: The ATR problem

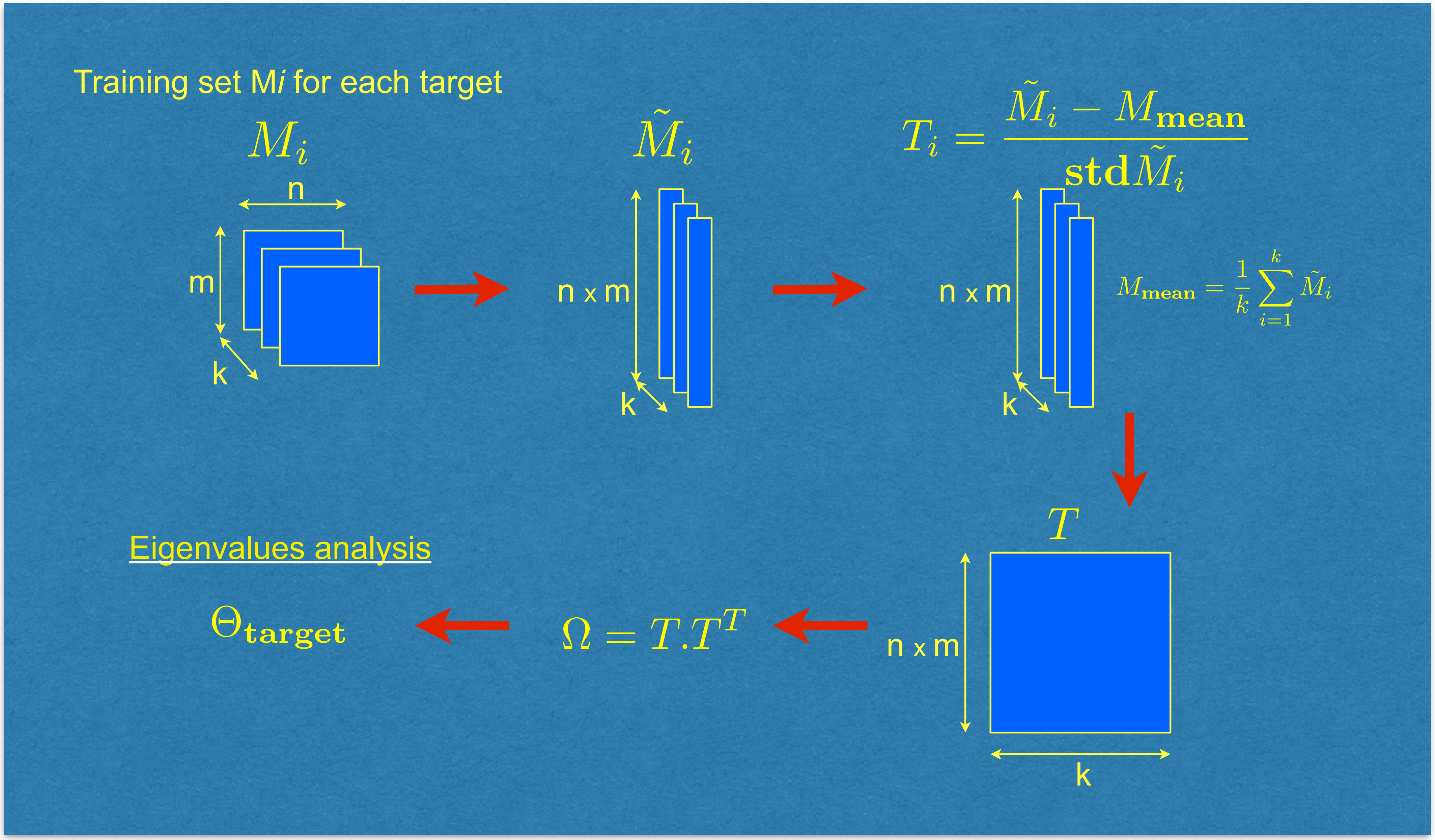
SAS and forward-looking sonar image of a manta mine.



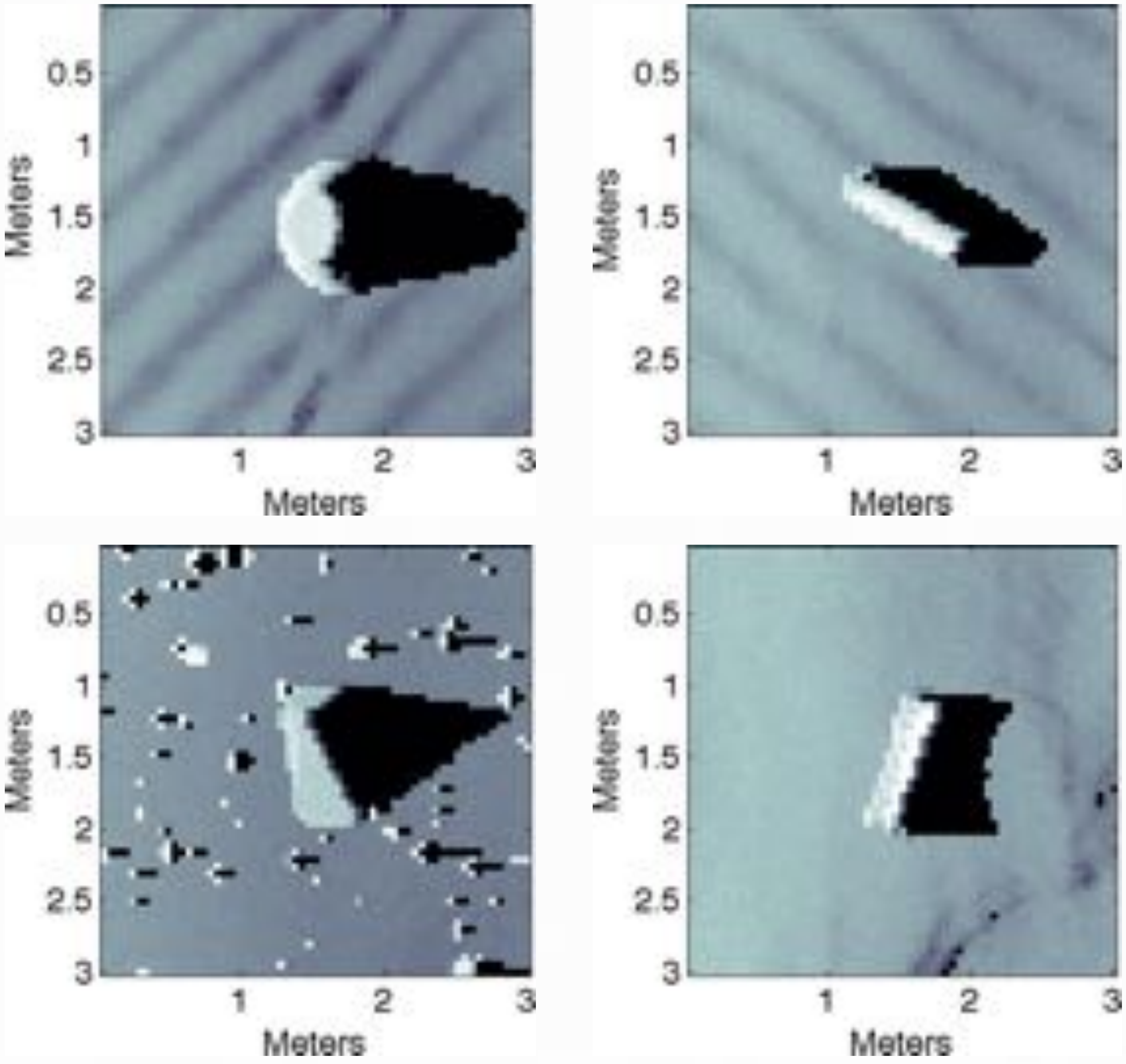


Sidescan Simulator: The ATR problem

PCA-based classifier:

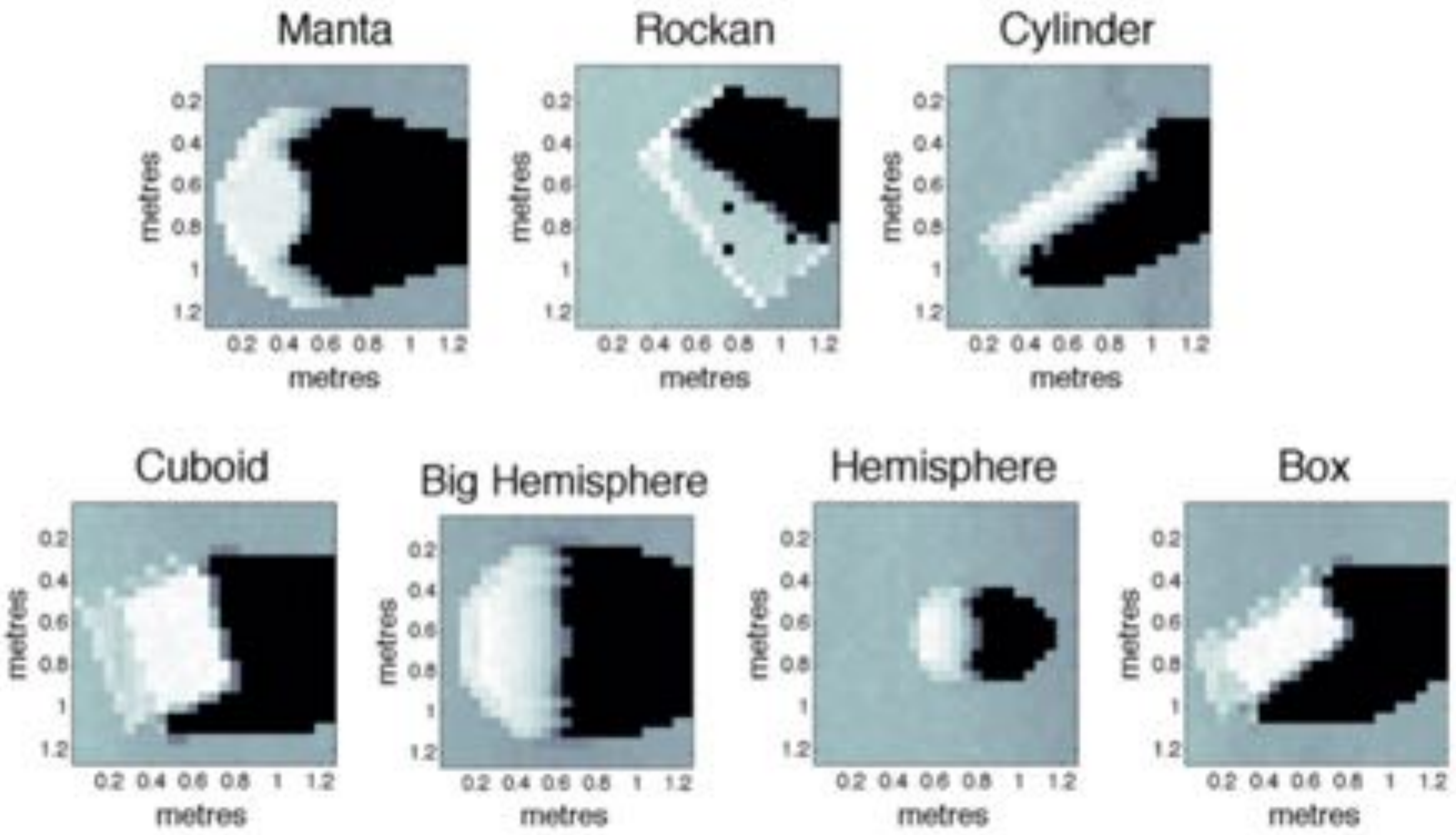


Sidescan Simulator: The ATR problem



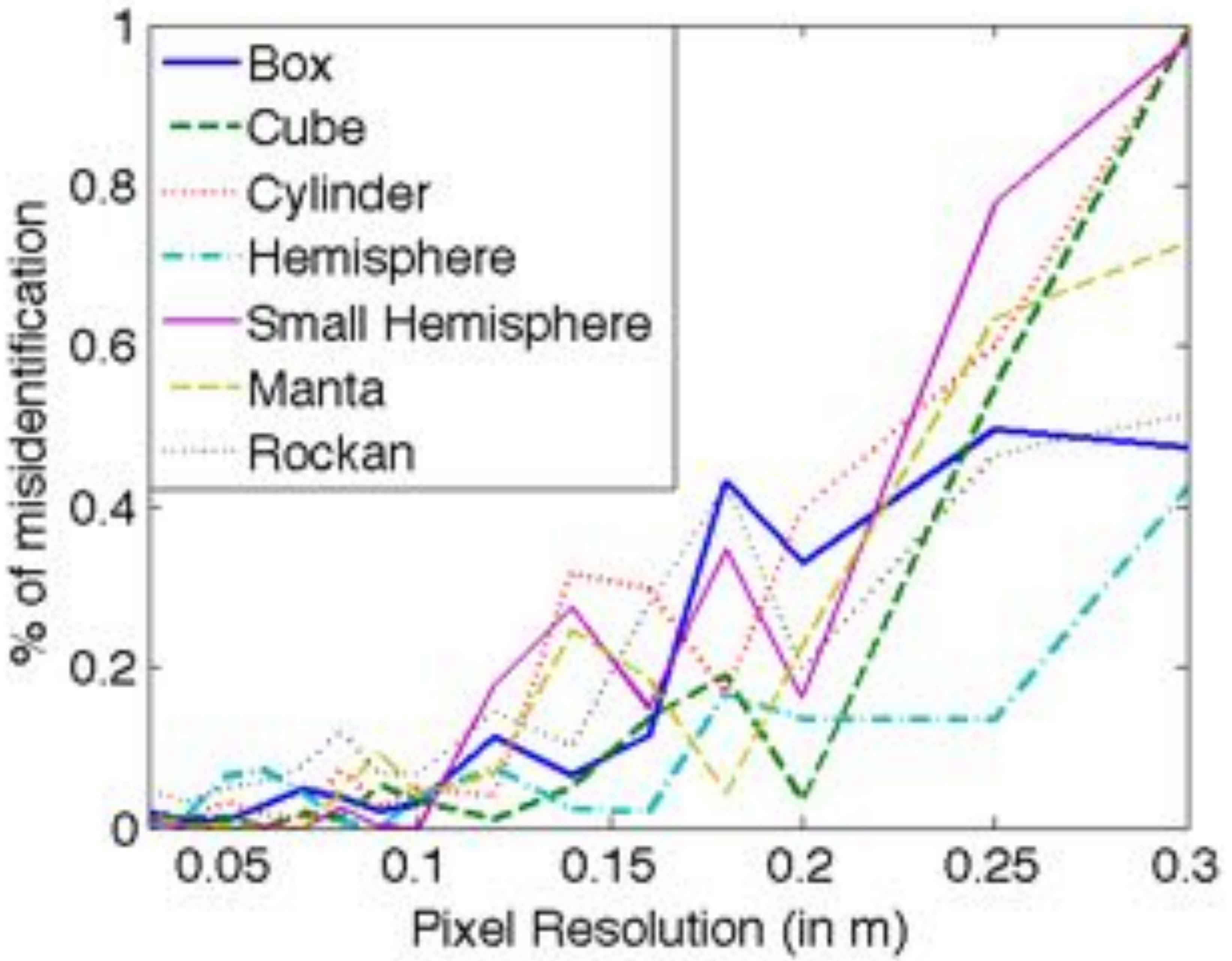
Sidescan Simulator: The ATR problem

Classification on highlights



Sidescan Simulator: The ATR problem

Classification on highlights

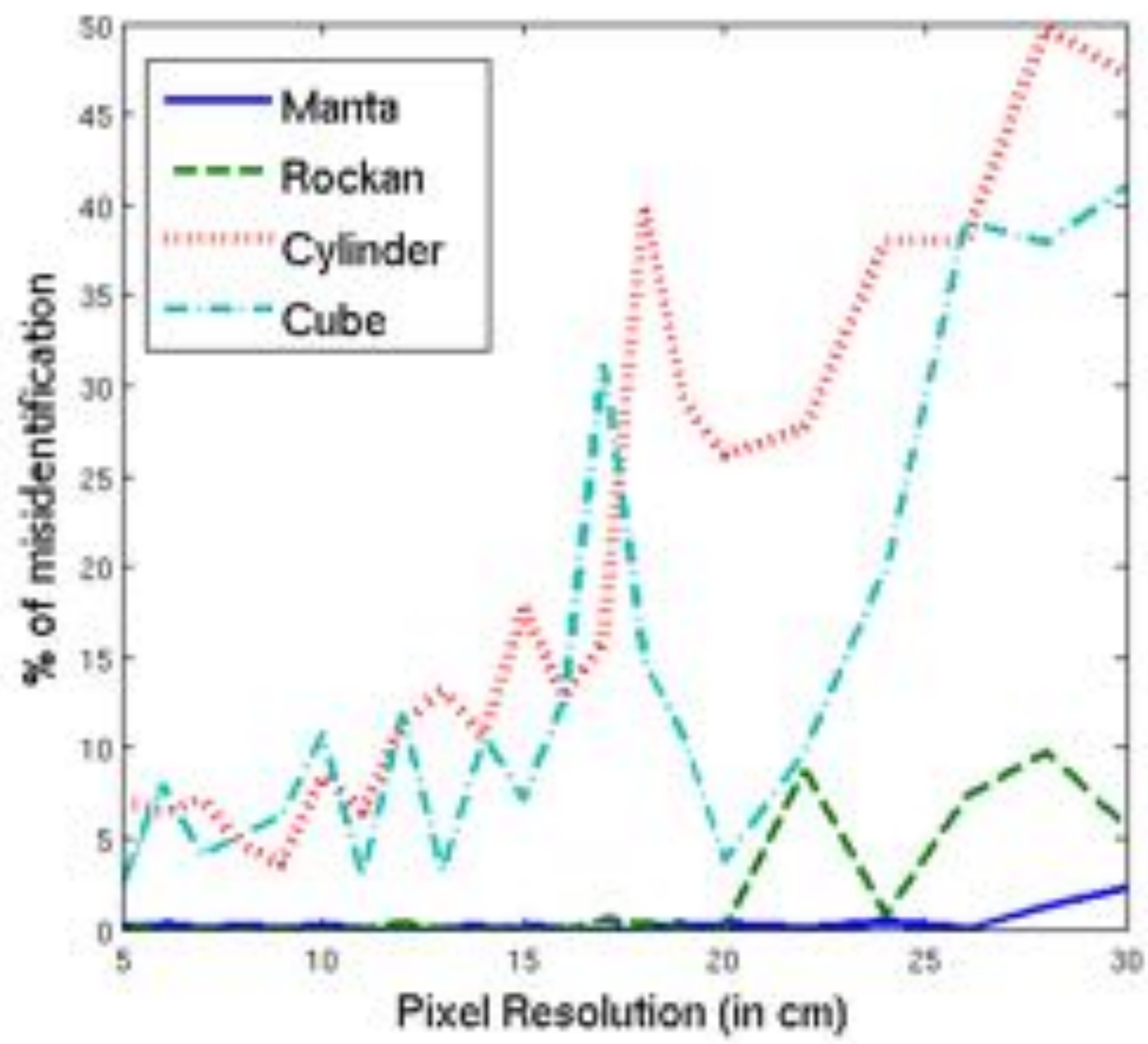


Sidescan Simulator: The ATR problem

Classification using shadows

Sidescan Simulator: The ATR problem

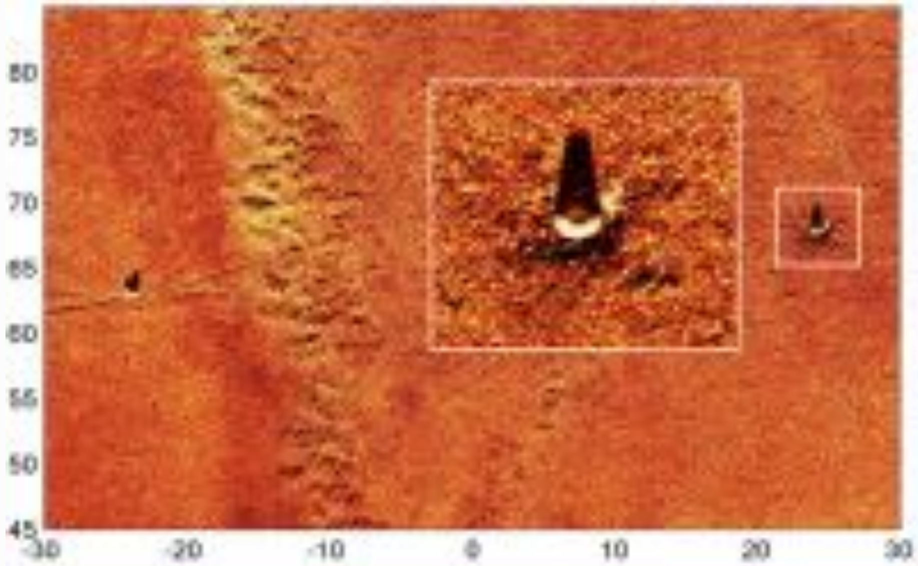
Classification using shadows



SAS

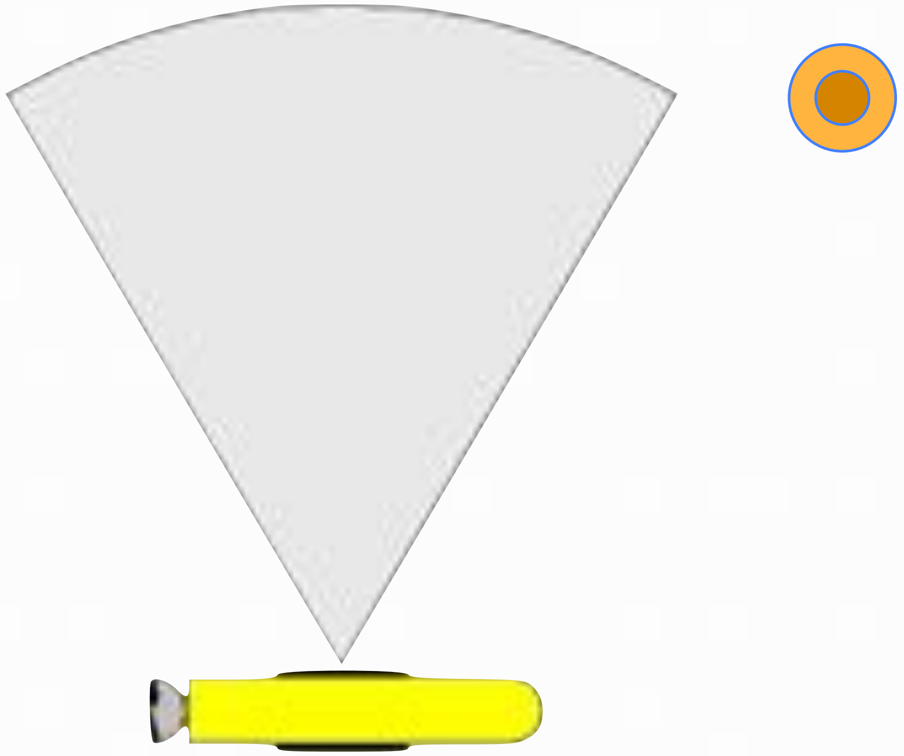
Synthetic Aperture Sonar

The last generation of sonar, SAS (Synthetic Aperture Sonar) systems, have been developed in the last 15 years embracing this vision. The centrimetric resolution of SAS systems provides a new powerful tool for mine detection, identification and classification. The main advantages of SAS systems are: a resolution close to the wavelength even at long range and a constant resolution across range.



Synthetic Aperture Sonar

Wide beam transducers: multiview



Synthetic Aperture Sonar

Several algorithms are used to compute SAS images. We will used time domain correlation and backpropagation algorithms. The reconstruction techniques take advantages of the broadband and wide beam transducers in order to beat the resolution of conventional sonar systems.

The range resolution is optimized thanks to match filtering:

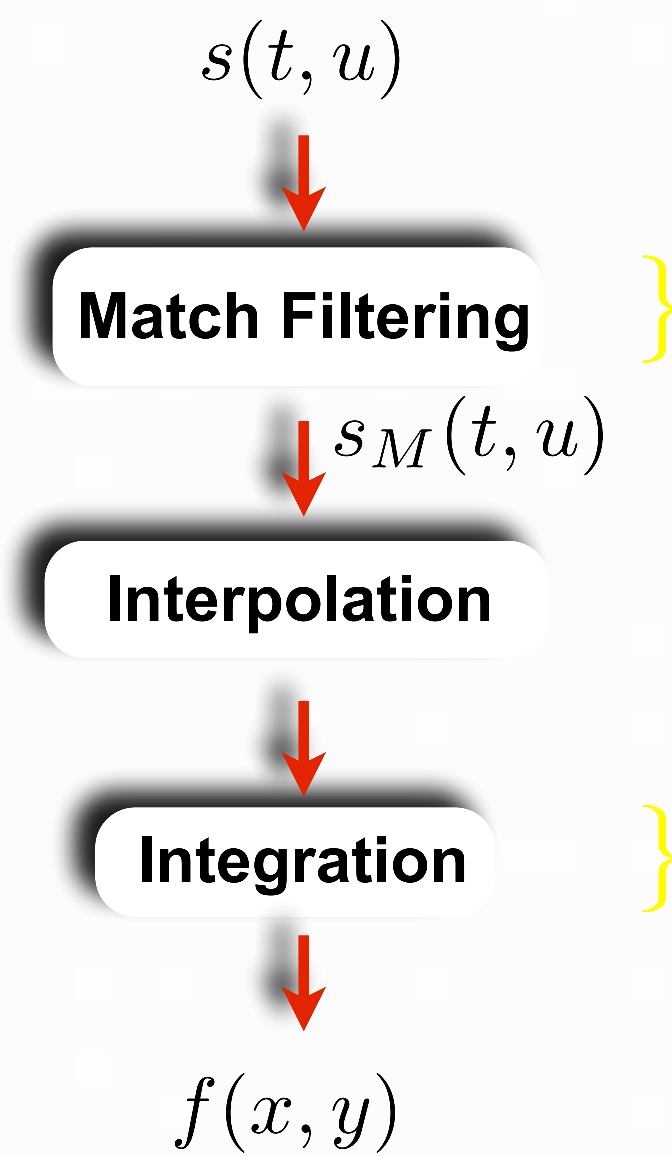
$$s_M(t,u) = s(t,u) * p^*(-t)$$

The cross range resolution is obtained through the backpropagation algorithm:

$$f(x,y) = \int_u s_M \left[t, \frac{\sqrt{x^2 + (y-u)^2}}{c} \right] \mathrm{d}u$$

Synthetic Aperture Sonar

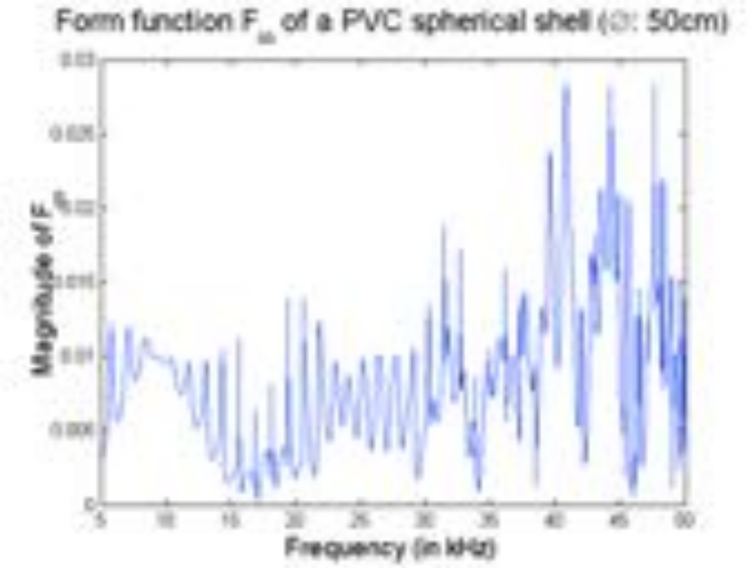
SAS image reconstruction via time domain correlation and backprojection algorithms:

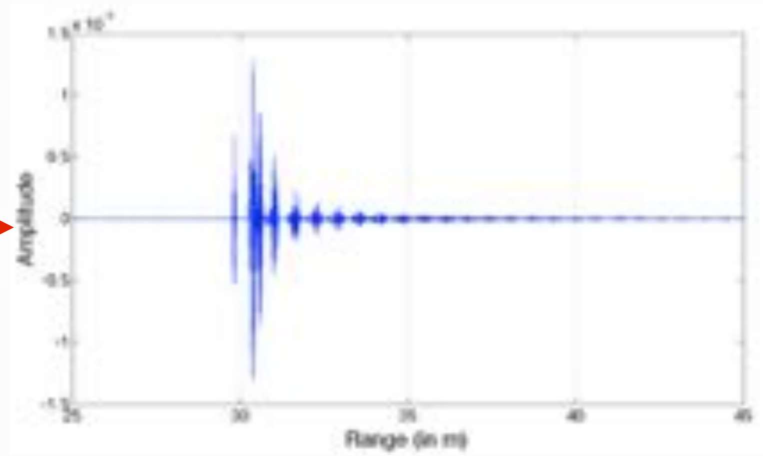


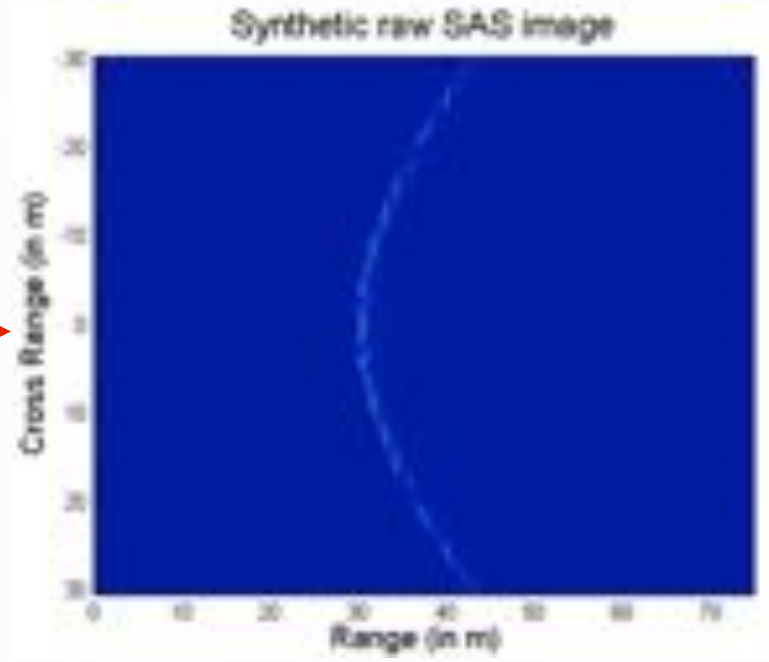
Broadband: range compression

Wide beamwidth: cross range compression

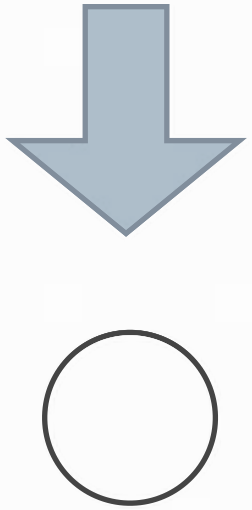
Synthetic SAS image





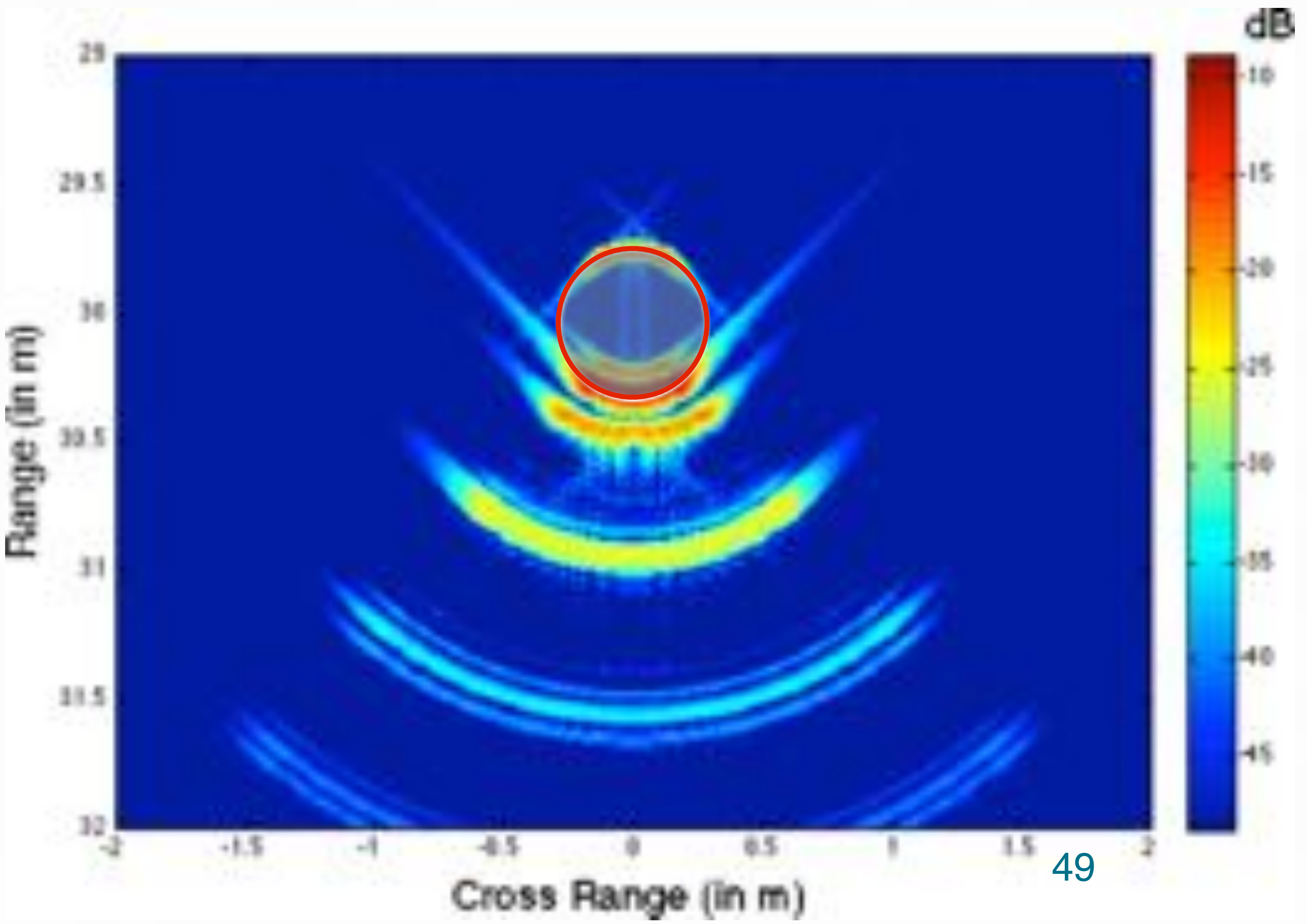


Configuration:



Sound

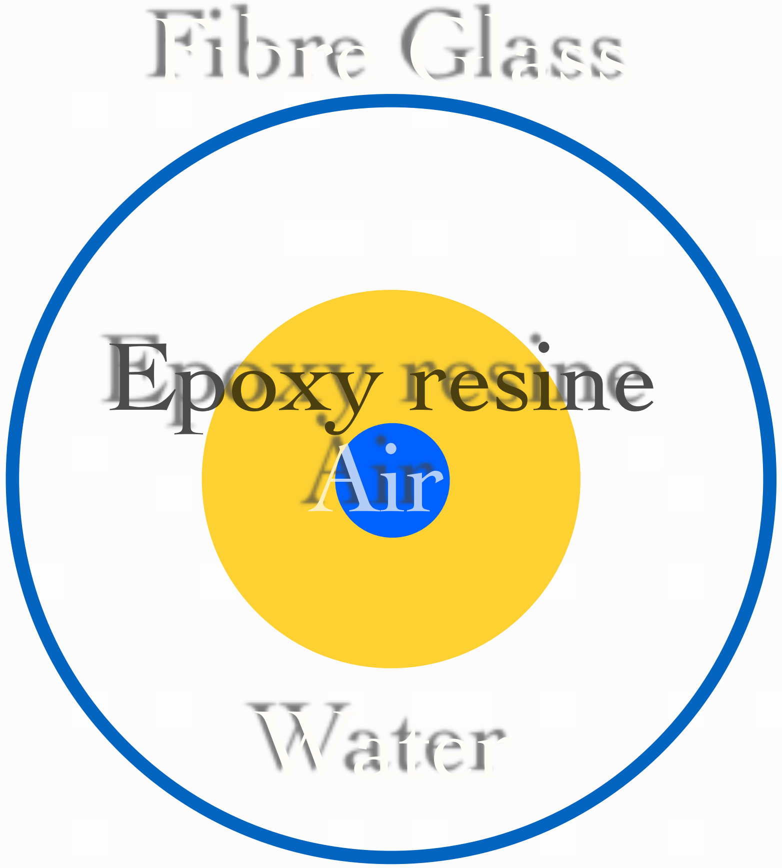
PVC spherical shell



High frequency Vs. Low frequency

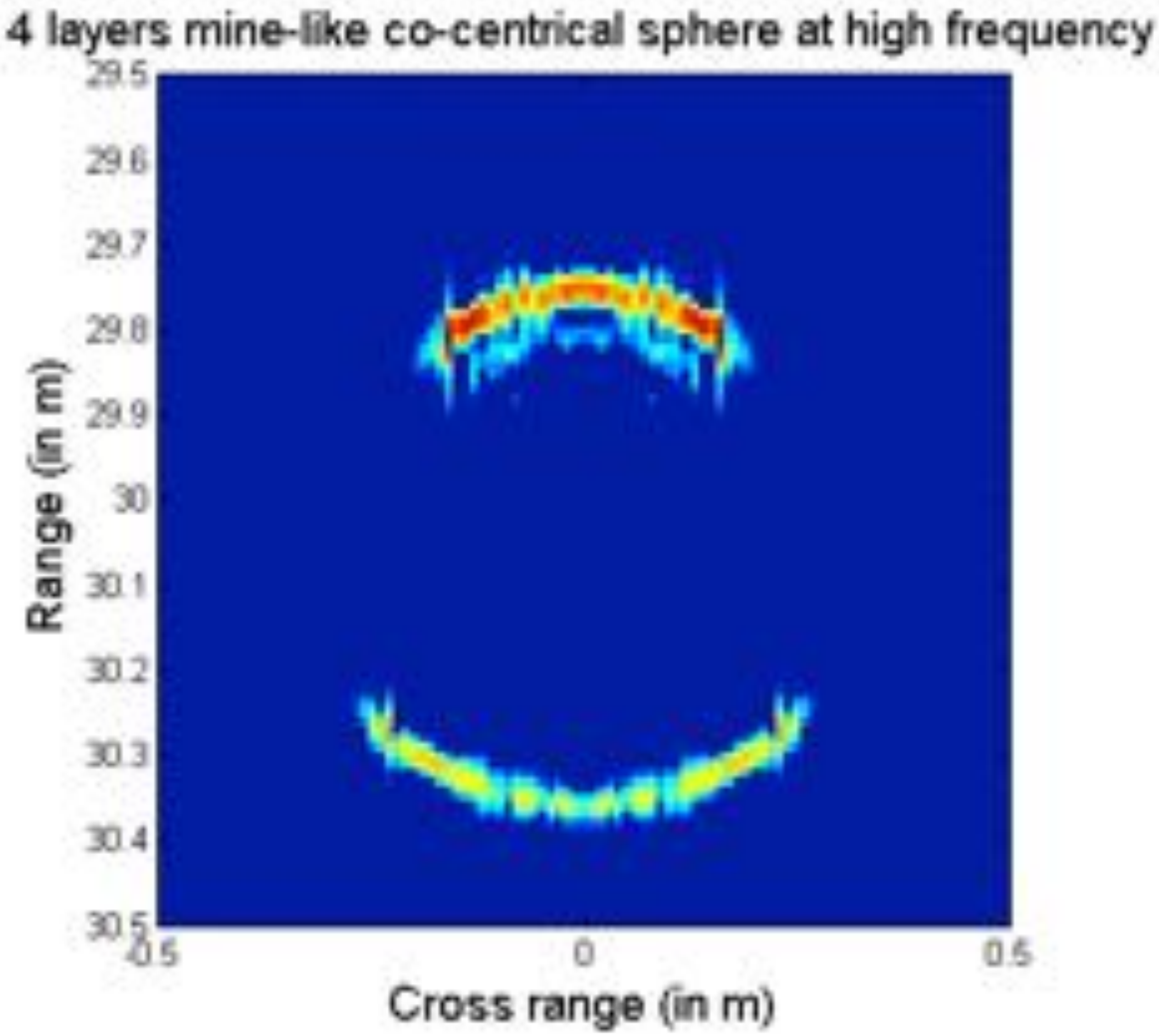
Imaging into the target with low frequency SAS.

configuration:

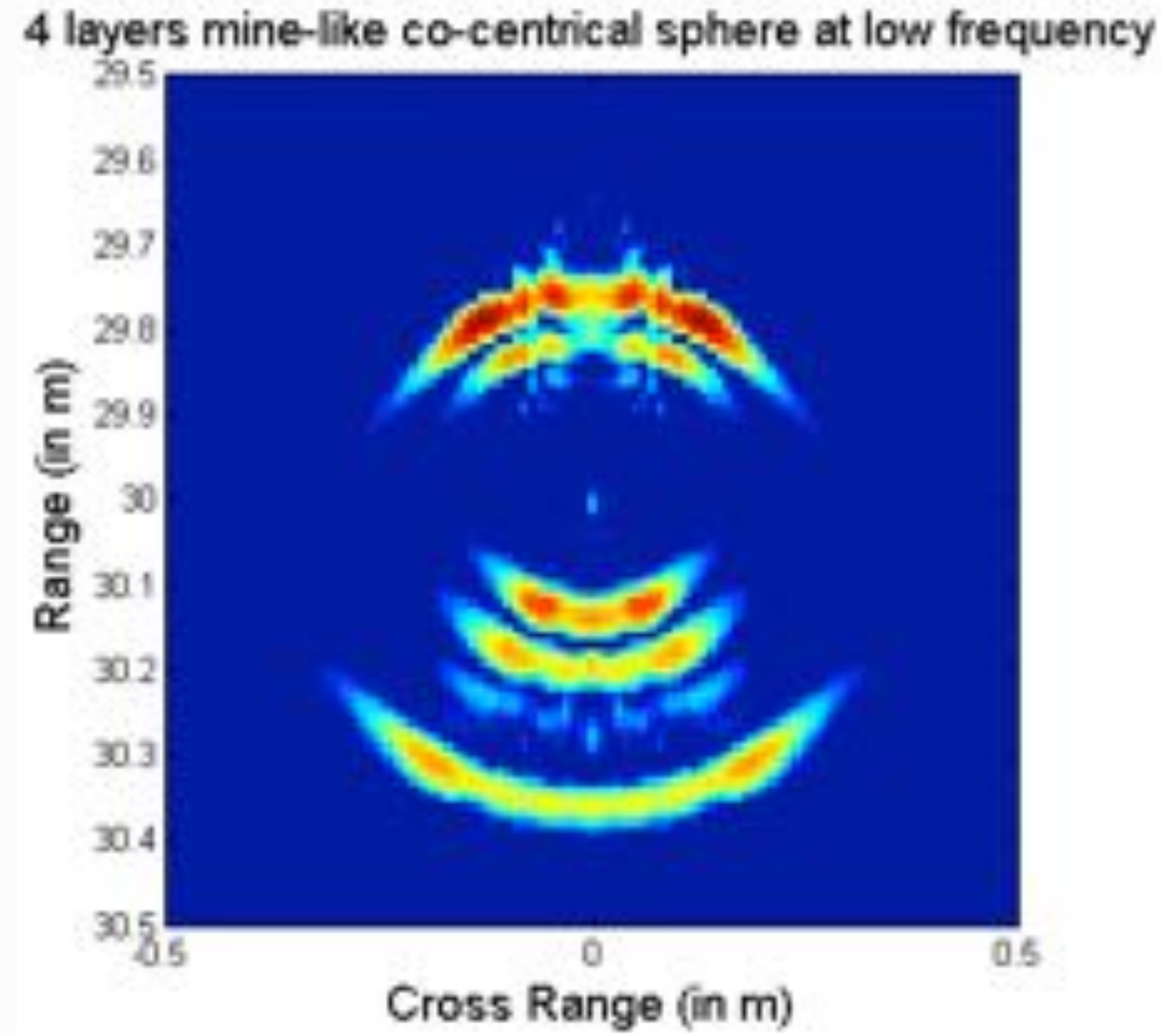


High frequency Vs. Low frequency

High Frequency



Low Frequency

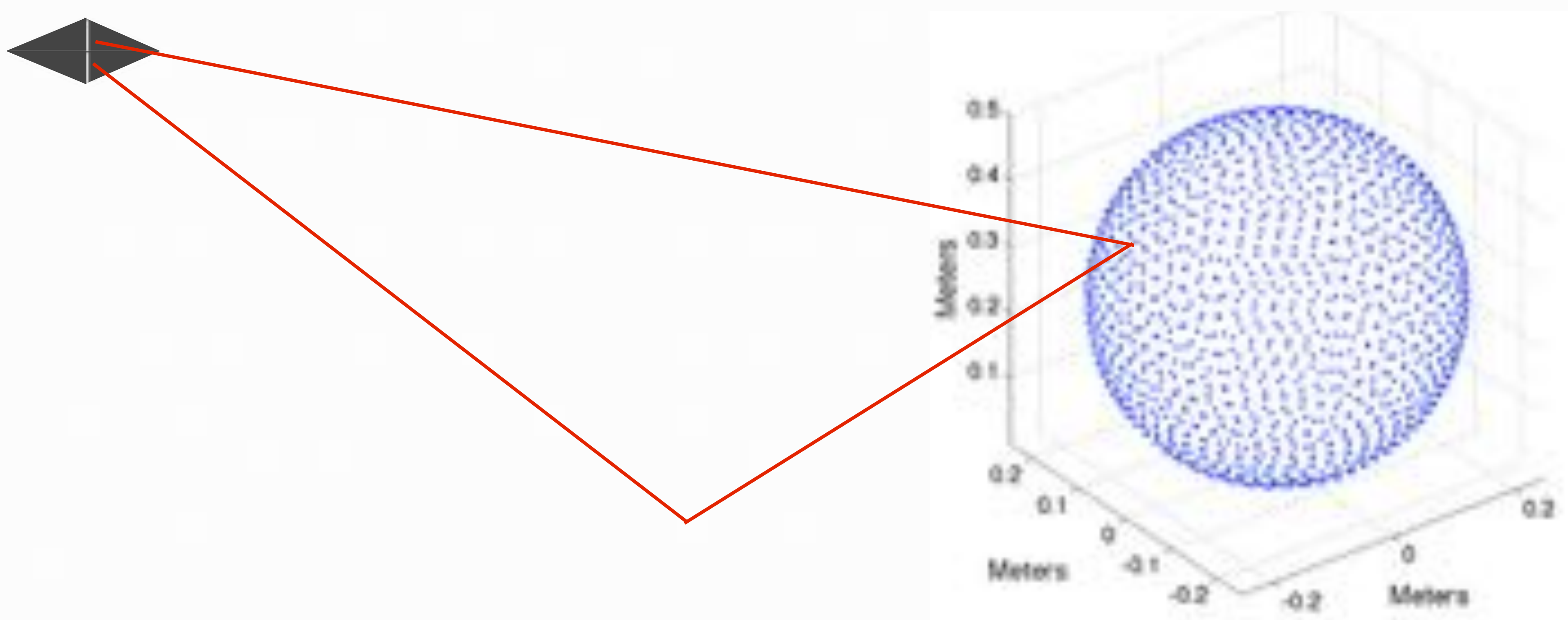


Imaging objects on the seafloor

Adding a simple interface to the problem breaks the symmetry. There is no analytical solution any more.

An approximation of the problem can be found by solving the Helmholtz-Kirchhoff equation:

$$p(r_i) = \sum_j \left(\frac{\partial G_{ij}}{\partial n_j} p_j - \rho(z_j)\omega^2 G_{ij}(u_n)_j \right) \mathrm{d}A_j$$



Imaging objects on the seafloor

Half-space Interaction

The tricky term is the Helmholtz-Kirchhoff equation is the Green function and its derivative.

Approximation of the Green function can be found in:

Zampolli et Al. Scattering from objects within layered media, JASA, Vol. 123,6, June 2008.

For targets on the surface:

$$G_{ij} = \frac{\mathrm{e}^{ikR}}{R} + \frac{\mathrm{e}^{ikR_1}}{R_1}\left[V(\xi) - i\frac{N}{kR_1}\right]$$

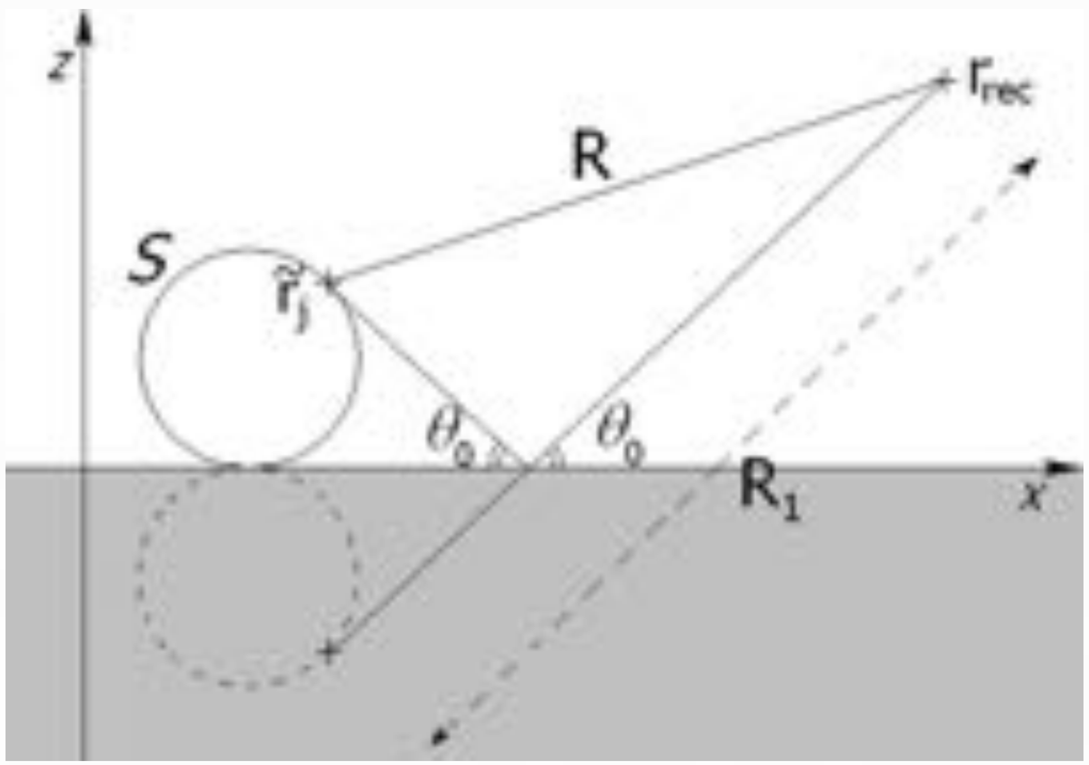
For targets below the surface:

$$G_{ij} = i\int_0^{+\infty} W(\xi_2) J_0(\xi_2 r) \mathrm{e}^{i(\mu_2 \tilde{z}_j - \mu_{2,1} z_1)} \frac{\xi_2}{\mu_2} \mathrm{d}\xi_2$$

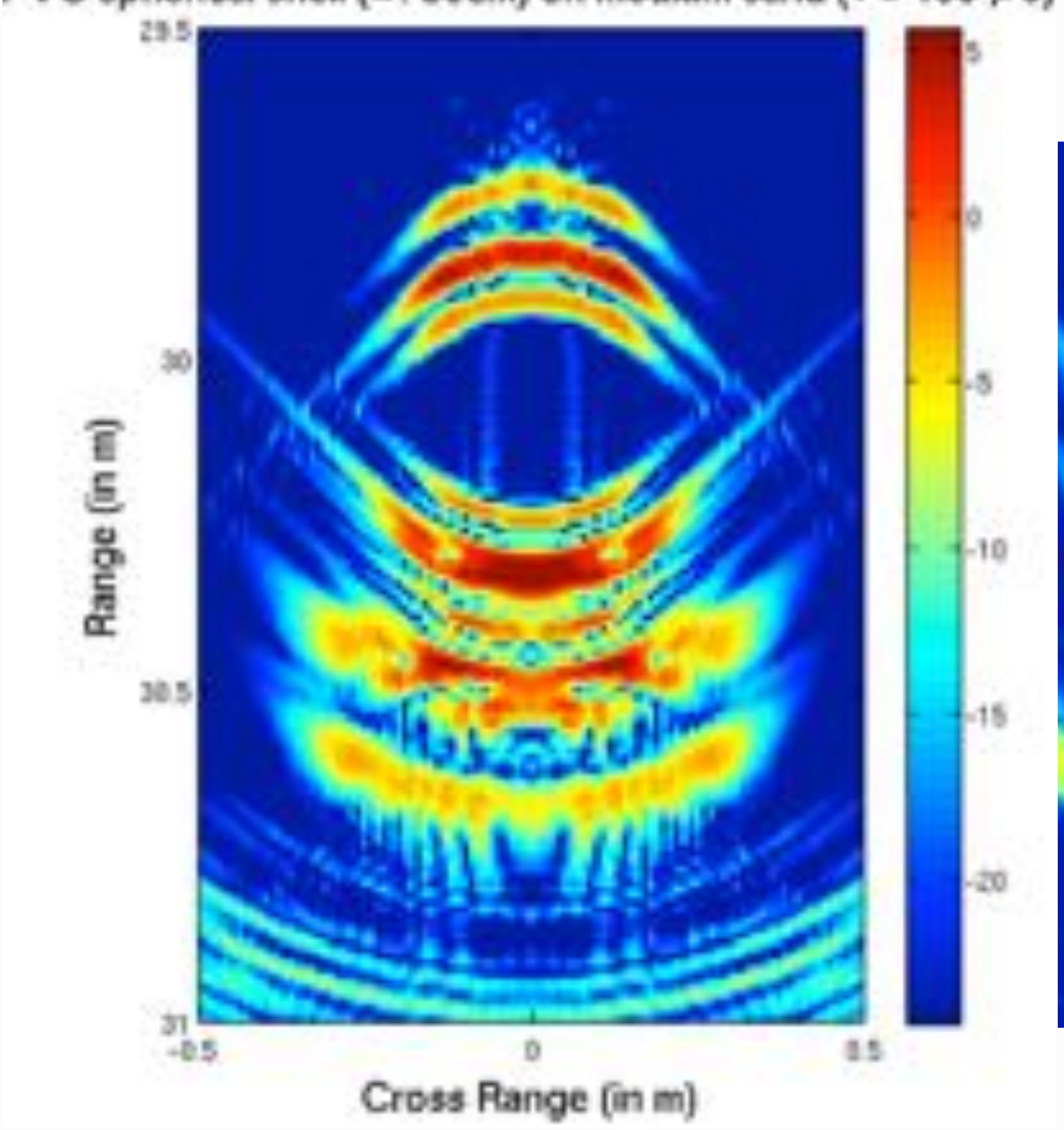
Imaging objects on the seafloor

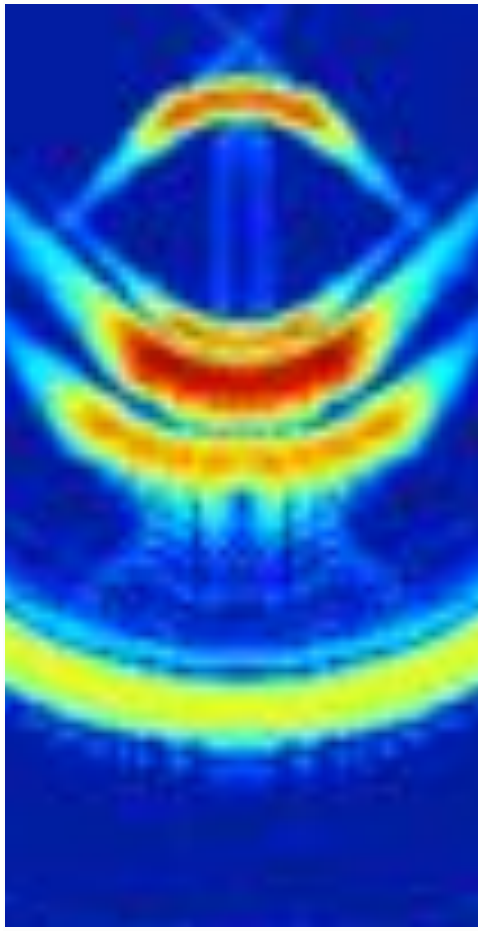
Half-space Interaction

Sphere on the surface configuration:



Simulation





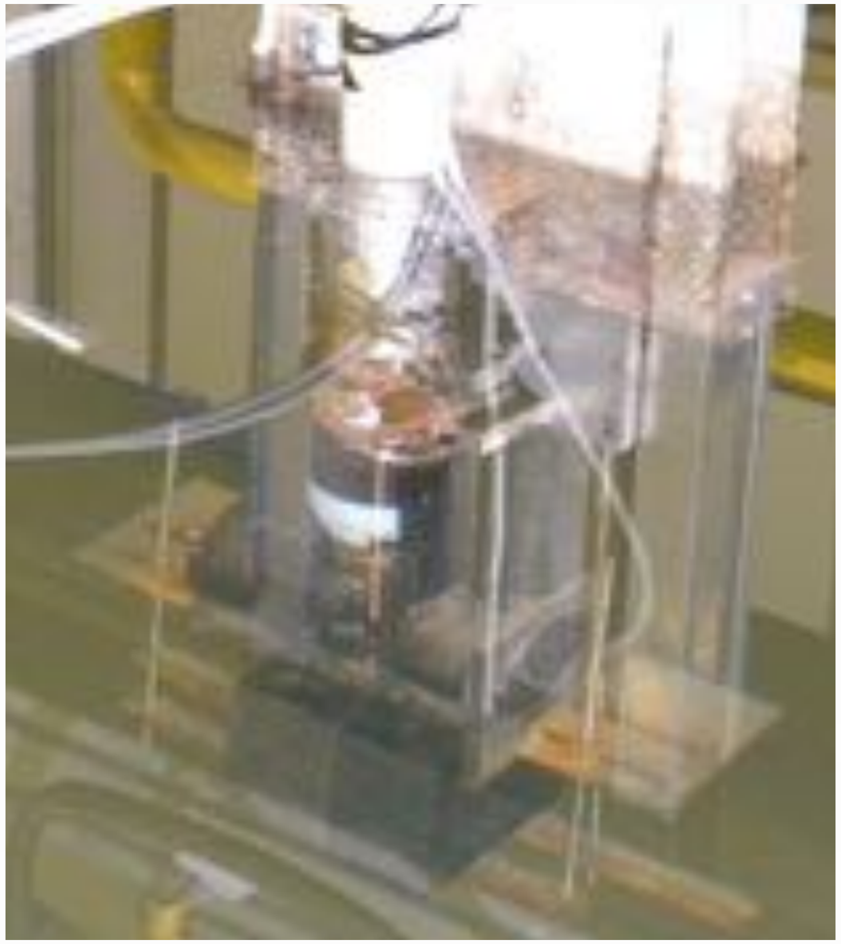
Experiments

Experiments on low frequency SAS has been done in our tank (dimension: 4 x 3 x 2 meters) which is equipped with a cartesian robot (precision = 0.1mm).

Experiments

The transducers were mounted on the cartesian robot.

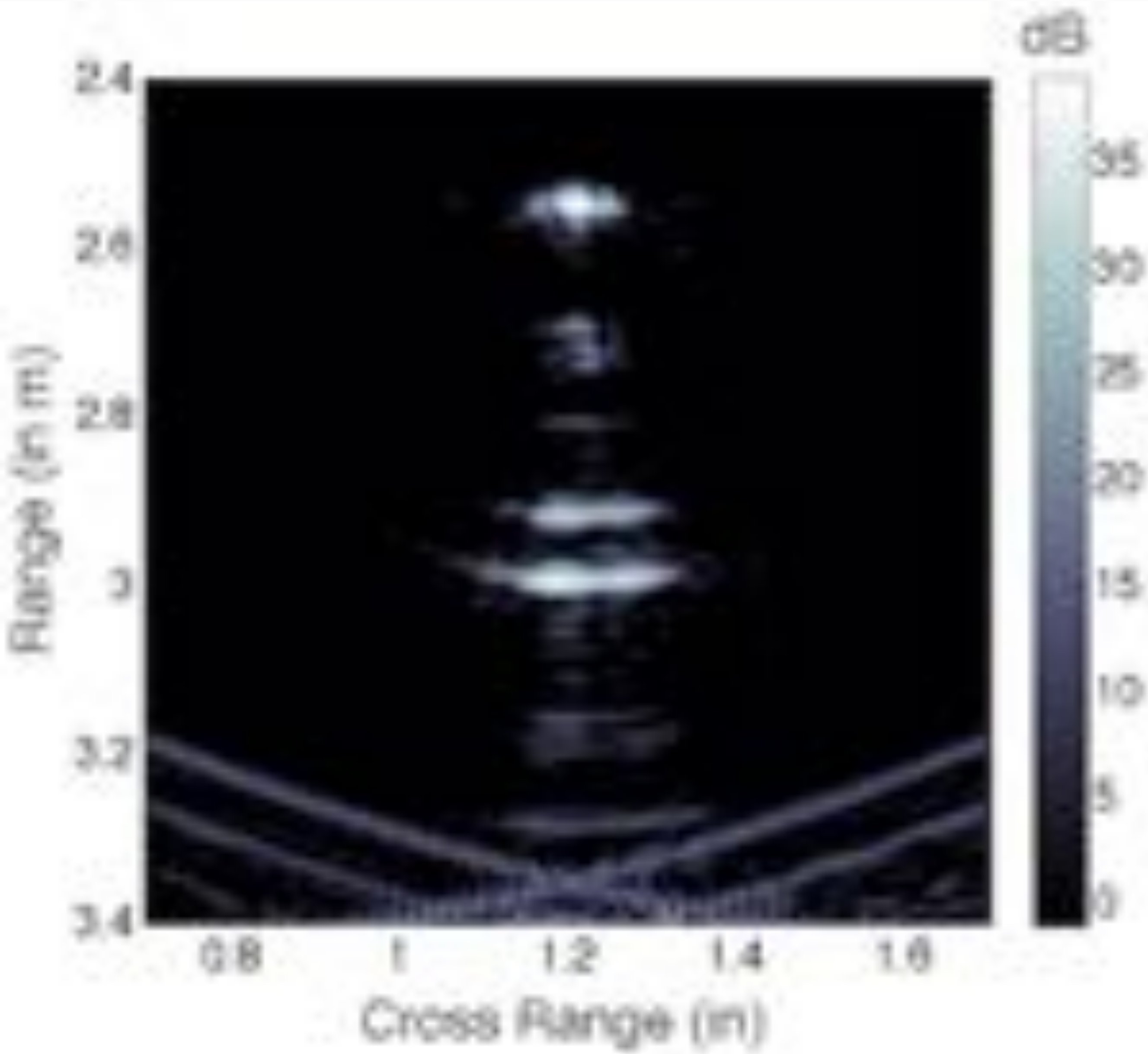
- Transducer frequency: (25-90kHz)
- Beamwidth: 40 degrees



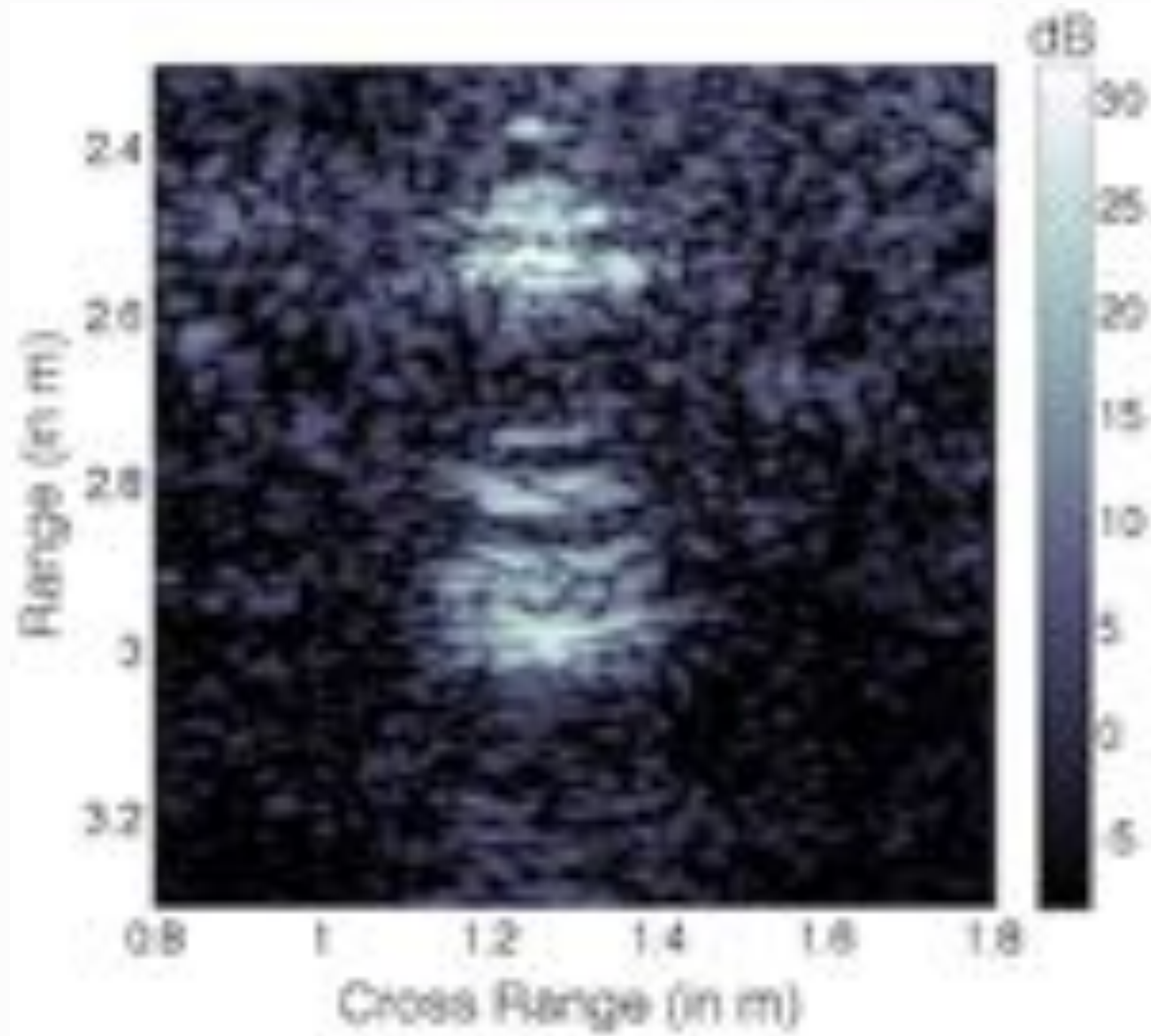
Experiments

Targets:

Experiments Results

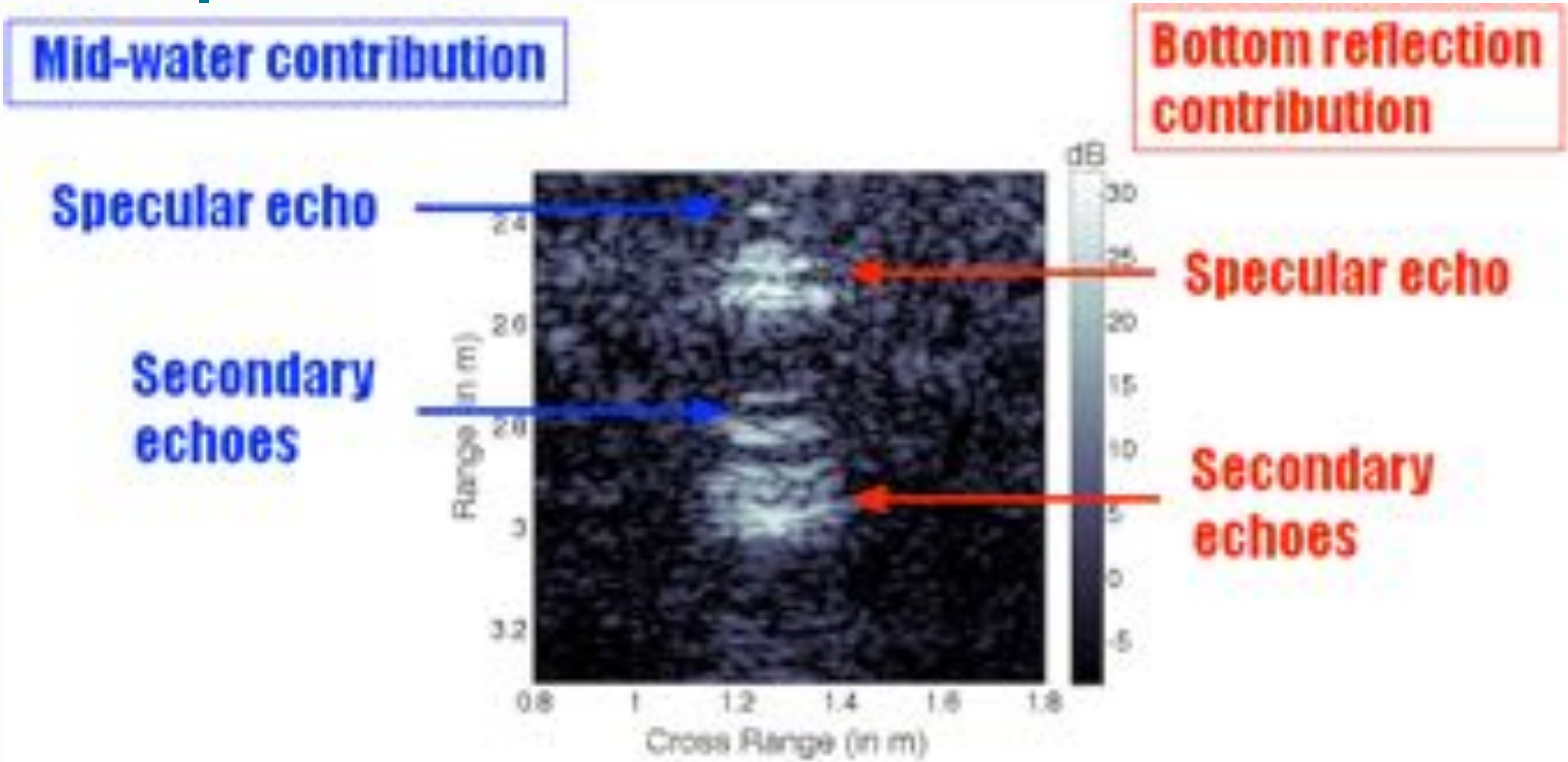


Free water



On sandy floor

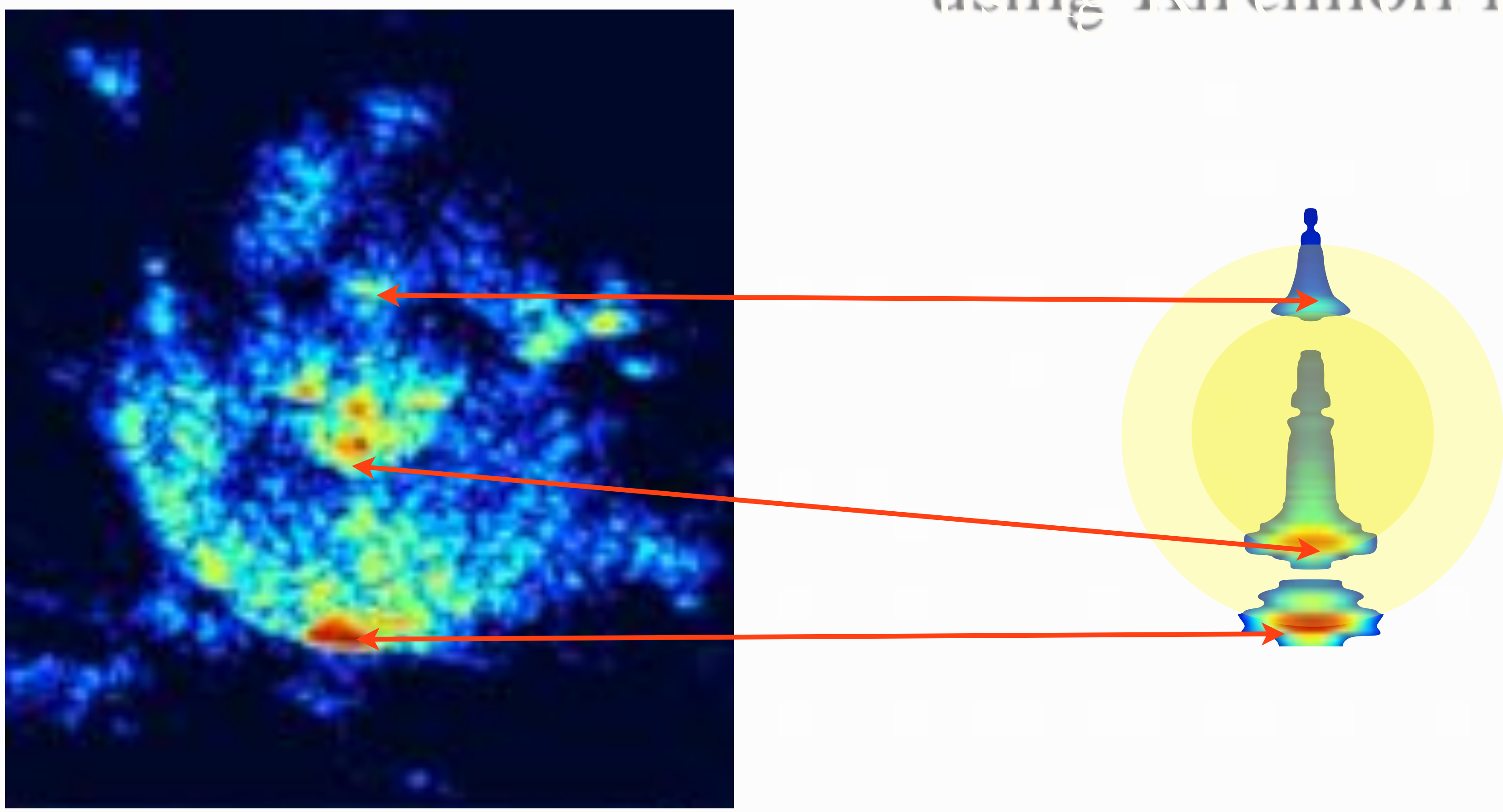
Experiments



Rough Surface Interaction

MUSCLE SAS image

Synthetic Data
using Kirchhoff model



The Kirchhoff model only take into account the specular echoes.

Rough surface interaction

Using Kirchhoff approximation & perfectly reflective material to model the target echo, the Helmholtz-Kirchhoff equation becomes:

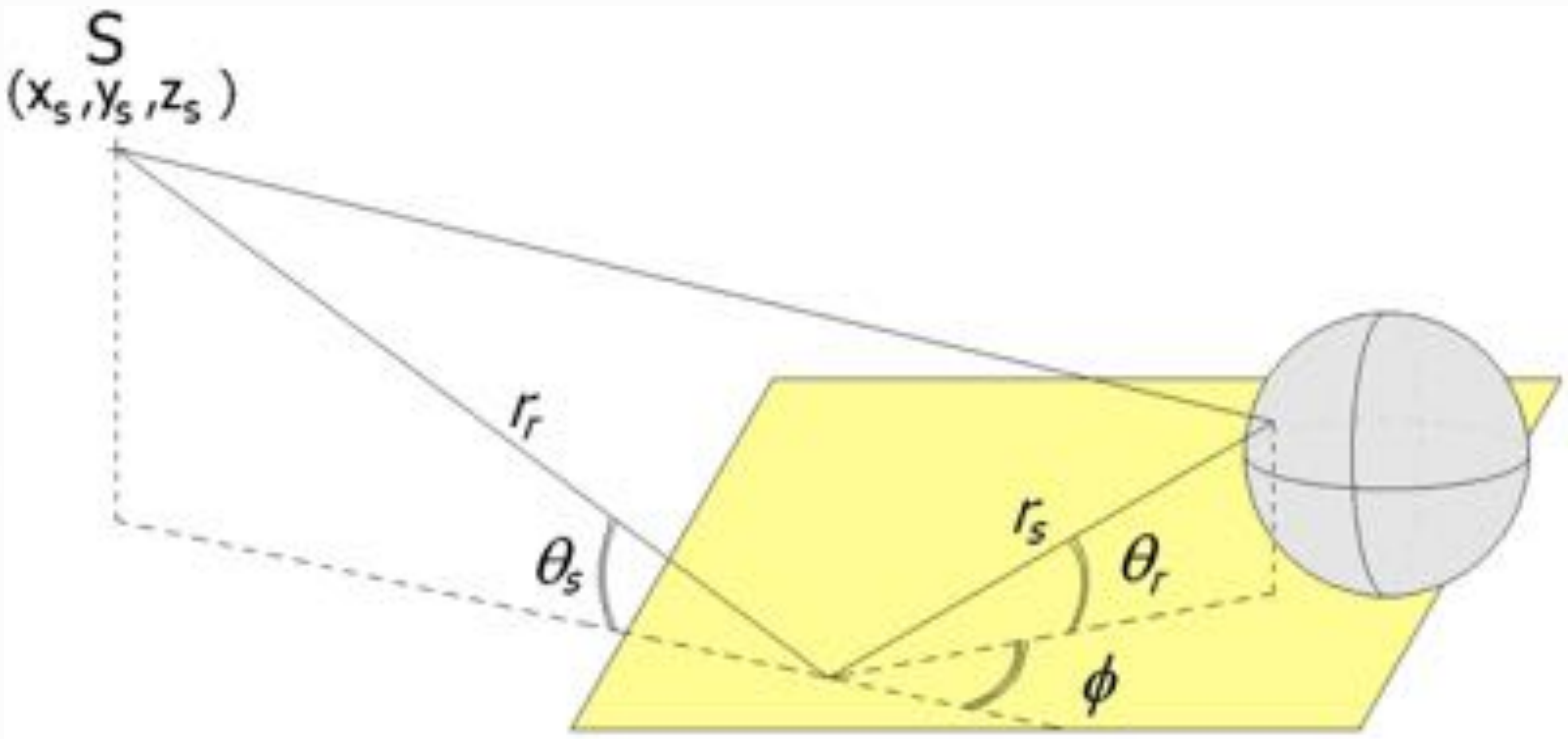
$$p(r_i) = \sum_j \frac{\partial G_{ij}}{\partial n_j} p(\tilde{r}_j) \mathrm{d}A_j$$

To model the seabed interaction, small perturbation fluid model:

$$\phi(f) = -S(f)\frac{k_1^2}{2\pi}\iint_{x,y} B(x,y)\tau(x,y)\zeta(x,y)\frac{\mathrm{e}^{ik_1(r_s+r_r)}}{r_s r_r}\mathrm{d}x\mathrm{d}y$$

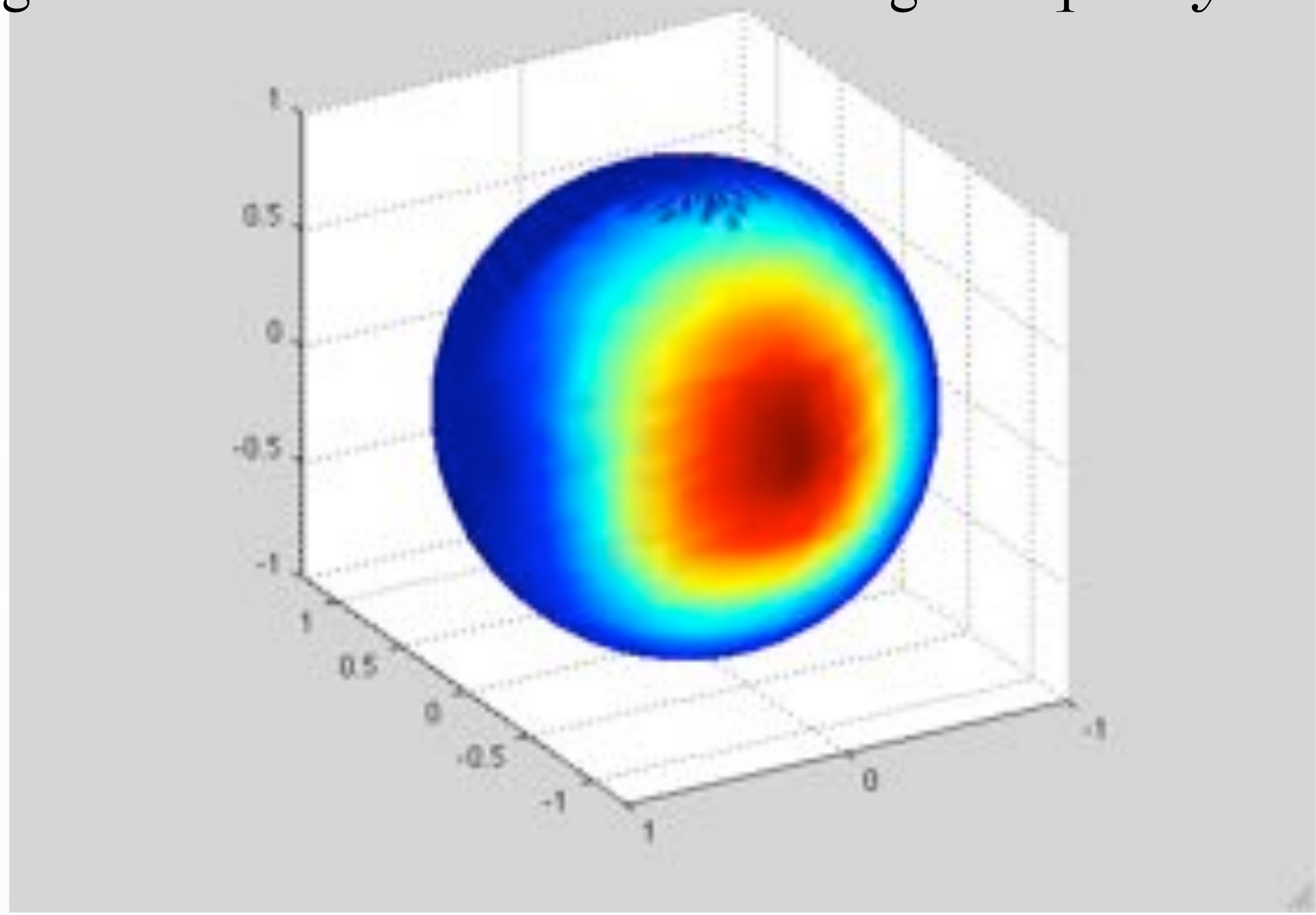
Rough surface interaction

Configuration:



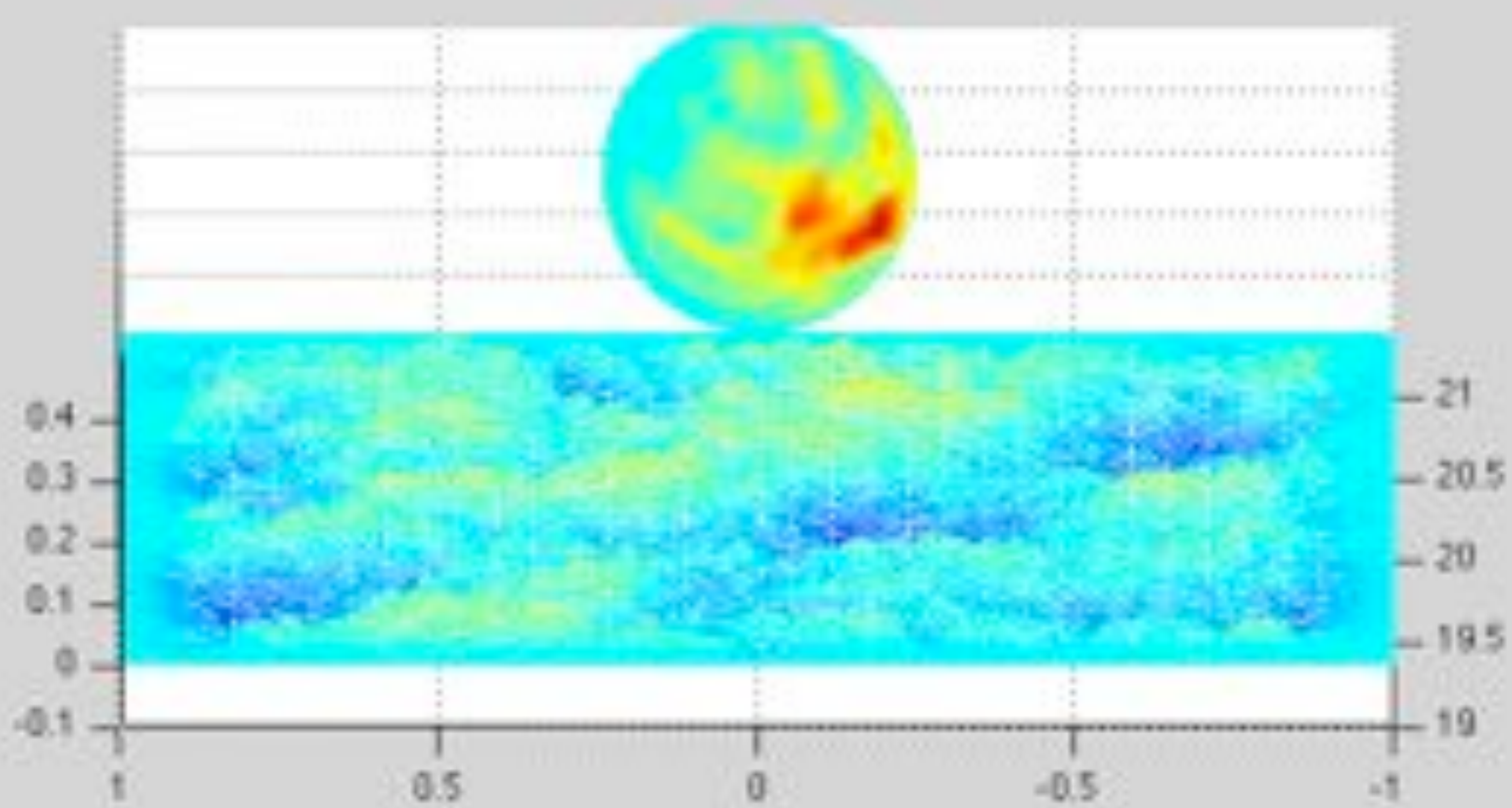
Rough surface interaction

Magnitude of the scattered field through frequency:

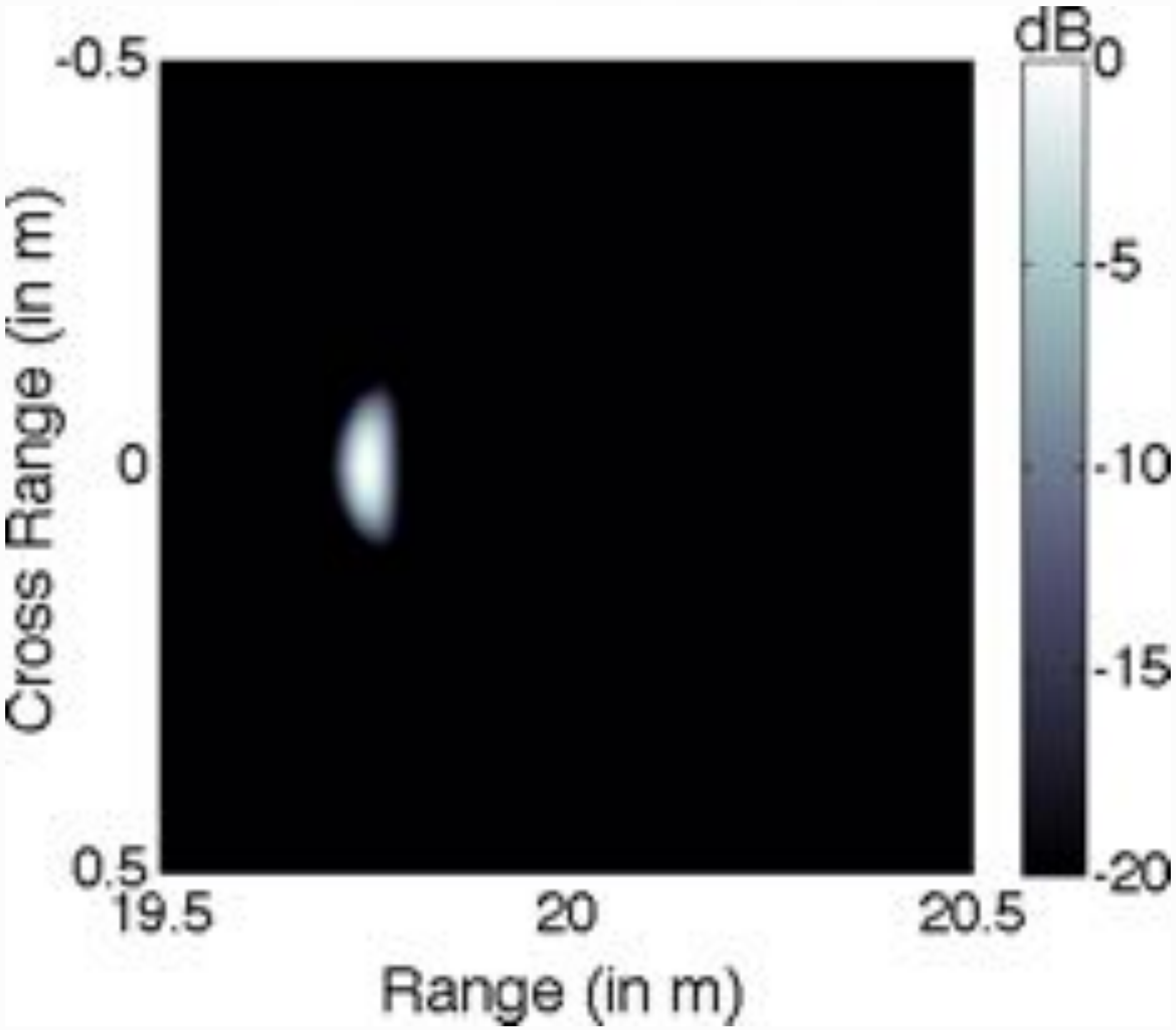


Rough surface interaction

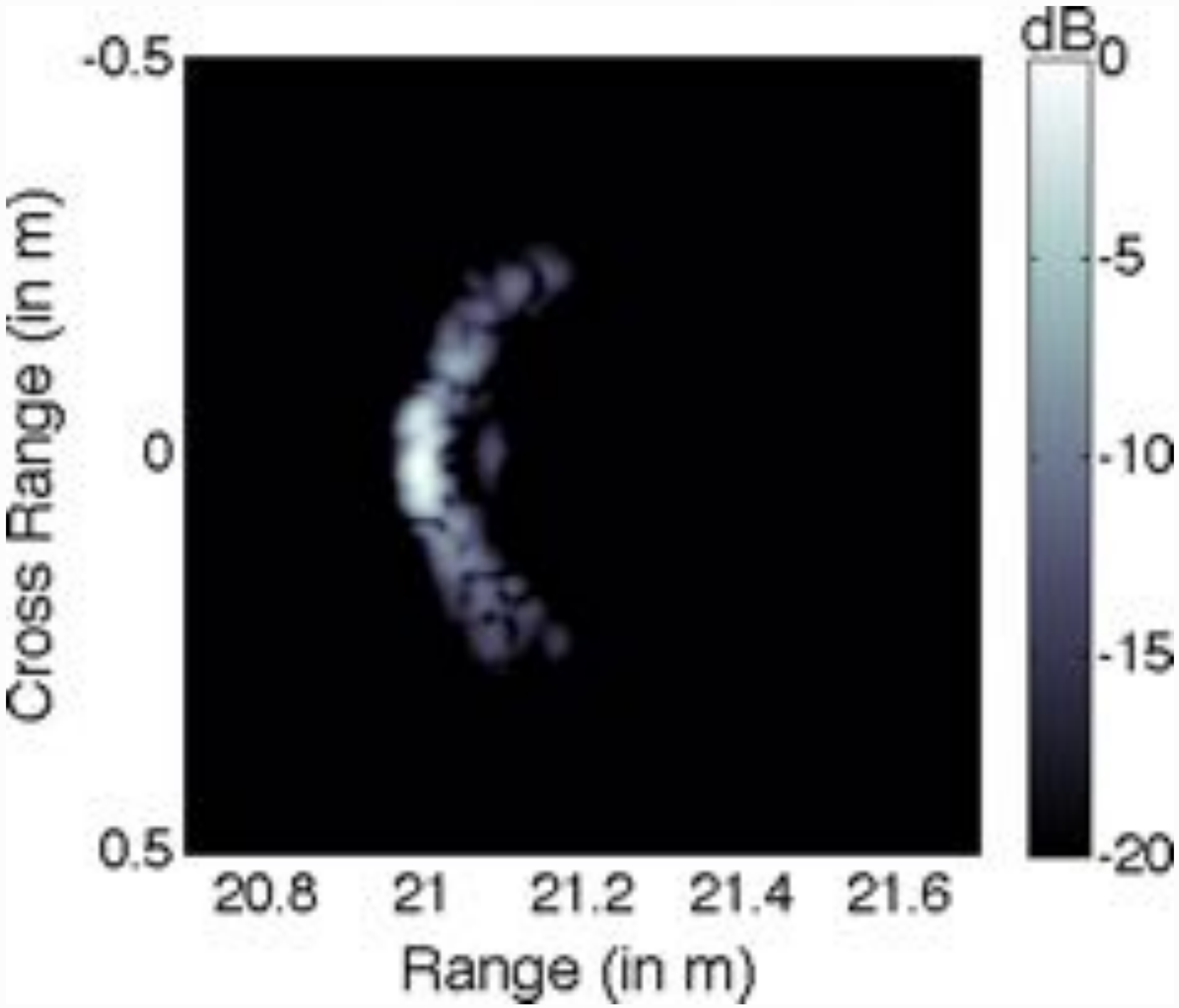
Magnitude of the scattered field through view angle:



Rough surface interaction

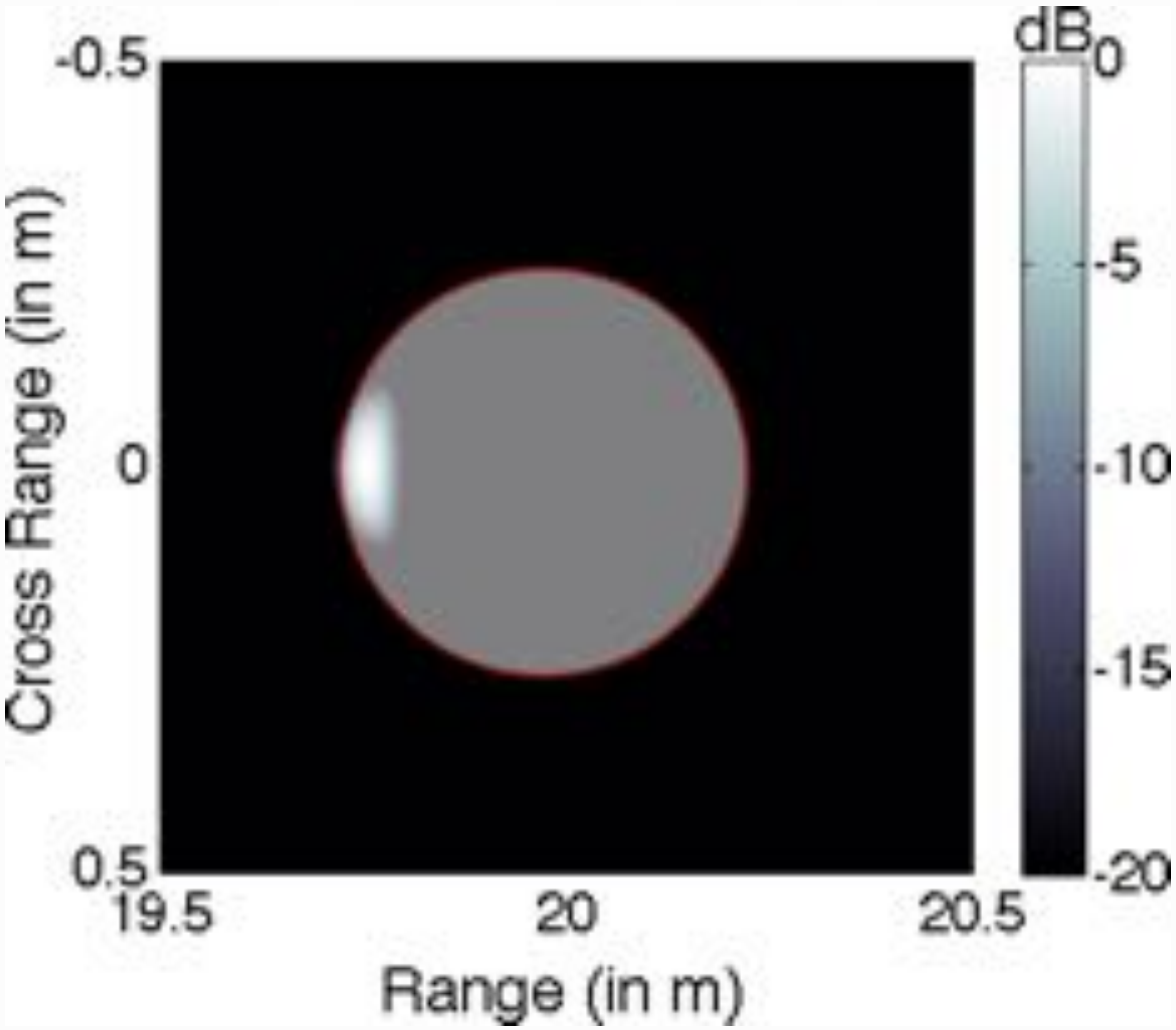


Specular echo
in free water

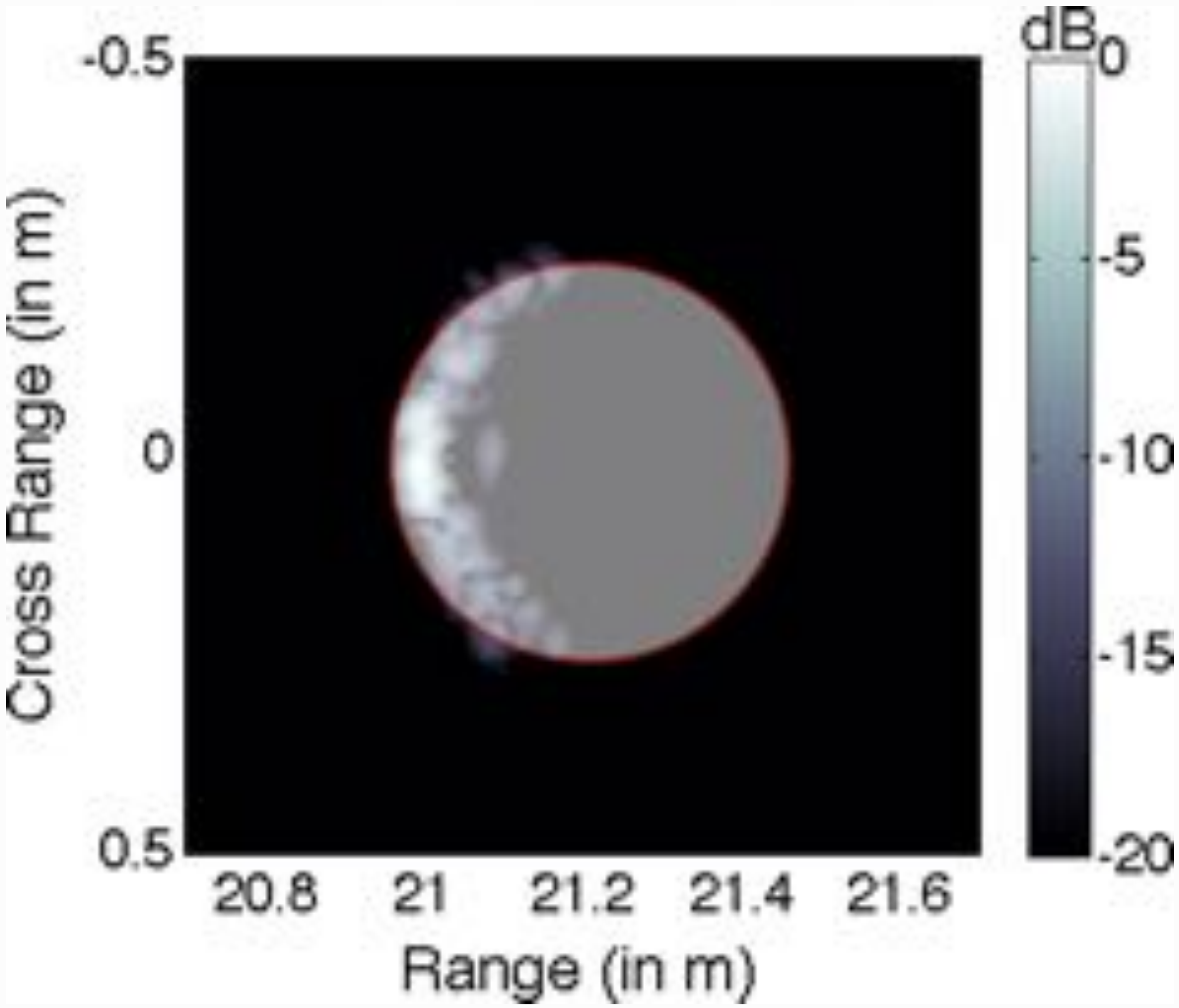


Specular echo from
the bottom contribution

Rough surface interaction



Specular echo
in free water



Specular echo from
the bottom contribution

Conclusion

What are we imaging?