ACOUSTICAL METHODS FOR THE MONITORING OF THE MARINE ENVIRONMENT

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Part I

Inverse problems of acoustic wave propagation

An acoustic wave is an efficient carrier of information on the medium through which it has propagated.

therefore

Measurements of an acoustic field in an oceanic waveguide provide extremely useful data for the inverse problem of determining parameters of the medium.

INVERSE PROBLEMS IN UNDERWATER ACOUSTICS

- REMOTE SENSING
  - GRAVITY WAVES
  - WATER PARAMETERS
  - SEA-BED PARAMETERS
- LOCALISATION

OCEAN ACOUSTIC TOMOGRAPHY

Water column parameters

Sound speed profile

Density variations

Current Speed

(Tomography)

Sea Bed Parameters

Geometry of the interface

Shape and Composition of Buried Objects

Composition of the Sea-Bed

(Sea-Bed Classification)

Methods for estimating Sea Bed Parameters

Local methods

Ocean Acoustic Tomography

Local Methods

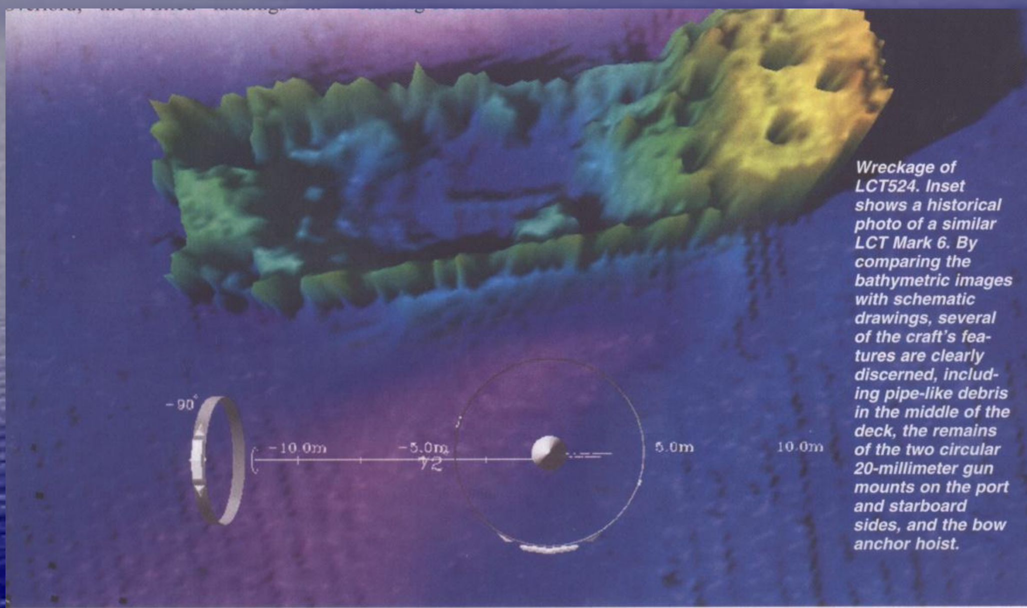
Use of sonar techniques

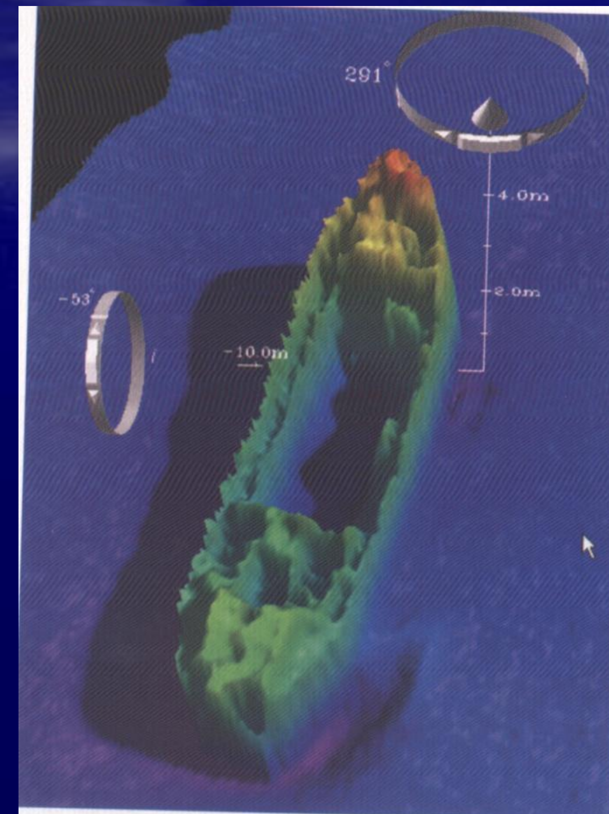
An acoustic beam is sent to the sea-bottom interface.

The reflected signal after suitable processing provide the information on the sea-bed structure.

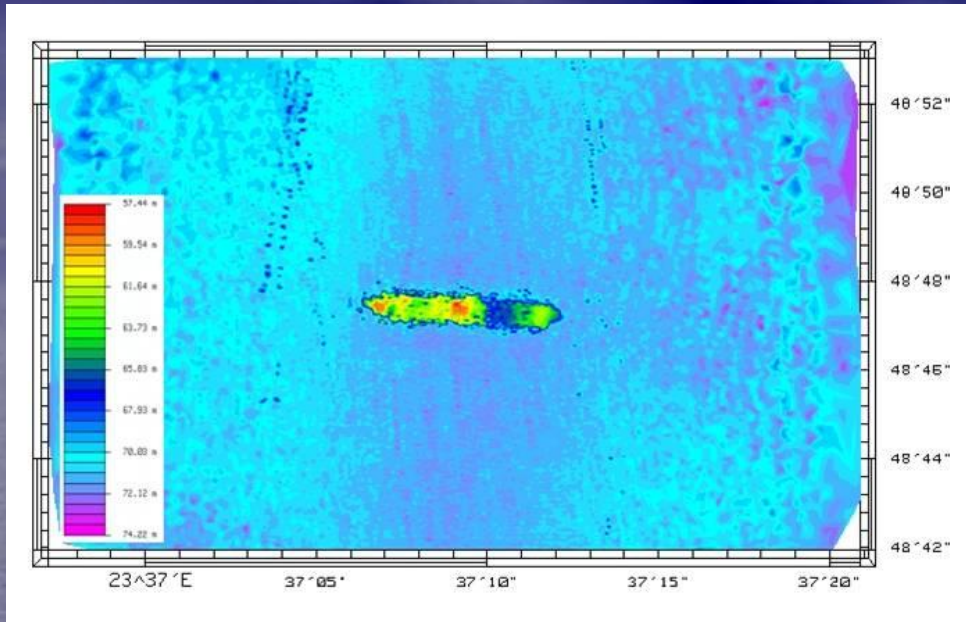
Narrow beams provide the resolution necessary to identify the geometrical properties of objects in the sea-bed.

Local Methods

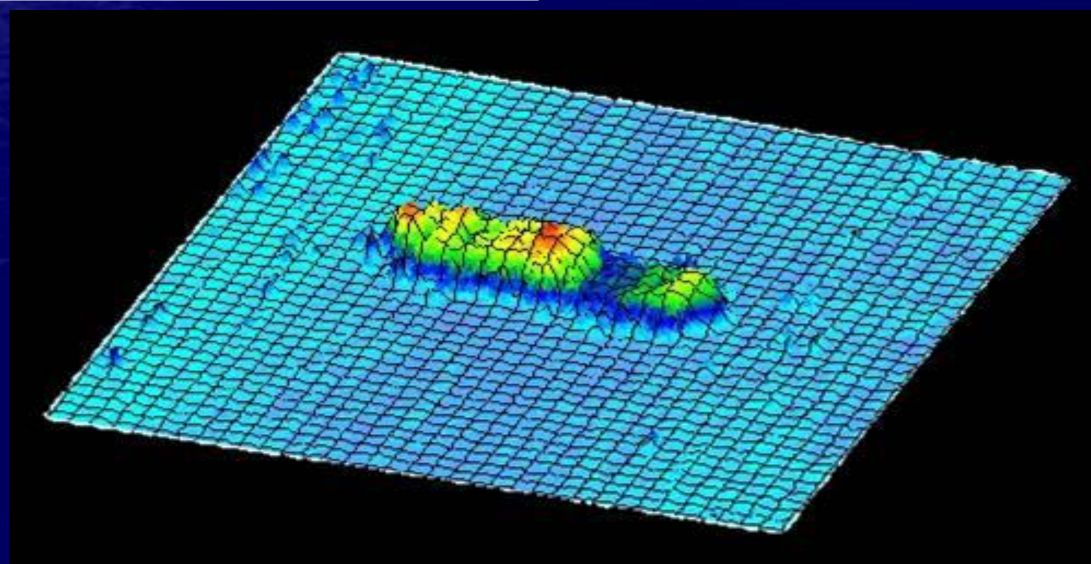




Wrecks of battle ships sunk during the D-Day off-shore Normandy as they are reconstructed using acoustic techniques



A wreck off-shore the Aegina island in Greece. Probably commercial ship of 100 m length (HCMR)



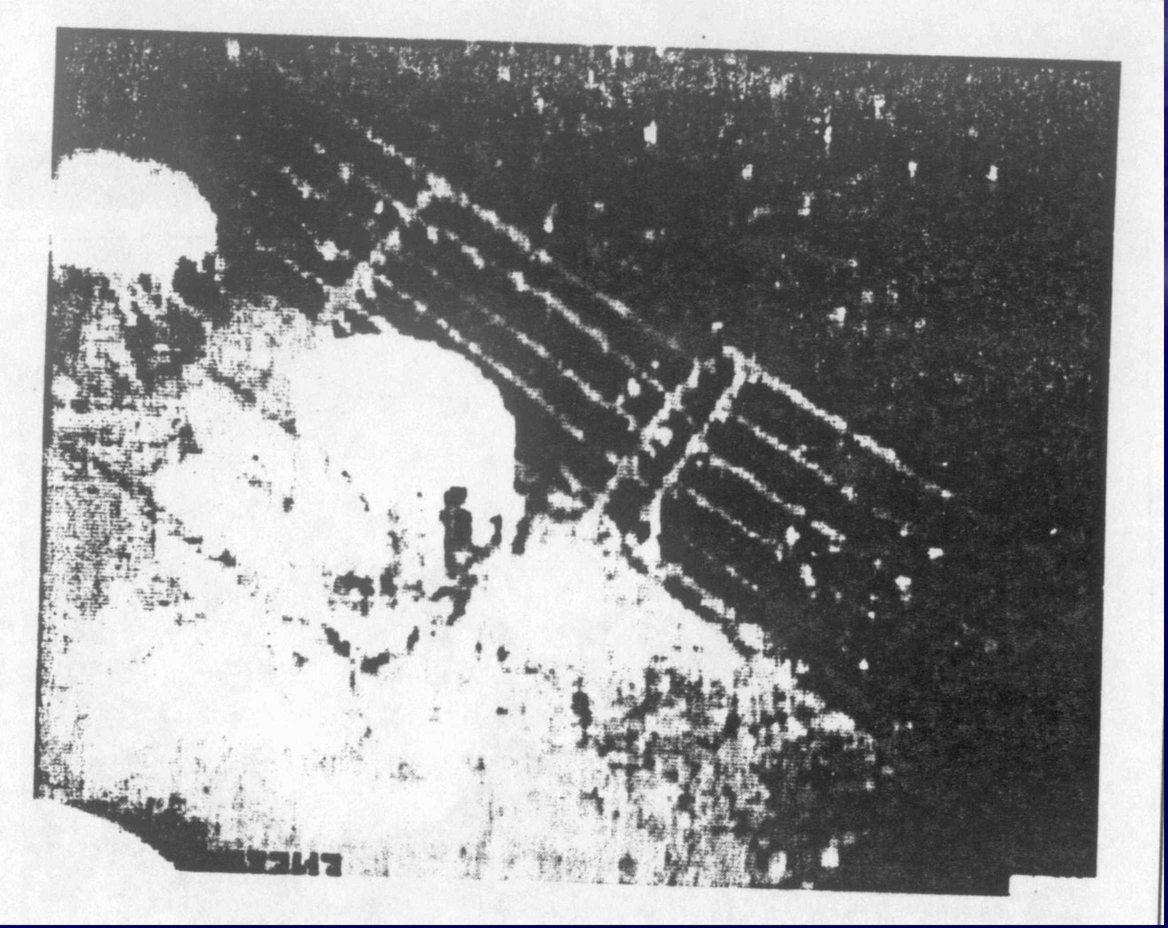
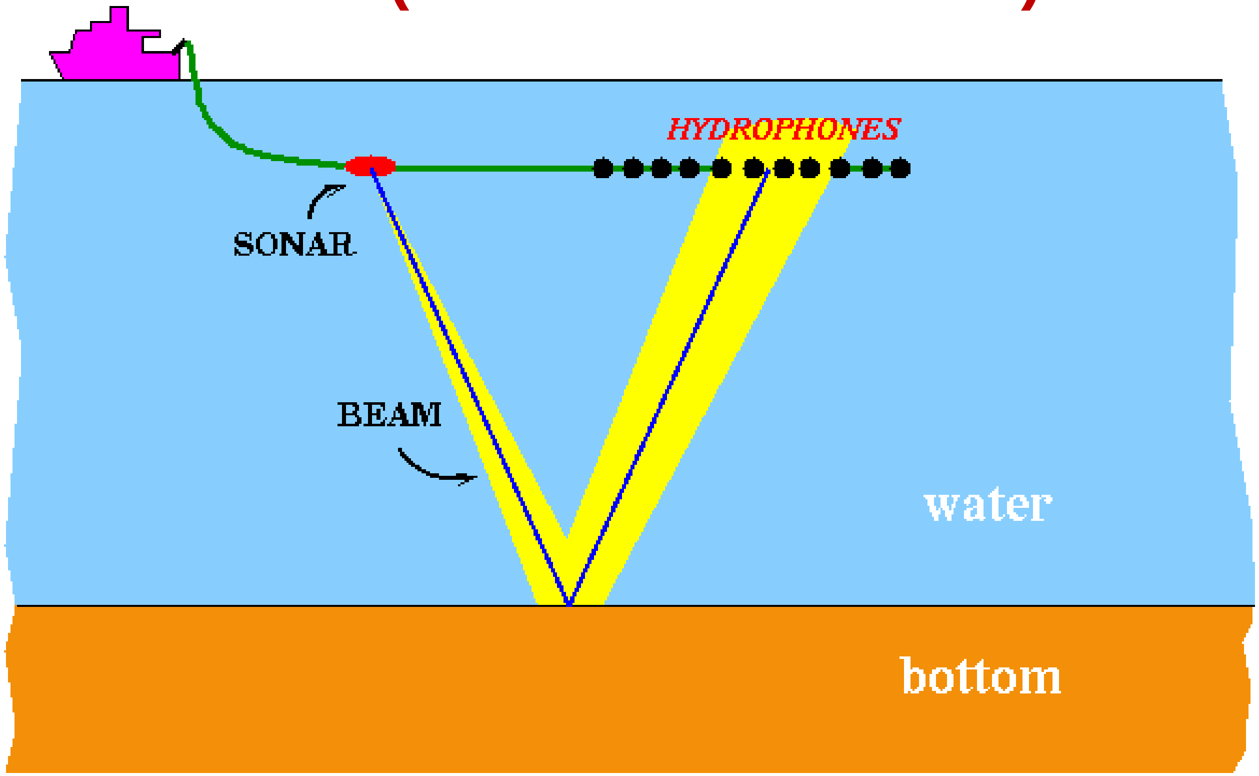


Image of the Titanic's wreck transmitted acoustically in the late '80s !!

Bottom recognition using a parametric array as a source and a hydrophone streamer as a receiver (REBECCA – SIGMA)



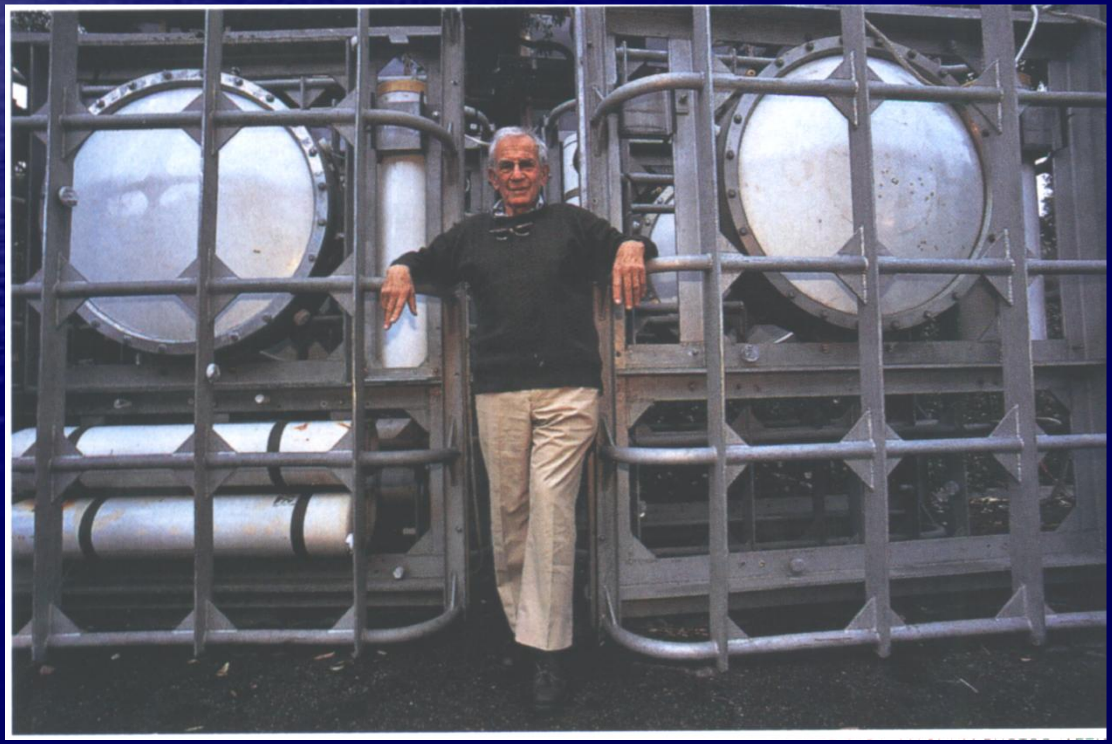
Sea and Climate

Some Facts……

- Even slight variations in the temperature of the sea currents at a certain region may affect the temperature of the atmosphere and the meteorological phenomena all over the globe.

- It is not possible to obtain long-term predictions of climate change without taking into account the ocean circulation.

Ocean acoustic tomography was introduced by Munk and Wunsch in 1979 following a demonstration in the ‘70s that about 99% of the kinetic energy of the ocean circulation is associated with mesoscale features, that is features that are about 100 km in diameter.



Walter Munk

Monitoring the changes of the mesoscale and larger-scale
features is therefore a useful process on the way of understanding global changes.

Use Acoustics !!

Sound propagates in a waveguide in different ways, (rays or modes) the number and type of which depend on the geometry, the environmental parameters and the frequency

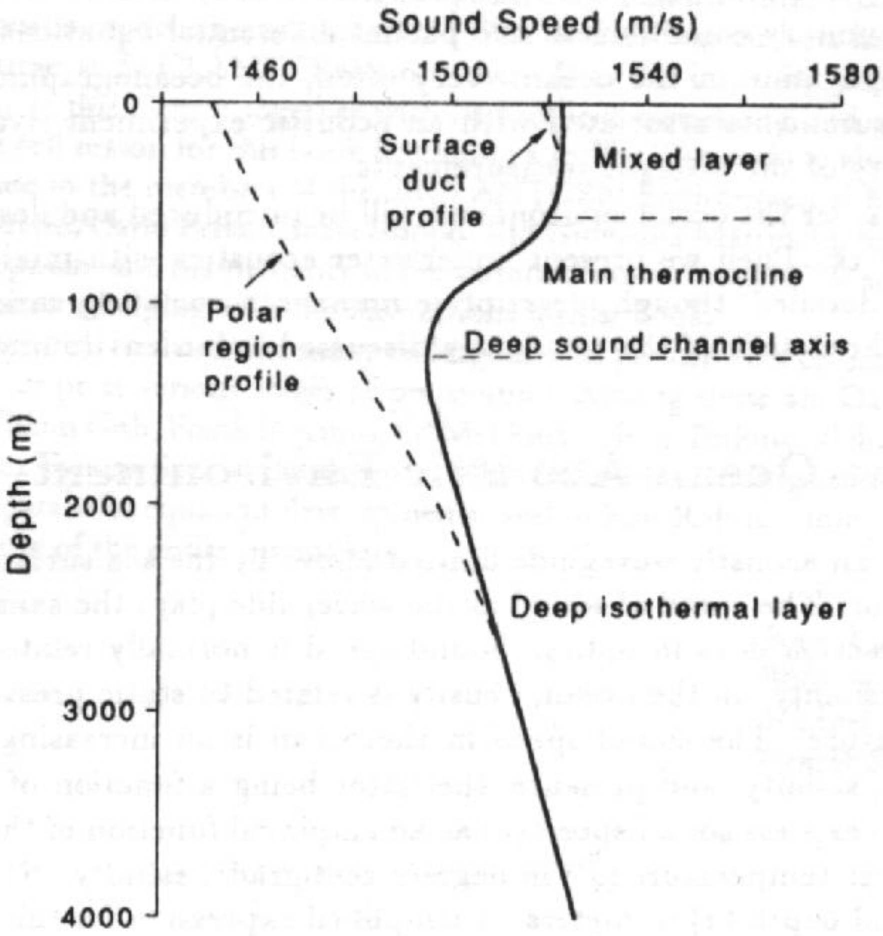
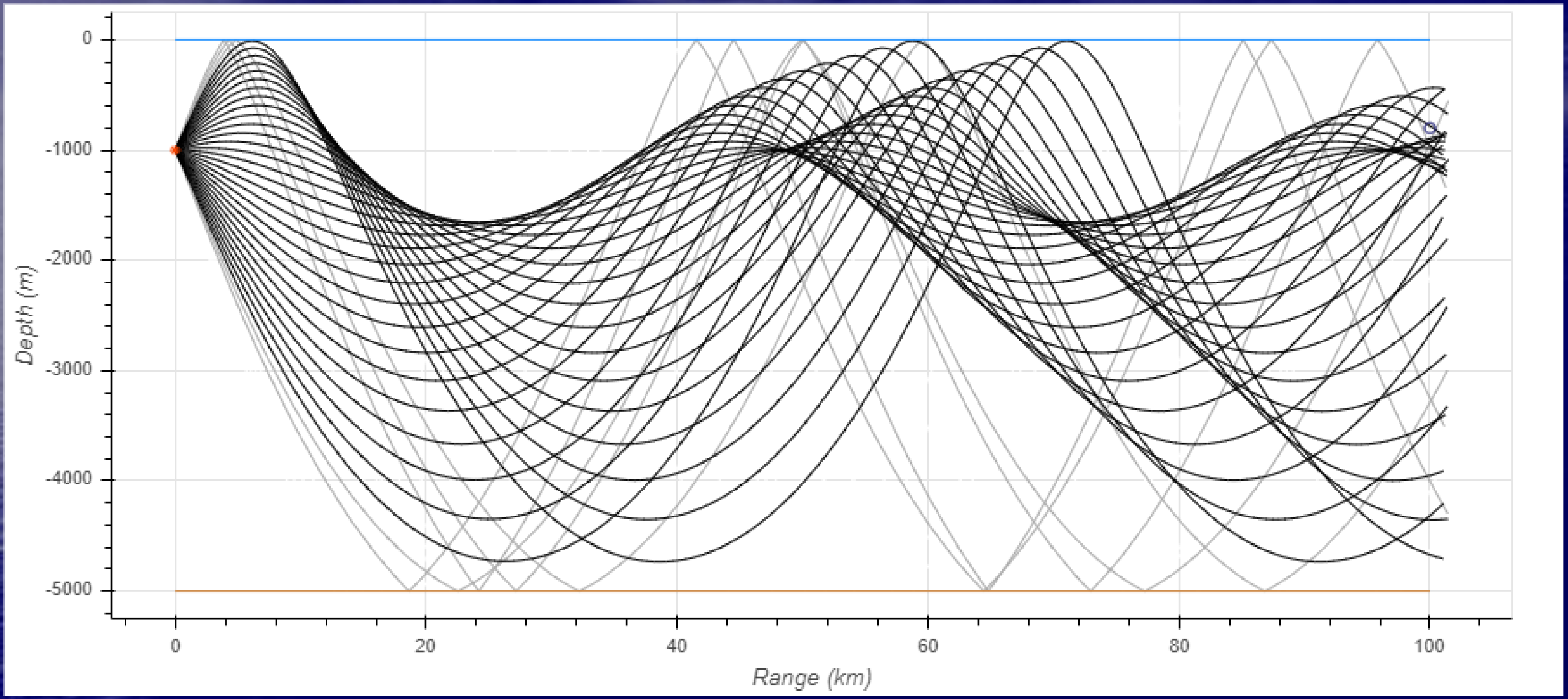
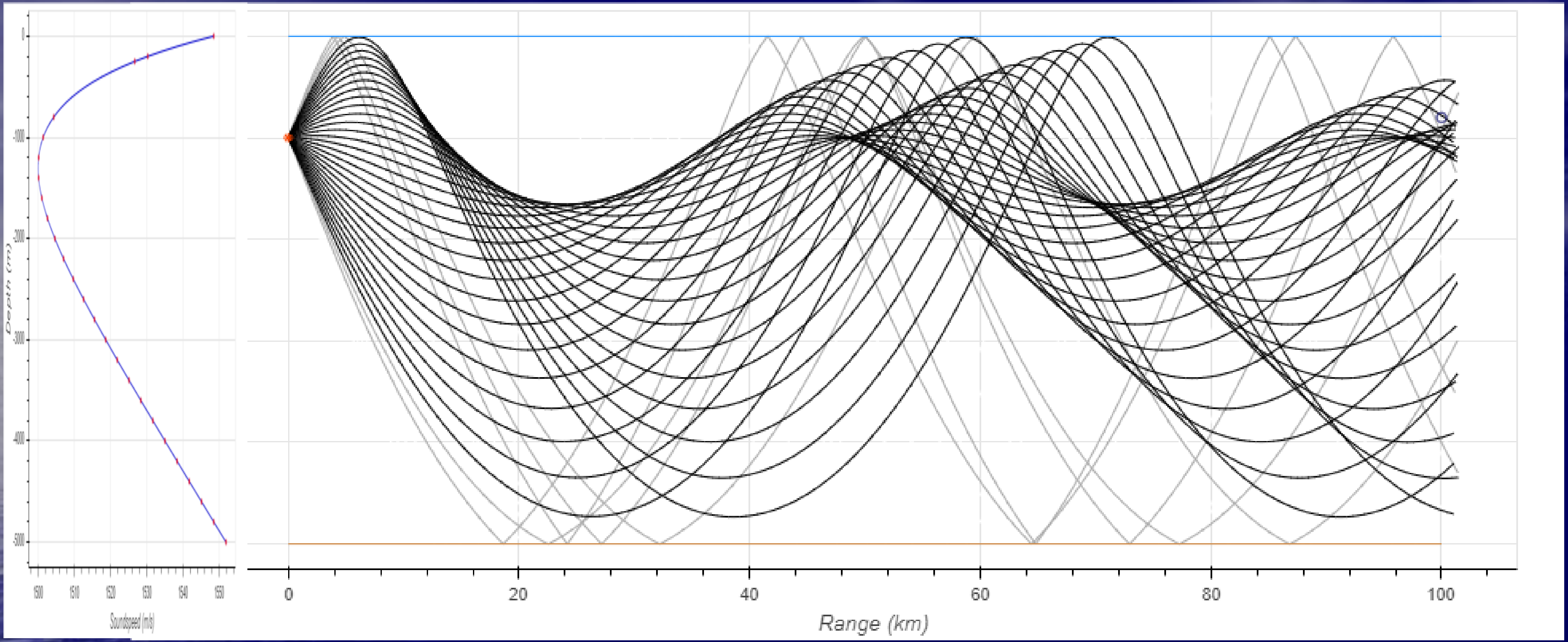


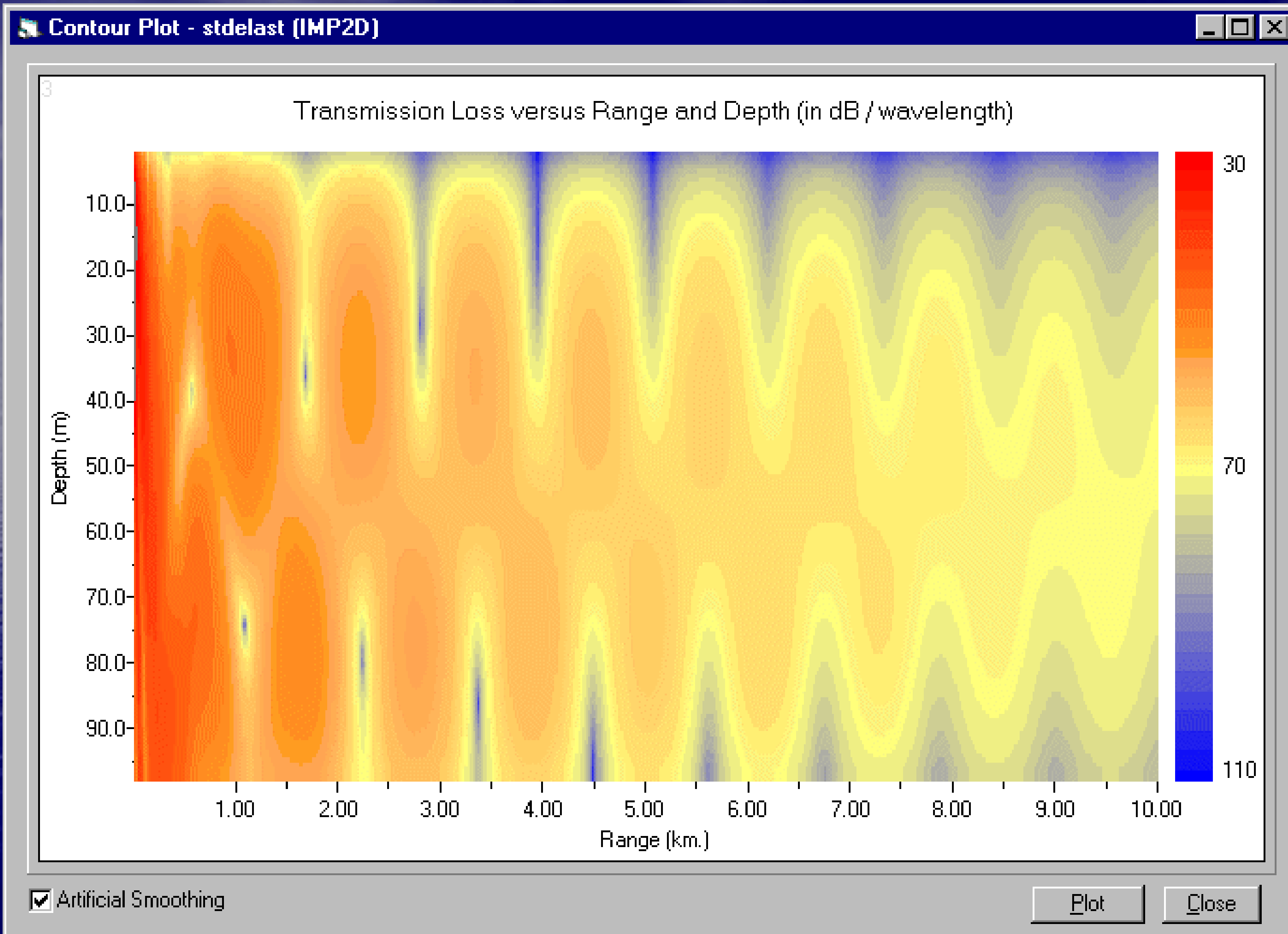
Fig. 1.1. Generic sound-speed profiles.



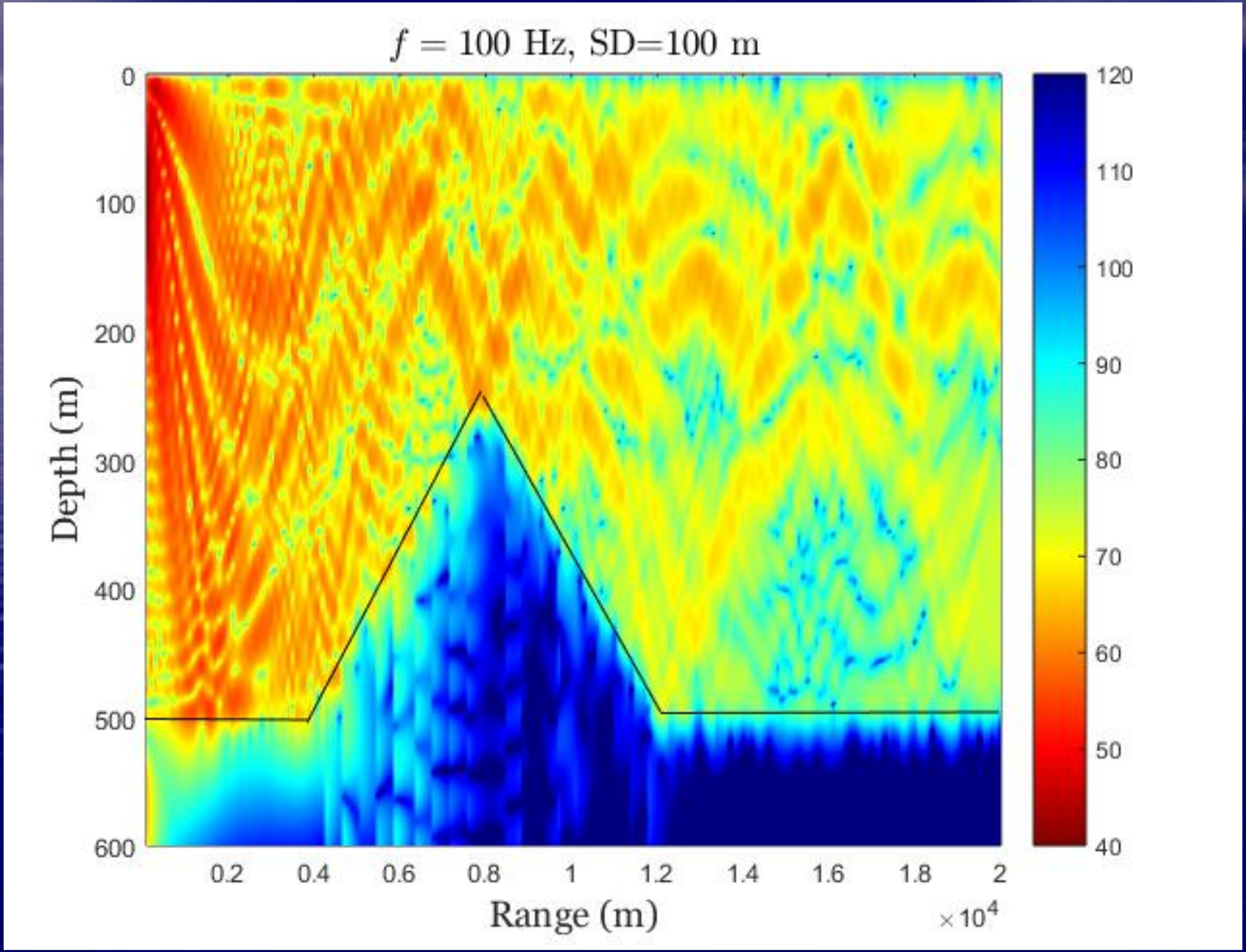
Ray plots



Ray plots



The acoustic field


f = 100 Hz, SD=100 m
Depth (m)
0
100
200
300
400
500
600
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Range (m)
$\times 10^4$
120
110
100
90
80
70
60
50
40

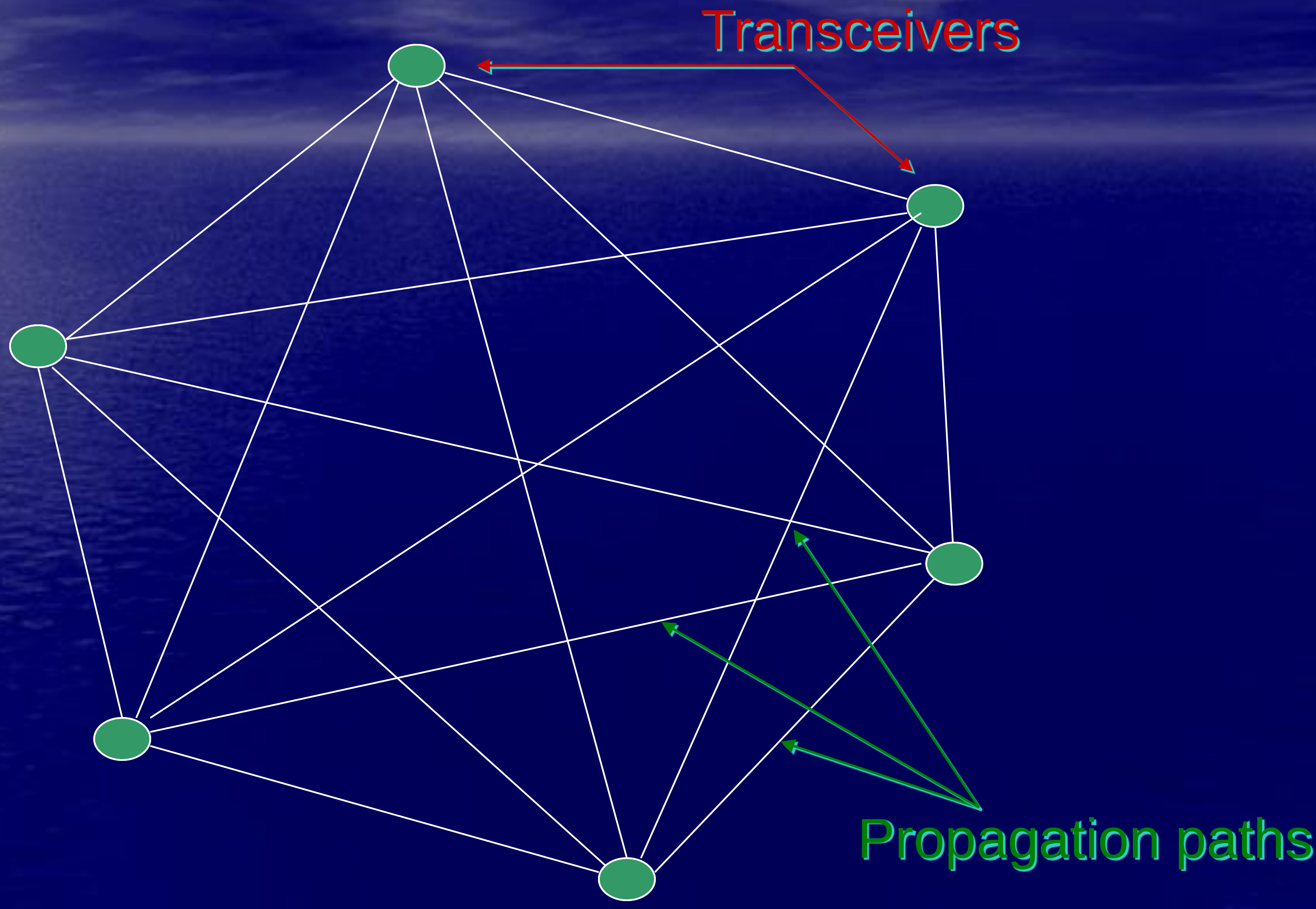
Measurements related to acoustic rays or propagation modes can therefore be used for the estimation of the environmental parameters.

These parameters include the characteristics of the water column (sound speed and density) and the sea-bed (compressional and shear wave speeds, densities, attenuation coefficients and thickness of the bottom layers.

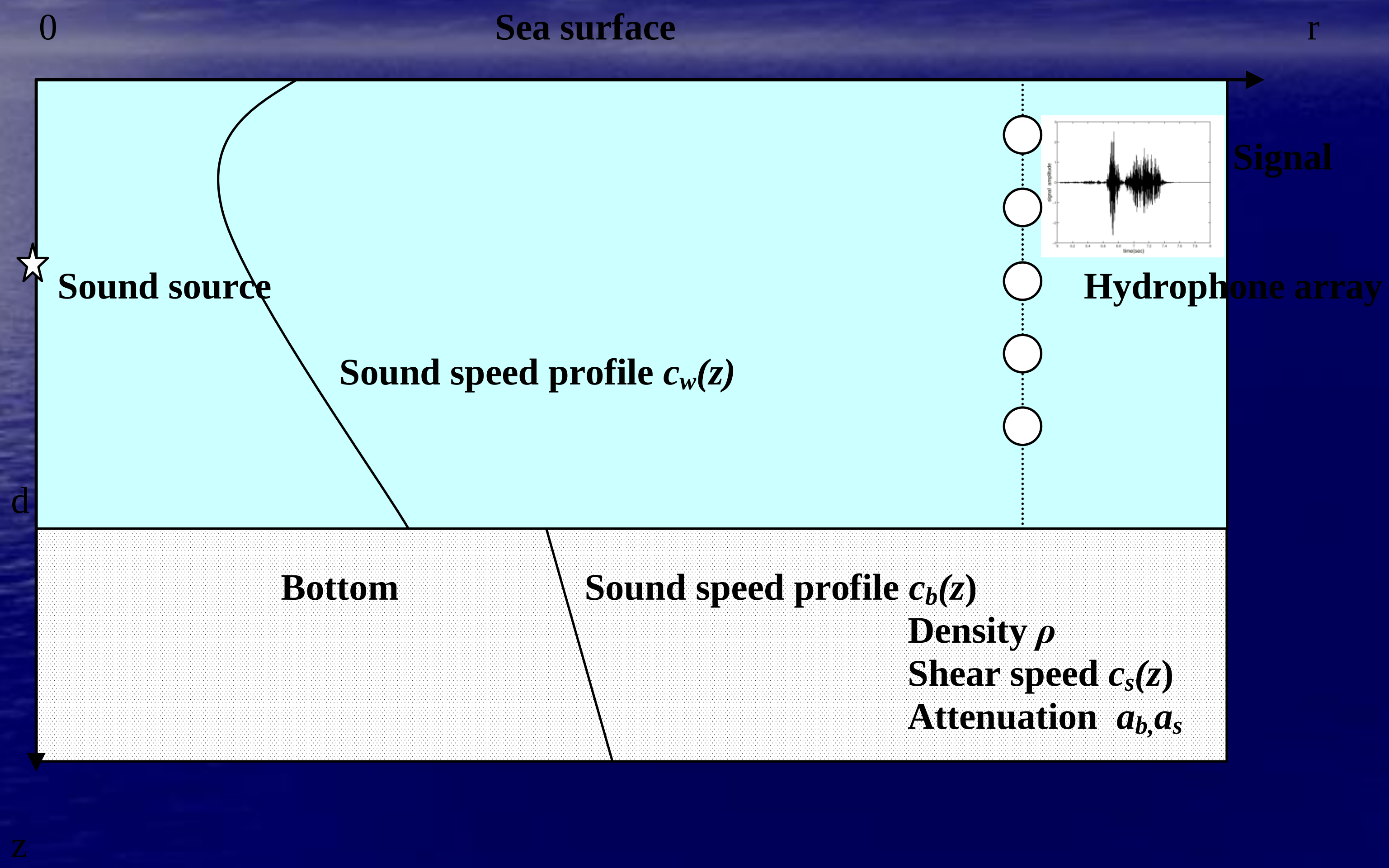
For a 3-D view of the ocean environment we need to define several slices (τομές – tomes) in each one of which to apply inversion procedures

Τομή +Γραφή → **Τομογραφία - Tomography**

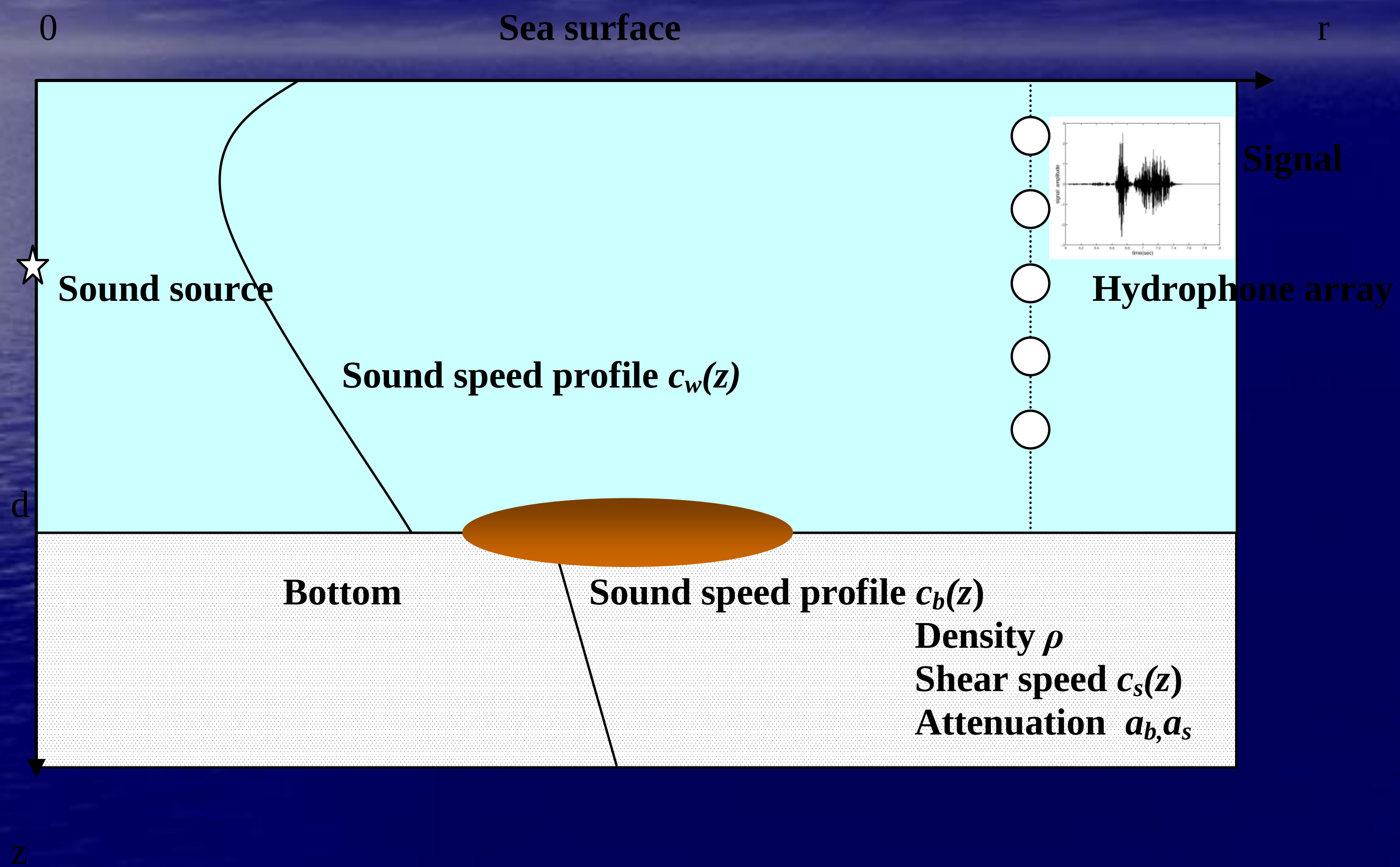
Geometrical Concept of Vertical Slice Ocean Acoustic Tomography



The geometry at a vertical slice



The geometry at a vertical slice



THE INVERSE PROBLEM OF OCEAN ACOUSTIC TOMOGRAPHY

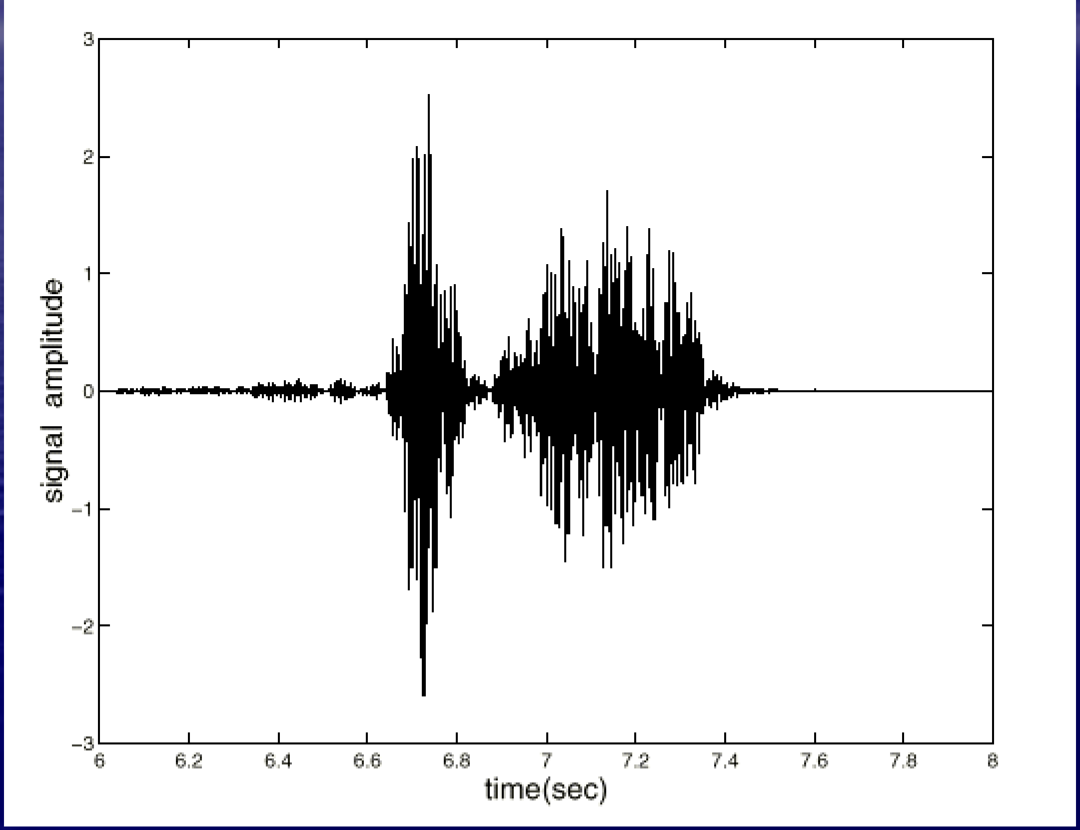
Given a set of measurements of the acoustic pressure at specific ranges and depths for a given source, estimate the sound speed in the water column *c(x,y,z)* and/or the current velocity *v(x,y,z)*

Additional unknowns : The exact position of source and receiver. The bottom structure (combined with bottom classification)

Type of sources : Special modulated sources. Sometimes cw sources. Also, alternative, providing transient signals.

Type of measurements : Usually time series of the emitted signal at a single hydrophone or at an array of hydrophones. From the time series one can obtain by Fourier transform the acoustic field in the frequency domain.

Reception of a tomographic signal in the ocean environment



The inverse problem

$$\mathbf{f}(\mathbf{m},\mathbf{d}) = 0$$

m: Recoverable parameters depending on the parameterization of the problem.

d: Measurements of specific “observables”

f: The mathematical/physical model describing acoustic propagation in the marine environment

The forward problem

$$\nabla^2 p(\vec{x},t) - \frac{1}{c^2(\vec{x})} p(\vec{x},t) = A(\vec{x}-\vec{x}_o,t)$$

+ boundary conditions

Harmonic waves : Helmholtz equation

$$\nabla^2 p(\vec{x};\omega) + \frac{\omega^2}{c^2(\vec{x})} p(\vec{x};\omega) = -\delta(\vec{x}-\vec{x}_o)$$

Cylindrical coordinate system

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 p}{\partial \varphi^2}+\frac{\partial^2 p}{\partial z^2}+k^2 p=-\frac{1}{r}\delta(r-r_0)\delta(\varphi-\varphi_0)\delta(z-z_0)$$

Axial symmetry

$$\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}+\frac{\partial^2 p}{\partial z^2}+k^2 p=-\frac{1}{2\pi r}\delta(r)\delta(z-z_0)$$

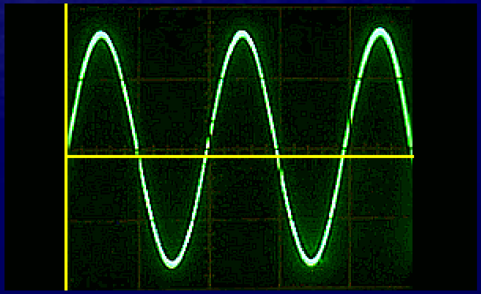
For a source excitation function S(ω)

$$p'(r,z;\omega) = p(r,z)S(\omega)$$

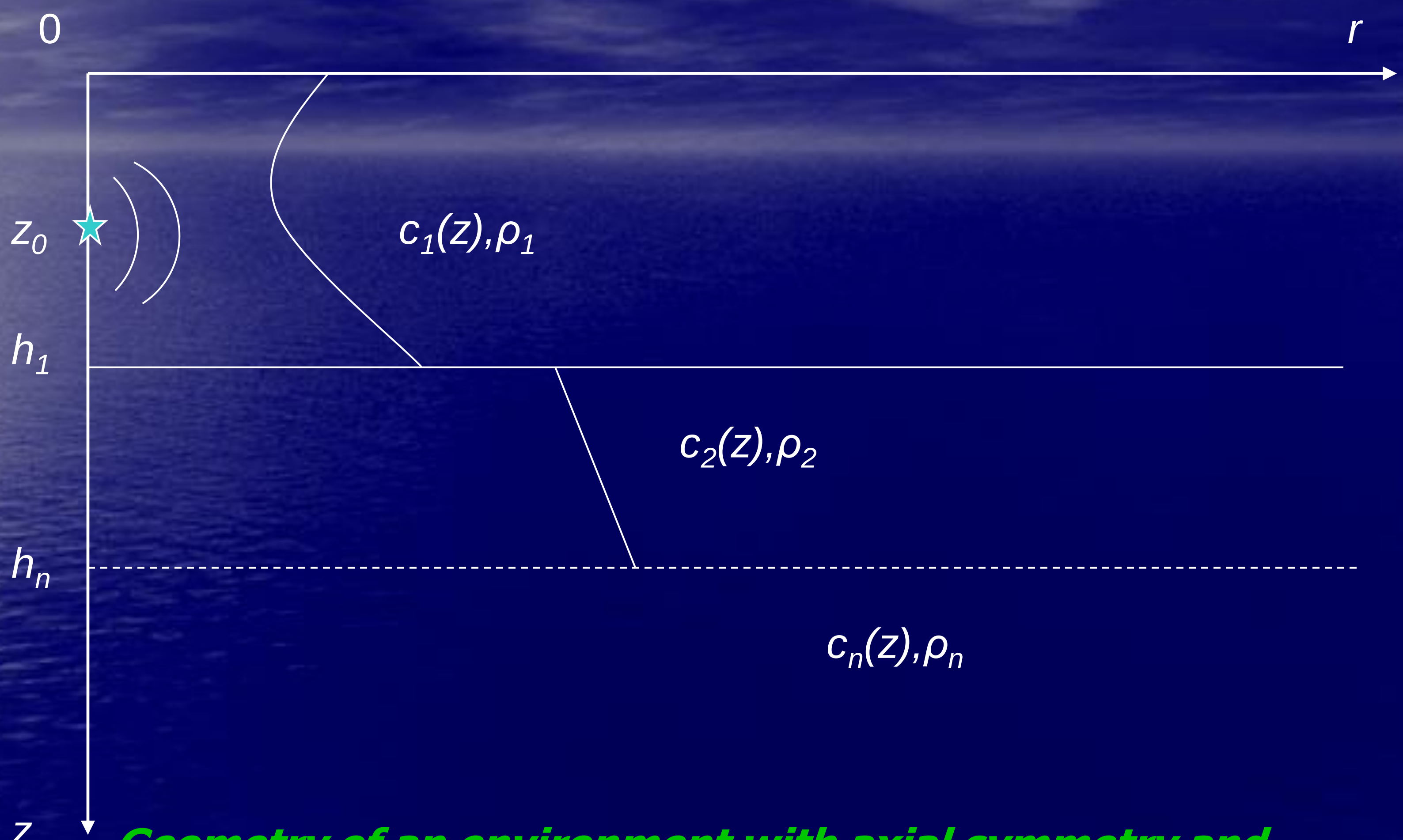
The pressure in the time domain

$$p(r,z;t) = \Im^{-1}\left[p(r,z,\omega)\right];\omega \rightarrow t$$

A monochromatic wave is characterized by its amplitude and period (in theory it has infinite duration)



A broad-band wave is characterized by a finite duration and several peaks



Geometry of an environment with axial symmetry and multiple fluid layers

$$\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}+\frac{\partial^2 p}{\partial z^2}-\frac{1}{\rho^{(0)}}\frac{\partial \rho^{(0)}}{\partial z}\frac{\partial p}{\partial z}+k^2 p=-\delta(r)\delta(z-z_0)$$

$$p^{(1)}(\cdot,0)=0$$

$$p^{(i)}(\cdot,h_i)=p^{(i+1)}(\cdot,h_i),\quad i=1,\ldots.I$$

$$\frac{1}{\rho_i}\frac{\partial p^{(i)}}{\partial z}(\cdot,h_i)=\frac{1}{\rho_{i+1}}\frac{\partial p^{(i+1)}}{\partial z}(\cdot,h_i),\quad i=1,\ldots.I$$

$$\lim_{z\to\infty} p^{(I+1)}(\cdot,z)=0$$

Sommerfeld radiation condition

The "Depth Problem"

$$\frac{d}{dz}\left(\frac{1}{\rho(z)}\frac{du}{dz}\right)+\left(\frac{k^2(z)}{\rho(z)}-\frac{\kappa^2}{\rho(z)}\right)u=0$$

$$u(z)=u^{(i)}(z) \quad for \quad h_{i-1}\le z\le h_i, \quad i=1,.....I, \quad h_0=0$$

$$\rho(z)=\rho^{(i)}(z) \quad for \quad h_{i-1}\le z\le h_i, \quad i=1,.....I, \quad h_0=0$$

$$k(z)=\frac{\omega}{c(z)}$$

Boundary Conditions

$$u^{(1)}(0)=0$$

$$u^{(i)}(h_i)=u^{(i+1)}(h_i), \quad i=1,....I$$

$$\frac{1}{\rho_i}\frac{du^{(i)}}{dz}(h_i)=\frac{1}{\rho_{i+1}}\frac{du^{(i+1)}}{dz}(h_i), \quad i=1,....I$$

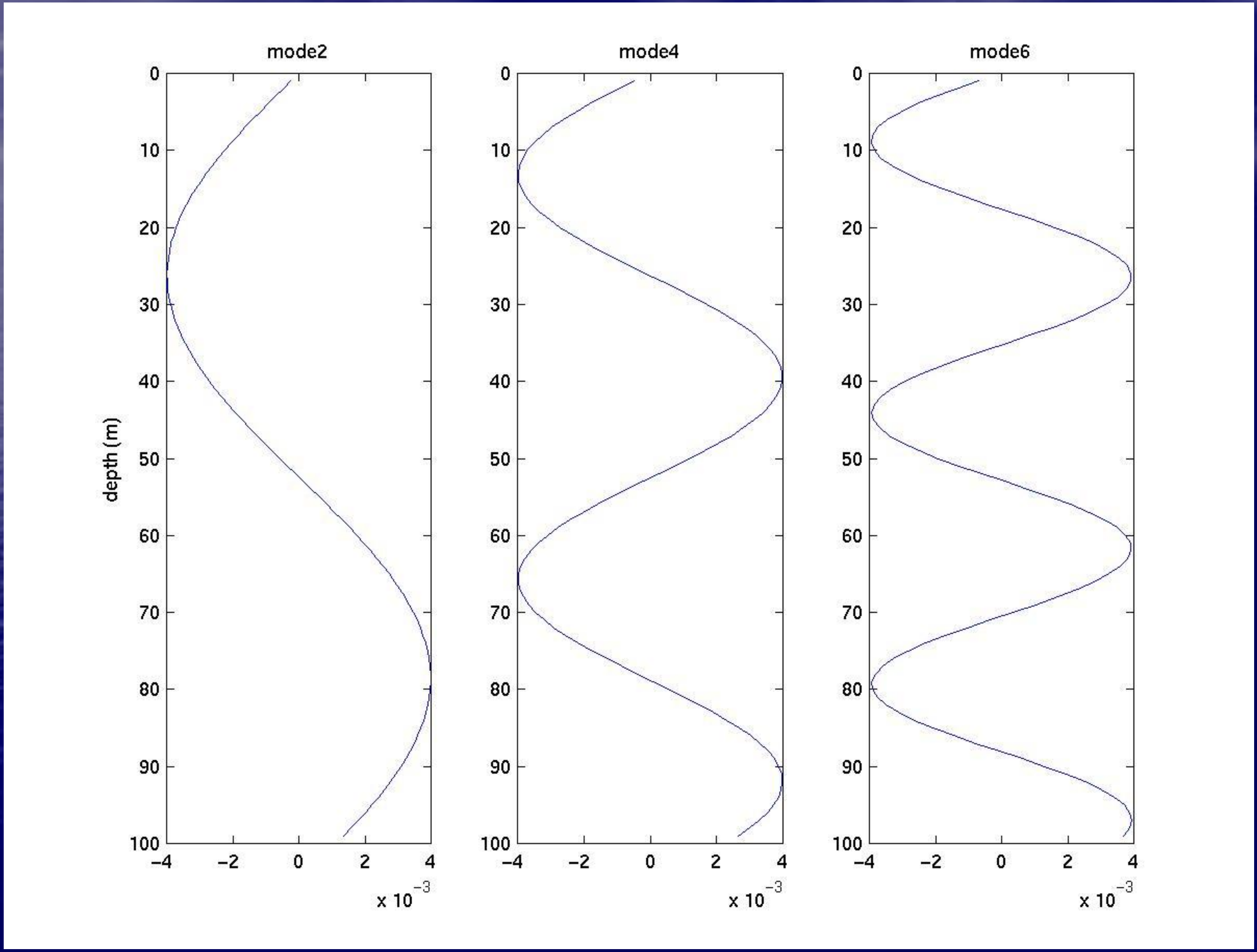
$$\lim_{z\to\infty} u^{(I+1)}(z)=0$$

By representation theorem the acoustic pressure can be expanded in terms of the eigenfunctions of the Depth Problem

$$p(r,z;\omega)=\sum_{n=1}^{N}A_n(r;\omega)u_n(z;\omega)$$

$$p(r,z;\omega)=\frac{i}{4\rho_1}\sum_{n=1}^{N}H_0^{(1)}(\kappa_n r)u_n(z_0;\omega)u_n(z;\omega)$$

Propagating Modes



Ray Acoustics – Forward Problem

$$p(\vec{x};\omega) = \sum_{n=1}^{N} p_n(\vec{x};\omega) = e^{i\omega\tau(\vec{x})} \sum_{n=1}^{N} \frac{A_n(\vec{x})}{(i\omega)^n}$$

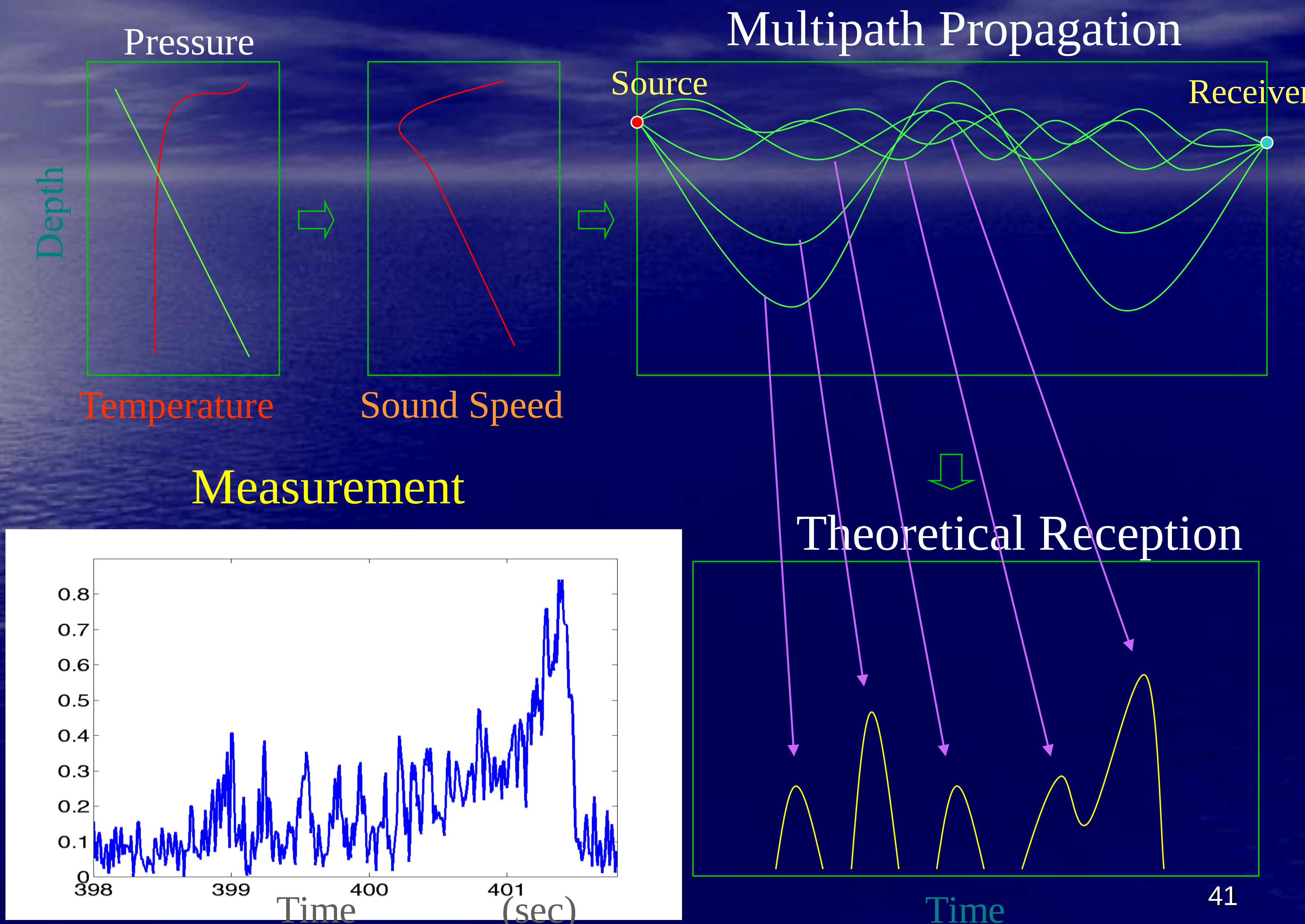
$\tau(x)$ and $A_n(x)$ are obtained through the eikonal and transport equations

The pressure field in the time domain

$$p(\vec{x},t) = \sum_{n=1}^{N} a_n(\vec{x})\,\delta(t - \tau_n(\vec{x}))$$

$$\tau_n = \int_{\Gamma_n} \frac{ds}{c(\vec{x}) \pm v(\vec{x})}$$

τ_n is the arival time of the n^{th} eigenray


Pressure
Depth
Temperature
Sound Speed
Multipath Propagation
Source
Receiver
Measurement
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
398
399
400
401
Time (sec)
Theoretical Reception
Time