声纳与雷达技术（物理篇）
3/8

浙江大学海洋学院

2023.11.29

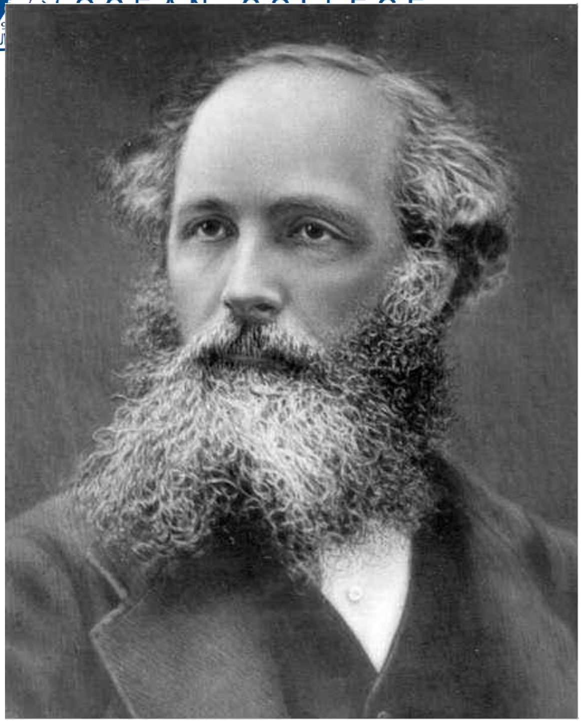
图书馆整理了本课程的7本教参电子资源：《水声学》、《水声传播原理》、《数字式声纳设计原理》、《声呐信号处理引论》、《水下矢量声场理论与应用》、《水声学原理》、《声呐技术》，除Cadal平台需要简单注册后使用外，其他平台均可校网IP直接访问或校外RVPN访问。资源链接如下：

1. http://book.sciencereading.cn/shop/book/Booksimple/show.do?id=B21515D73A2B14446AADA83450C7DB837000
2. （1994版）http://cadal.edu.cn/cardpage/bookCardPage?ssno=06509418
3. http://cadal.edu.cn/cardpage/bookCardPage?ssno=33041255
4. http://cadal.edu.cn/cardpage/bookCardPage?ssno=58003540
5. http://book.sciencereading.cn/shop/book/Booksimple/show.do?id=B1E02CA02B1C841859C72C461E7E34690000
6. http://book.sciencereading.cn/shop/book/Booksimple/show.do?id=B979E853CCAAE846FE053010B0A0AF15E000
7. （2000版）http://cadal.edu.cn/cardpage/bookCardPage?ssno=32033055

内容提纲

- 声学基础 Acoustic Fundamental
  - 波动方程 Wave Equation
  - 简正模态 Normal Mode
  - 射线理论 Ray Theory
- 声学工具箱 Acoustic Toolbox
  - 计算声学 Computational Acoustics
  - Kraken Model
  - Bellhop Model
- 水声传感器 Underwater Sensor
  - 水听器 Hydrophone
  - 换能器 Transducer
  - 传感器阵列 Sensor Array

麦克斯韦



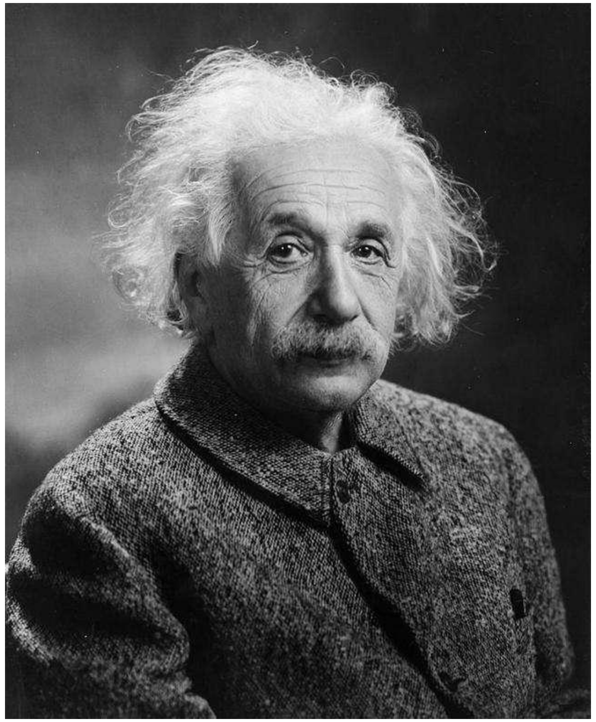
$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

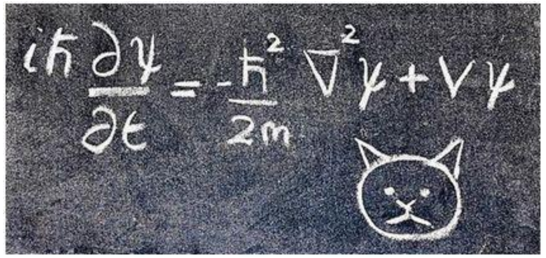
$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

爱因斯坦



$$E=mc^2$$

薛定谔



波尔

麦克斯韦方程组

名称	微分形式	积分形式
高斯定律	$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$	$\oiint_S D \cdot ds = \frac{Q}{\varepsilon_0}$
高斯磁定律	$\nabla \cdot B = 0$	$\oiint_S B \cdot ds = 0$
法拉第感应定律	$\nabla \times E = -\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}}$	$\oint_L E \cdot dl = -\frac{d\Phi_B}{dt}$
麦克斯韦-安培定律	$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}}$	$\oint_L H \cdot dl = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$

	曲面积分	曲线积分
积分形式	通量	环量
联系	高斯定理	斯托克斯定理
微分形式	散度	旋度

直角坐标系中梯度、散度、旋度和拉普拉斯展开式

$$\vec{\nabla} u = \vec{e}_x \frac{\partial u}{\partial x} + \vec{e}_y \frac{\partial u}{\partial y} + \vec{e}_z \frac{\partial u}{\partial z}$$

$$\vec{\nabla} \times \vec{A} = \begin{vmatrix} \vec{e}_x & \vec{e}_y & \vec{e}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$$

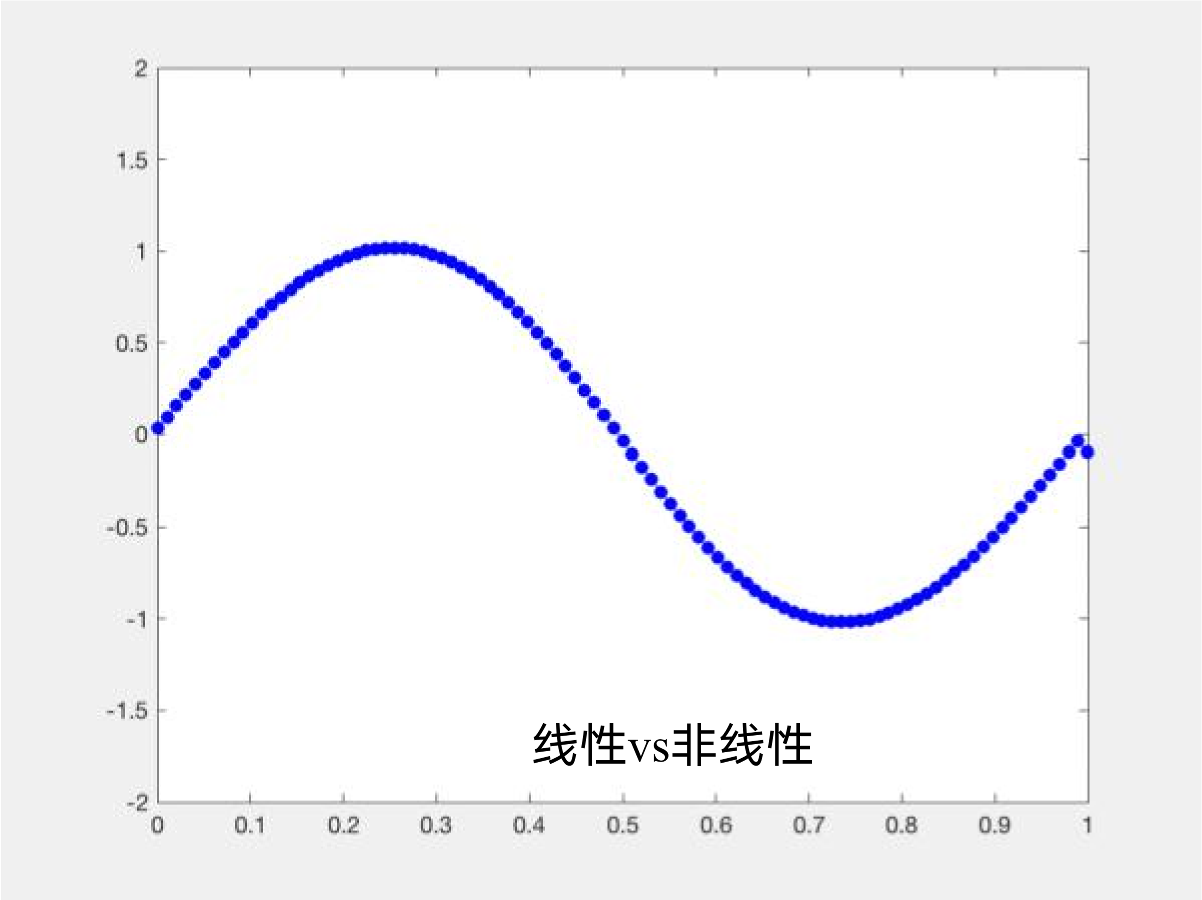
$$\vec{\nabla} \cdot \vec{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

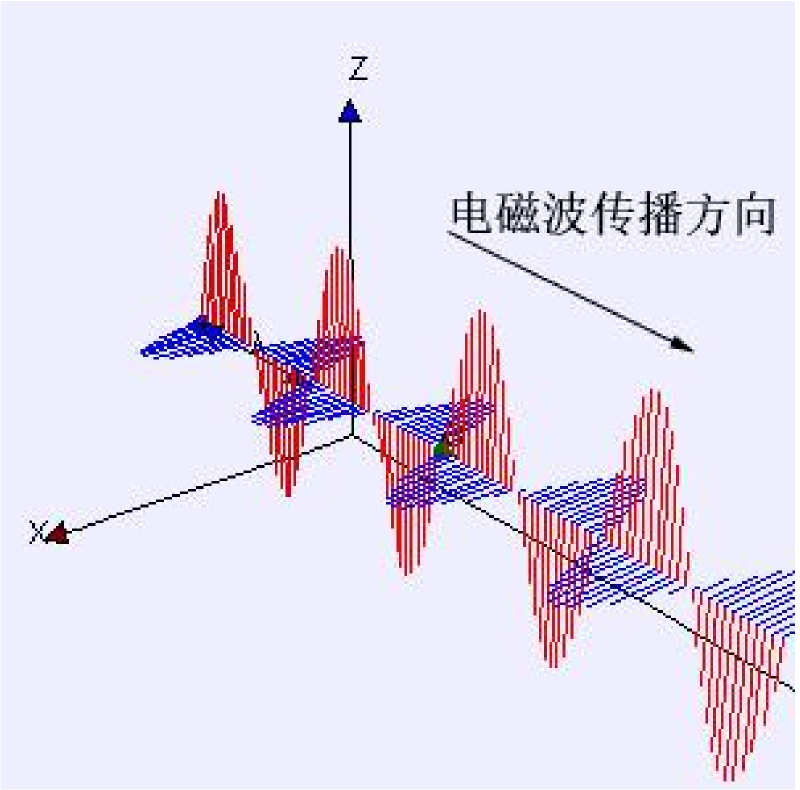
$$\nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}$$

- 方程1描述静电场E特征：静电场是有源场，来源于电荷ρ。
- 方程2描述静磁场B特征：静磁场是无源场，散度为零$\nabla \cdot \boldsymbol{B} = 0$。
- 方程3/4描述电场和磁场关联：变化的磁场$\frac{\partial B}{\partial t}$产生电场，变化的电场$\frac{\partial E}{\partial t}$产生磁场。
- 电场强度E，磁感应强度B，电流密度J，电位移矢量D，磁场强度H，ε_0介电常数，磁导率μ_0，电导率σ_0。
- $D = \varepsilon E$，$B = \mu H$，$J = \sigma E$，对于各向同性线性介质。

1、声学基础

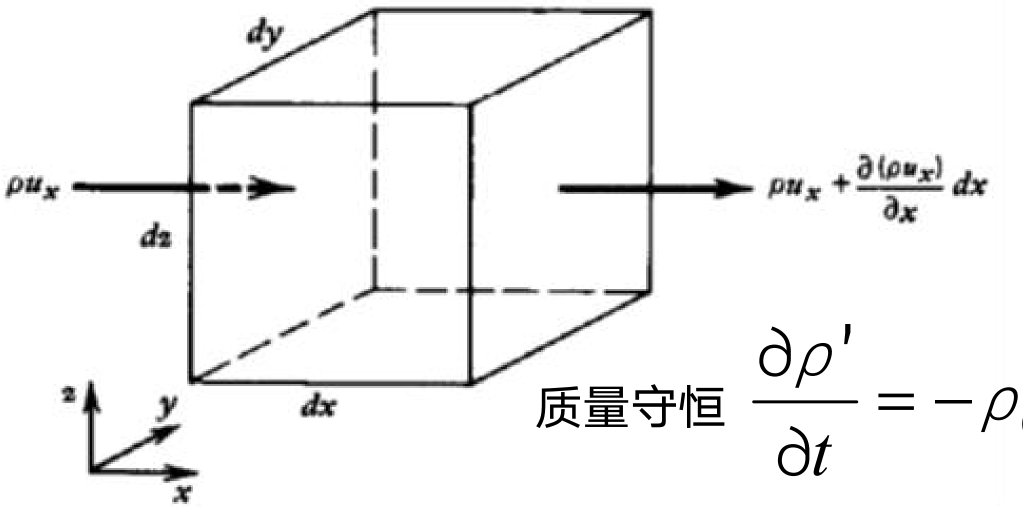
- 波动方程
- 简正模态
- 射线理论





1.1、波动方程

$$\tilde{p}(x) - \tilde{p}(x+dx) \approx -\frac{\partial p}{\partial x}dx \qquad -\frac{\partial p}{\partial x} = \rho\frac{\partial^2 u}{\partial t^2}$$



压缩　　惯性力

质量守恒 $\frac{\partial \rho'}{\partial t} = -\rho_0 \nabla\cdot\mathbf{v}$

动量守恒 $\frac{\partial \mathbf{v}}{\partial t} = -\frac{1}{\rho_0}\nabla p'(\rho)$

状态方程 $p' = \rho' c^2$

$$\Rightarrow \begin{cases} \rho\nabla\left(\frac{1}{\rho}\nabla p\right) - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 & \text{Pressure} \\ \frac{1}{\rho}\nabla\left(\rho c^2 \nabla\cdot\mathbf{v}\right) - \frac{\partial^2 \mathbf{v}}{\partial t^2} = 0 & \text{Particle Velocity} \\ \nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 0 & \text{Velocity Potential} \\ \nabla^2\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0 & \text{Displacement Potential} \end{cases}$$

$$\boldsymbol{v} = -\nabla\Phi, p = \rho\frac{\partial\Phi}{\partial t}$$

∇哈密顿算子

$\Delta=\nabla^2$拉普拉斯算子

$\rho\frac{\partial \boldsymbol{v}}{\partial t} = \nabla p$ 欧拉方程

质点振速无旋 $\boldsymbol{v} = -\nabla\Phi \qquad \mathrm{rot}\boldsymbol{v} = 0$

质点振速有旋 $\boldsymbol{v} = -\nabla\Phi + \nabla\times\boldsymbol{\Psi}$

$$\Downarrow$$

$$\left[\nabla^2 + k^2(\mathbf{r})\right]\psi(\mathbf{r},\omega) = 0$$ Helmholtz Equation

$$\nabla^2\Phi = \frac{1}{C^2}\frac{\partial^2\Phi}{\partial t^2}$$ Wave equation

$$\Phi = \phi e^{-i\omega t}$$ Harmonic solution

$$\nabla^2\phi + k^2\phi = 0$$ Helmholtz equation 双曲型

$\phi = F(x, y, z)e^{iG(x, y, z)}$

Range-dependent (3D)

- Ray theory

$F \rightarrow$ Amplitude function

$G \rightarrow$ Phase function

Transport Eq 迁移方程

Eikonal Eq 程函方程

$\phi = F(z)\, G(r)$

Range-independent

- Normal mode
  - Extended to range dependence (2D/3D)
- Multipath expansion
- Fast field

$F \rightarrow$ Normal-mode equation $\rightarrow$ Green's function

$G \rightarrow$ Bessel equation $\rightarrow$ Hankel function

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$\phi = F(r, \theta, z)\, G(r)$

Range-dependent (3D)

- Parabolic equation

抛物型

$F \rightarrow$ Parabolic equation

$G \rightarrow$ Bessel equation $\rightarrow$ Hankel function

海洋声传播模型

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- 海洋声学环境通常非常复杂，具有距离和深度有关的特性。这种环境一般不适于对声传播作简单的分析预测。即使在距离无关的环境中，也存在许多路径(多路径)，这些路径组合起来形成复杂的干涉图样。例如，收敛区是一个无法用单调几何扩展定律描述的更复杂结构的例子。声学模型在声传播预测中起着重要作用；这些模型的输入是海洋学量，最终转化为与声学有关的参数，如声速、密度和衰减。
- 海洋中的声传播用波动方程进行数学描述，波动方程的系数和边界条件由海洋环境导出。基本上有四种类型的模型(波动方程的计算机解)来描述海洋中的声传播：射线、频谱或快速场程序(FFP)、简正模态(NM)和抛物方程(PE)。射线理论是波动方程的一种渐近高频近似，而后三种模型或多或少是波动方程在各种温和约束下的直接解。高频极限不包括衍射现象。这些模型都能很好地处理海洋声环境的深度变化。同时考虑到环境水平变化(例如，倾斜的海底或空间可变的海洋学)的模型被称为距离有关模型。对于高频率(几千赫或以上)，射线理论最实用。其他三种类型在较低频率(1kHz以下)下更适用和可用。水声模型的层次结构如图1所示。这些模型的输出通常是传播损失，即在单位距离上相对于单位源强度，以分贝表示。传输损耗Transmission loss是传播损失propagation loss的负值，因此是一个正值。
- 传播模型的输出示例如图2所示，表明模型之间的一致性。然而，我们也看到不同模型之间的差异，射线理论预测的阴影区比波动理论模型更尖锐(即图8B中的10-30 km区域)；这是无限频率射线近似的预期结果。

W.A._Kuperman, Acoustics, Deep Ocean, [Encyclopedia of Ocean Sciences (Third Edition) Volume 5](), 2019, Pages 296-307

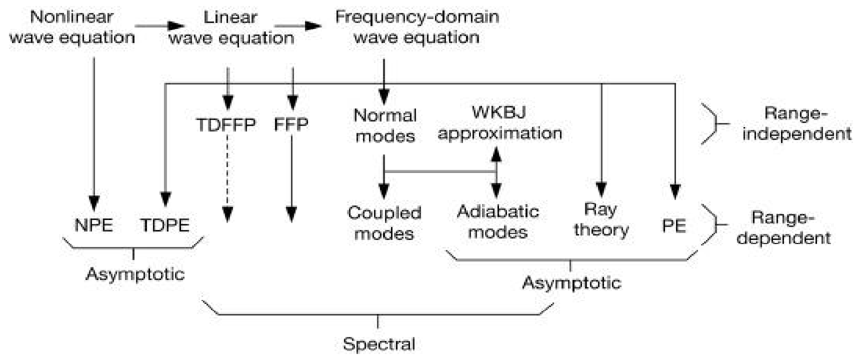

图1 水声模型层次结构。TD表示时域。NPE是描述高振幅(如冲击波)传播的非线性抛物方程。箭头指向模型的派生流程。

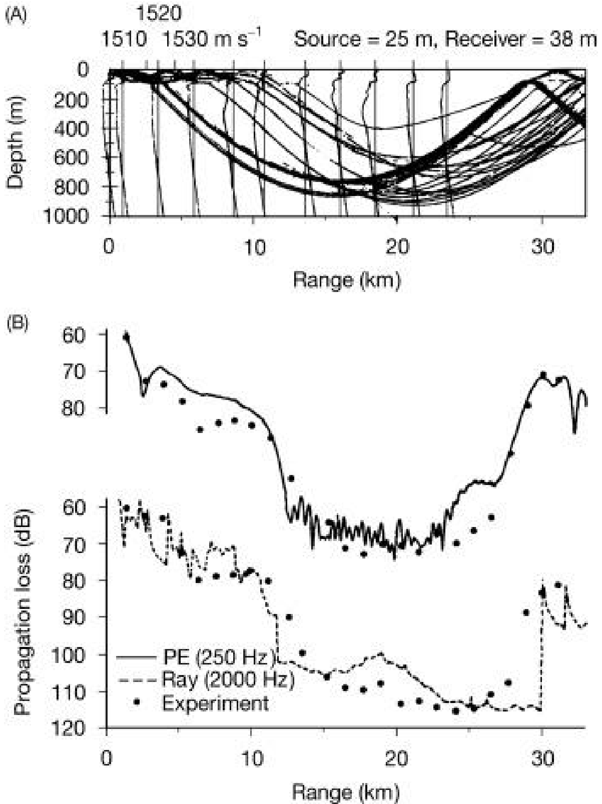

图2 一个距离有关的深水案例的模型和数据比较。(A)作为距离函数的声速剖面，以及显示海面波导传播分解的射线轨迹。(B) 250Hz数据的抛物线方程与2000Hz数据的射线理论的比较。

Model type	Applications							
	Shallow water				Deep water			
	Low frequency		High frequency		Low frequency		High frequency	
	RI	RD	RI	RD	RI	RD	RI	RD
Ray theory	○	○	◐	●	◐	◐	●	●
Normal mode	●	◐	●	◐	●	◐	◐	○
Multipath expansion	○	○	◐	◐	◐	◐	●	◐
Fast field	●	◐	●	◐	●	◐	◐	◐
Parabolic equation	◐	●	○	○	◐	●	◐	◐

Low frequency (<500 Hz)
High frequency (>500 Hz)

RI: Range-independent environment
RD: Range-dependent environment

● Modeling approach is both applicable (physically) and practical (computationally)

◐ Limitations in accuracy or in speed of execution

○ Neither applicable nor practical

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1.2、简正模态

$$\phi = F(z)\cdot S(r)$$

$$\frac{d^2F}{dz^2} + (k^2 - \xi^2)F = 0$$

$$\frac{d^2S}{dr^2} + \frac{1}{r}\frac{dS}{dr} + \xi^2 S = 0$$

$$\phi = \int_{-\infty}^{\infty} G(z, z_0; \xi)\cdot H_0^{(1)}(\xi r)\cdot \xi\, d\xi$$

G is Green's function, $H_0^{(1)}$ is a zero-order Hankel function of the first kind

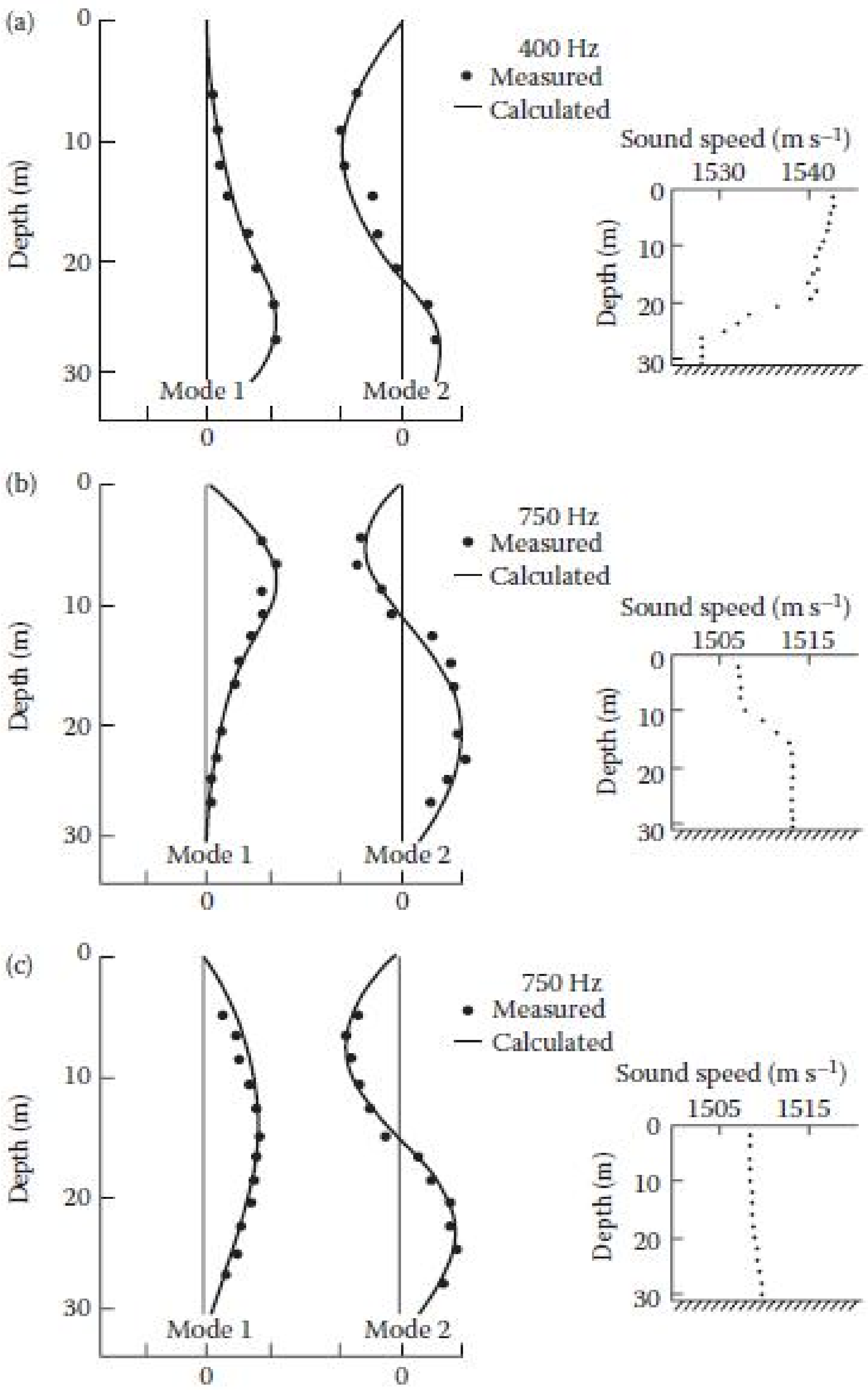
$$\phi = \oint \sum \frac{u_n(z)\cdot u_n(z_0)}{\xi^2 - \xi_n^2} H_0^1(\xi r)\cdot \xi\, d\xi + \text{branch-cut integral}$$

$$H_0^{(1)}(\xi r) \approx \sqrt{\frac{2}{\pi \xi r}} e^{i(\xi r - \pi/4)} \quad \text{for } \xi r \gg 1$$

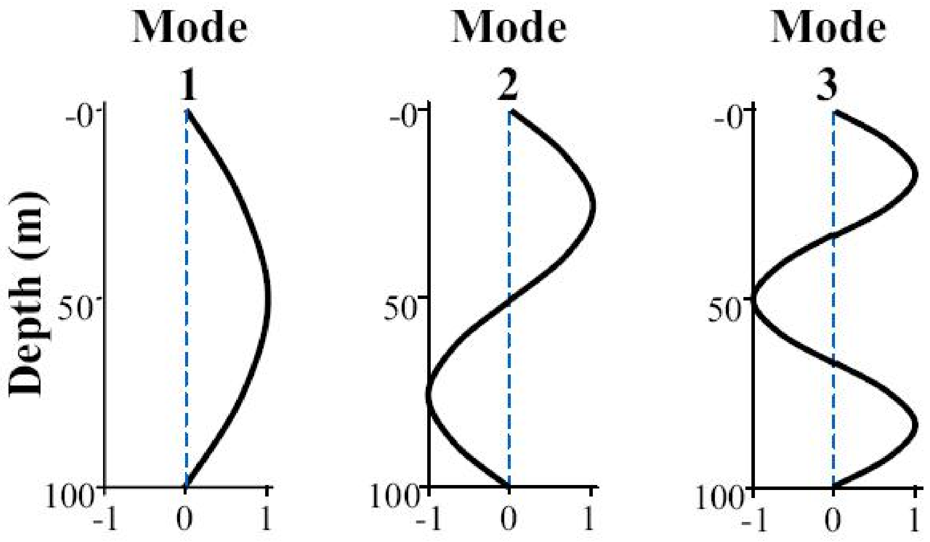
$$\phi = g(r,\rho)\sum \frac{u_n(z)\cdot u_n(z_0)}{\sqrt{\xi_n}} \exp\left[i(\xi_n r - \pi/4)\right]\exp(-\delta_n r)$$

$g(r,\rho)$ is a general function of range (r) and water density (ρ).

简正截止
模态色散
模态干涉
模态转换



理想波导Ideal Waveguide



Depth dependence of the first 3 normal modes in ideal waveguide at 20Hz.

First Three Modal Shapes

Modal Expansion

$$\psi(r,z) = -\frac{iS_\omega}{2D}\sum_{m=1}^{\infty}\sin(k_{zm}z)\sin(k_{zm}z_s)H_0^{(1)}(k_{rm}r)$$

$$k_{zm} = \frac{m\pi}{D}$$ Vertical Wavenumber

$$f_{0m} = \frac{mc}{2D}$$ Modal Cut-off Frequency

Modal Phase Velocity

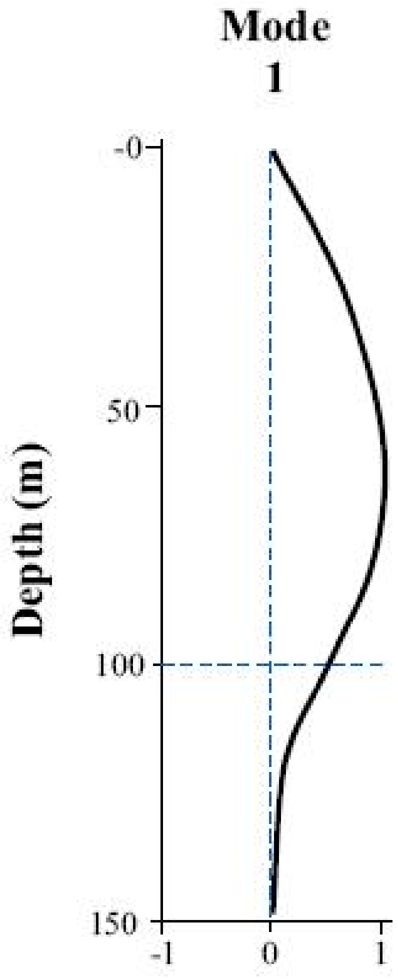
$$v_m = \frac{\omega}{k_{rm}}$$

$$k_{rm} = \sqrt{k^2 - k_{zm}^2} = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{m\pi}{D}\right)^2}$$ Horizontal Wavenumber

Modal Group Velocity

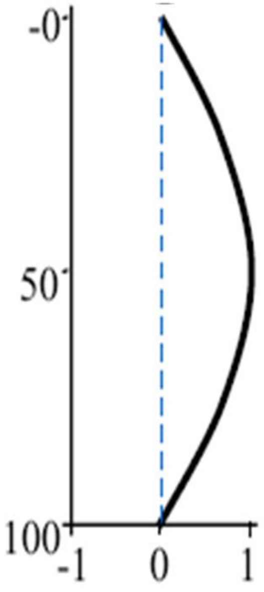
$$u_m = \frac{d\omega}{dk_{rm}}$$

匹科瑞斯波导Pekeris Waveguide



Pekeris Waveguide

Mode 1



Ideal Waveguide

Mode 1

Modal Expansion

$$\psi(r,z) \approx -\frac{iS_\omega}{2D}\sum_{m=1}^{\infty} a_m(k_{rm})\sin(k_{zm}z)\sin(k_{zm}z_s)H_0^{(1)}(k_{rm}r)$$

Modal Cut-off Frequency

$$f_{0m} = \frac{(m-0.5)c_1c_2}{2D\sqrt{c_2^2 - c_1^2}}$$

1.3、射线理论

振幅-相位表示

$$\phi = Ae^{iP}$$

程函方程

$$\frac{1}{A}\nabla^2 A - [\nabla P]^2 + k^2 = 0$$

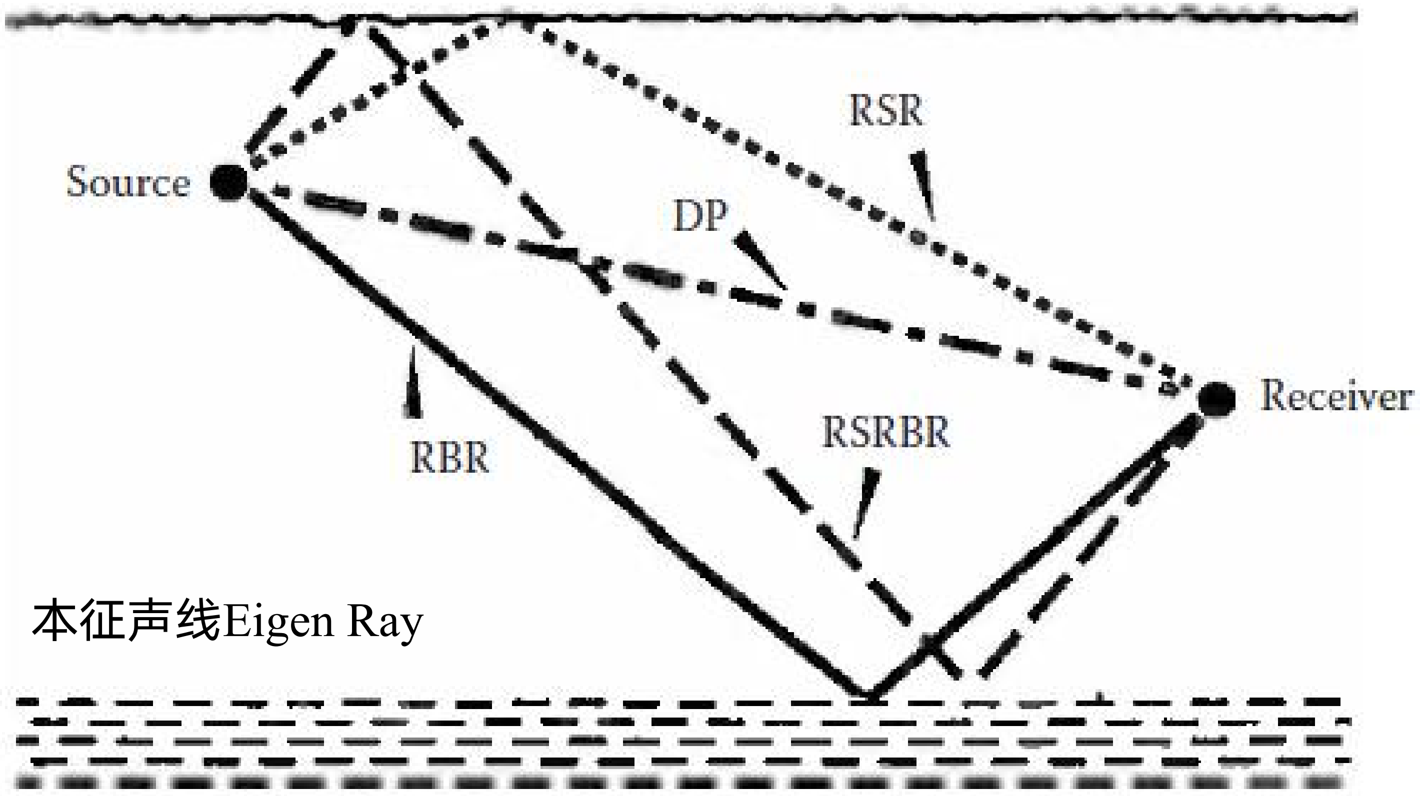
$$[\nabla P]^2 = k^2 \qquad \frac{1}{A}\nabla^2 A \ll k^2$$

迁移方程

$$2[\nabla A \cdot \nabla P] + A\nabla^2 P = 0$$

$$f > 10\frac{c}{H}$$

高斯射线
距离有关



f is the frequency, H is the duct depth, and c is the speed of sound

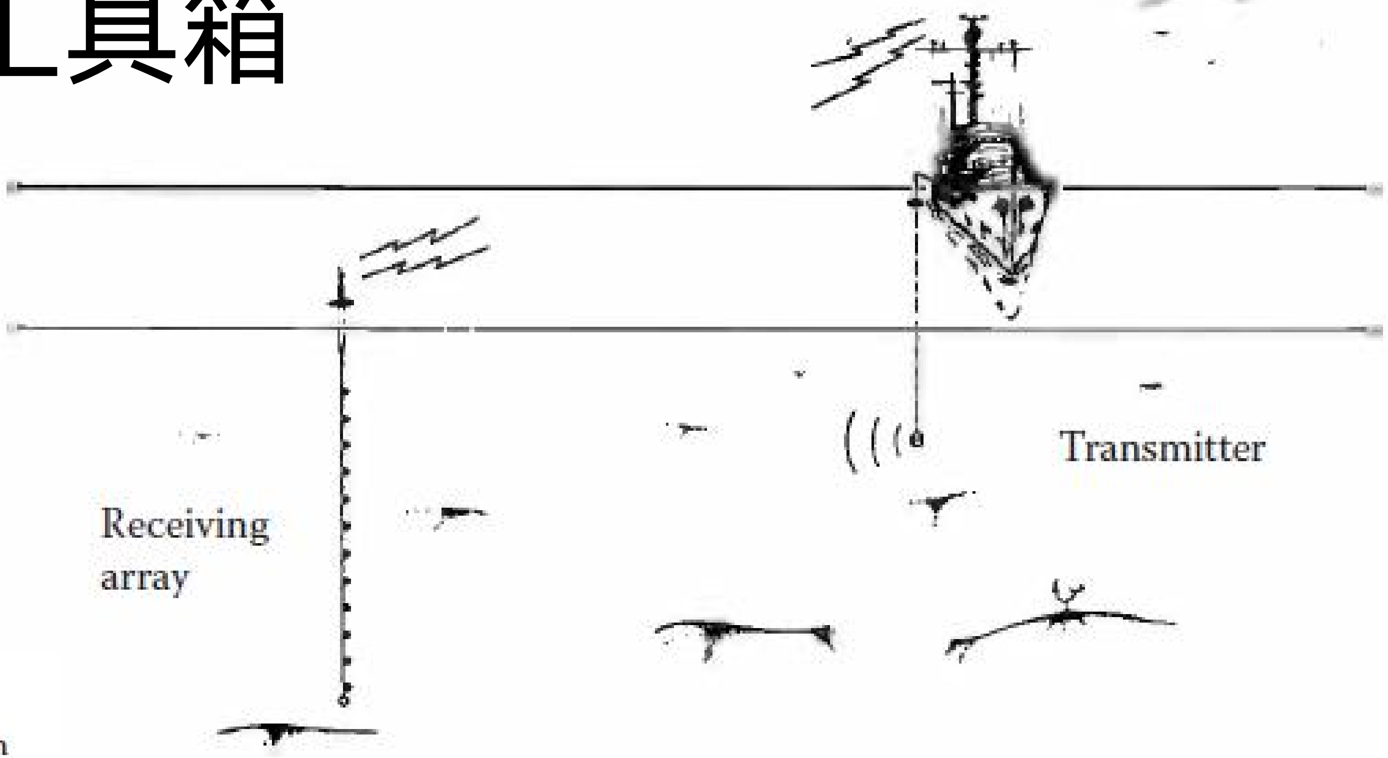
波粒二象性 vs 量子理论

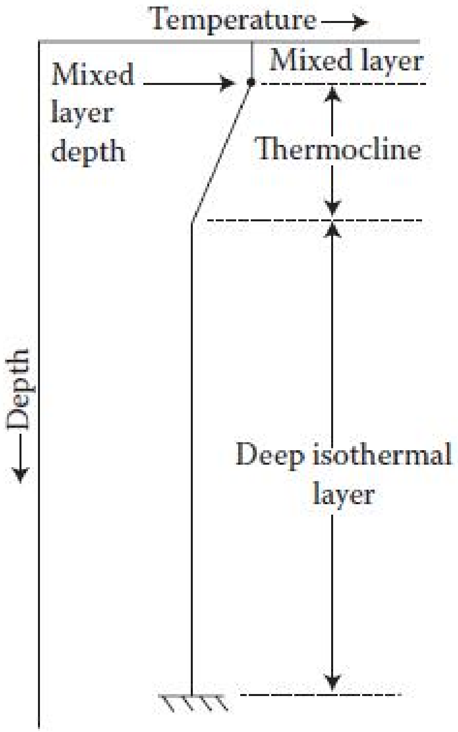
wave-particle dualism

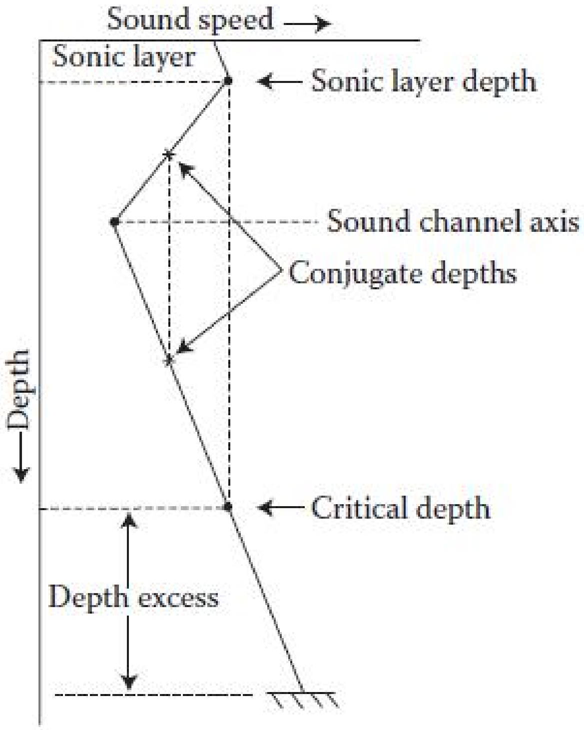
quantum theory

2、声学工具箱

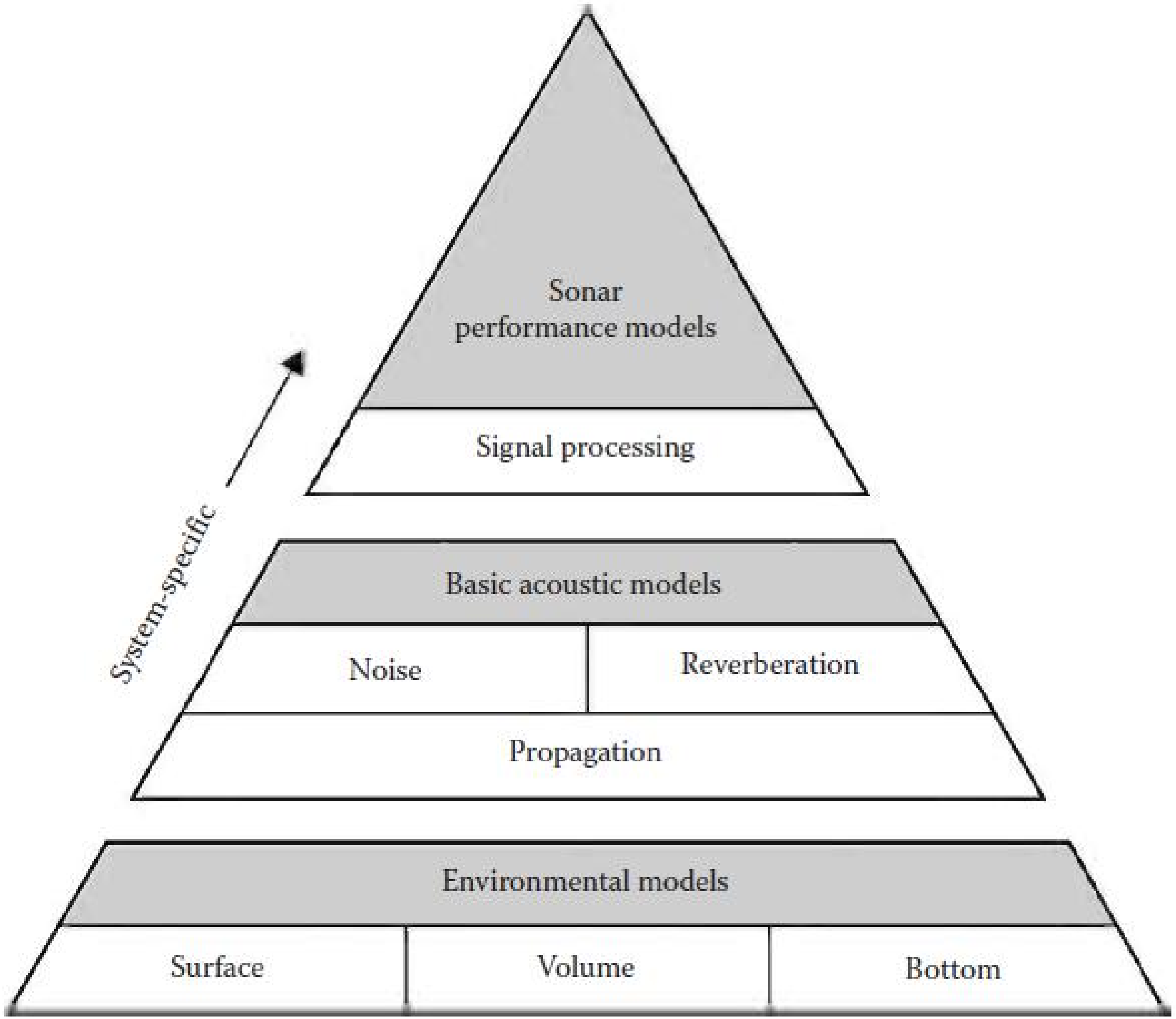
- 声场建模
- Kraken模型
- Bellhop模型



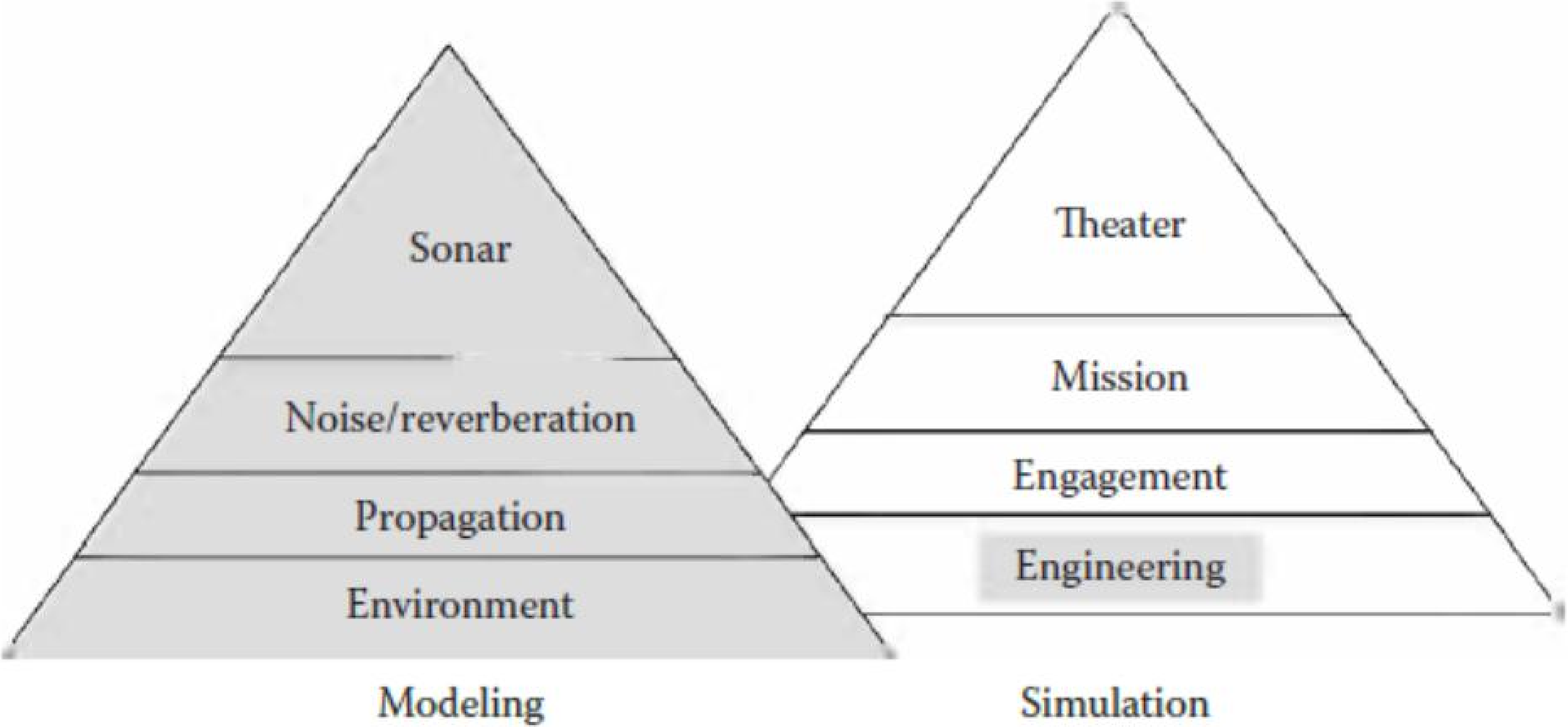


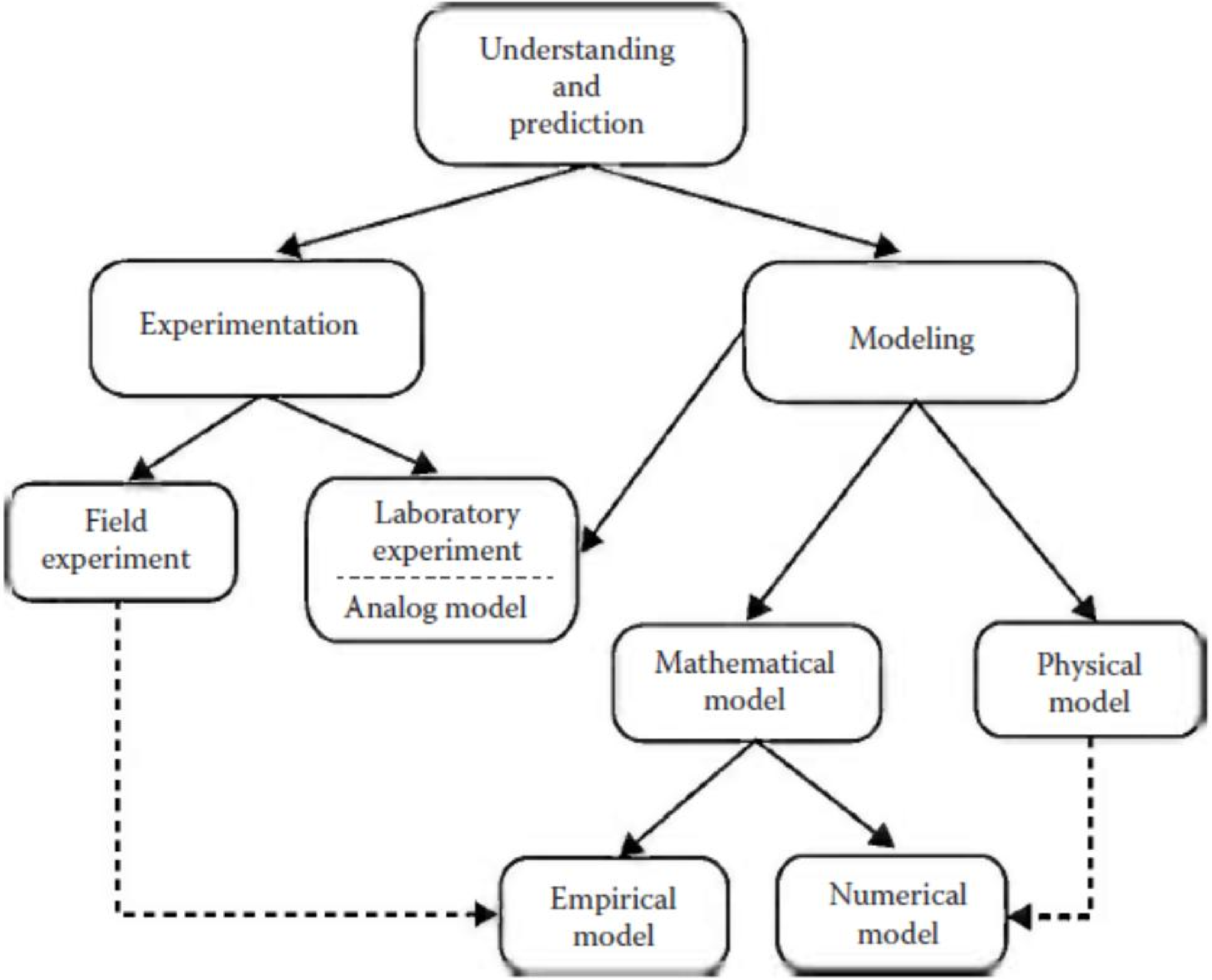


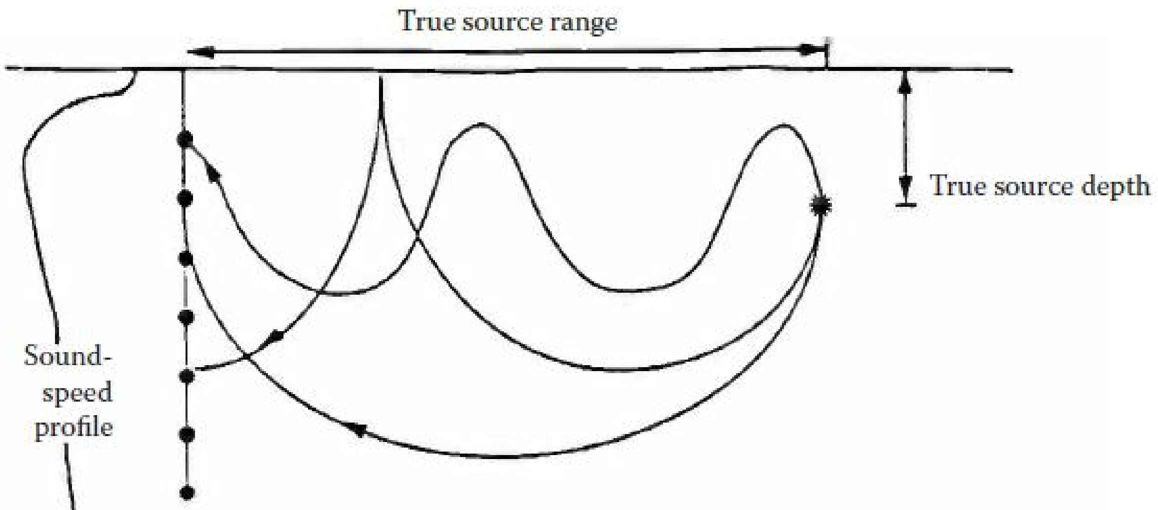
2.1、声场建模

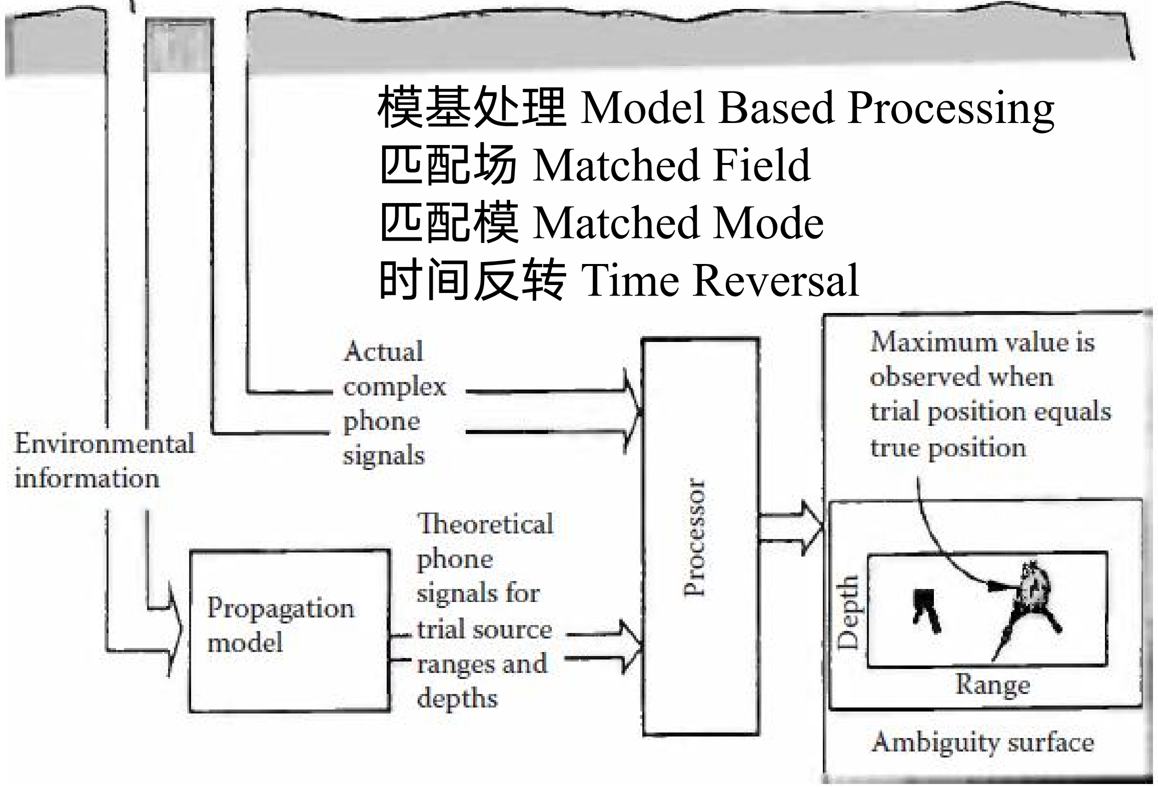


Sonar
performance models
Signal processing
System-specific
Basic acoustic models
Noise
Reverberation
Propagation
Environmental models
Surface
Volume
Bottom

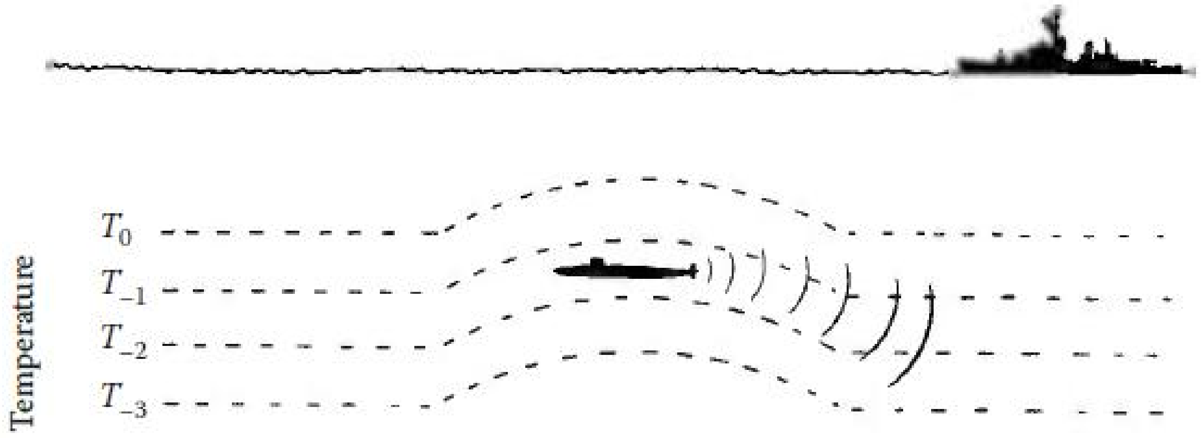

Sonar
Noise/reverberation
Propagation
Environment
Modeling
Theater
Mission
Engagement
Engineering
Simulation


Understanding and prediction
Experimentation
Modeling
Field experiment
Laboratory experiment
Analog model
Mathematical model
Physical model
Empirical model
Numerical model

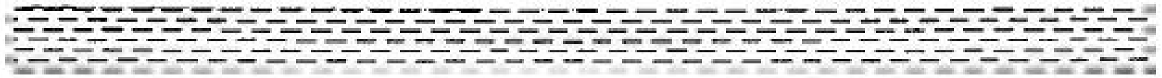




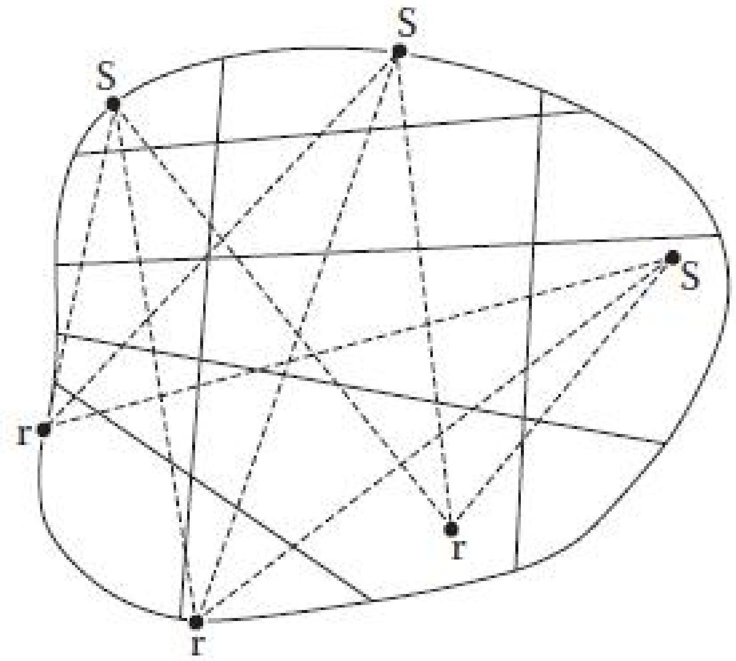
模基处理 Model Based Processing
匹配场 Matched Field
匹配模 Matched Mode
时间反转 Time Reversal



潜艇隐身



海洋参数声学反演

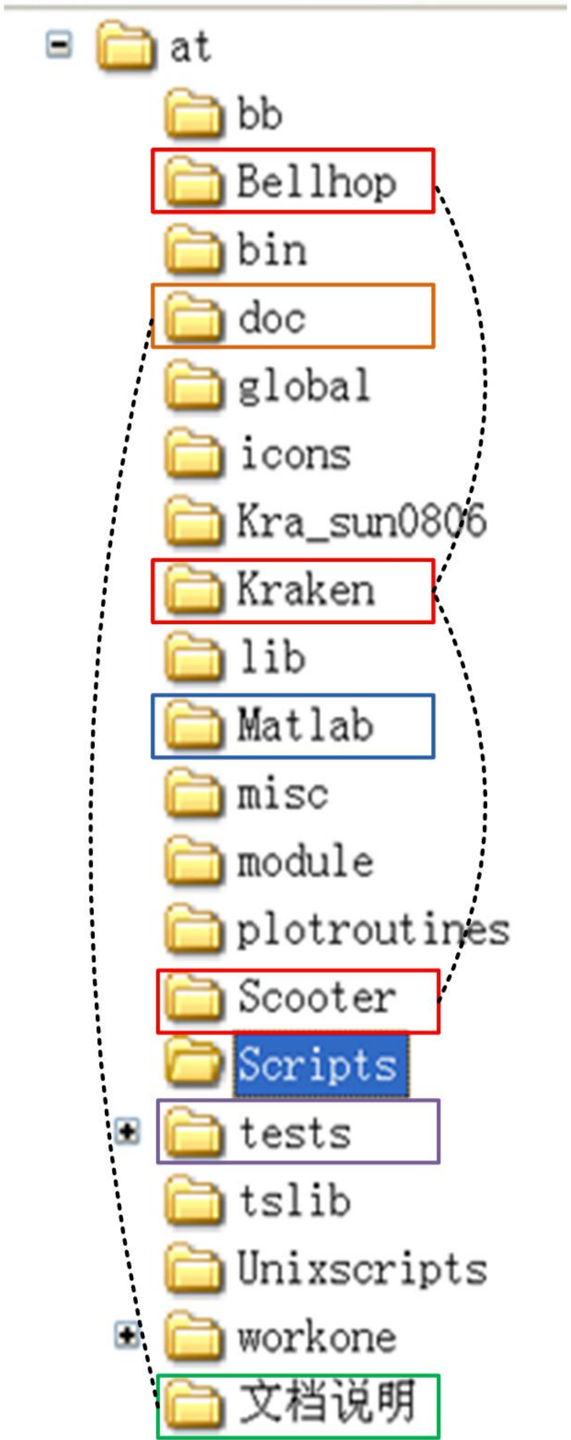


What’s AT

AT是声学工具箱AcousticToolbox的英文字头缩写，是由Michael Porter等开发的用于声场建模计算的开源水声场计算软件，主要程序用Fortran90语言编写，后置处理和显示部分则用Matlab、Python编写。AT代表了已被广泛认可的现代海洋计算声学的高水准。

简单实用、精度较高、速度较快。已被广泛用于海洋声学计算。

除AT之外，还有ComSol多物理场有限元软件等。



2.2、Kraken简正模型

语法:

1) ！ c:\at\bin\kraken.exe < EnvFile.env（命令窗口调用kraken.exe）

2) ！ c:\at\bin\kraken EnvFile（命令窗口调用kraken.bat）

3) eval ([‘! c:\at\scripts\kraken ’ EnvFile]);（用于程序调用kraken.bat ）

4) 批处理文件（bat）比执行文件（exe）多一个计算声场的函数field.bat，需要输入文件field.flp

5) Krakenc用于计算复数本征值问题，后缀c表示complex。

6) 两个重要的输入配置文件：EnvFile.env和field.flp，EnvFile可以任意取名，field.flp则不能更名。

2.2.1、Kraken输入配置文件env

Kraken.exe需要*.env文件计算声场模态*.mod

```
'Pekeris problem'
100.0
1
'NVF'
500  0.0  100.0
    0.0  1500.0 /
  100.0  1500.0 /
'A'  0.0
  100.0  2000.0  0.0  2.0 /
1400.0  2000.0              ! CMIN CMAX (m/s)
100.0                       ! RMAX (km)
1                           ! NSD
50.0 /                      ! SD(1:NSD) (m)
501                         ! NRD
0.0 100.0 /                 ! RD(1:NRD) (m)
```

2.2.2、Kraken输入配置文件flp

Field.exe需要field.flp文件计算整个声场*.shd。

```
/,                    ! TITLE takes from *.mod file
'RA'                  ! OPT 'X/R' (coords), 'C/A' (couple/adiab)
9999,                 ! M  (number of modes to include)
1                     ! NPROF number of SSP
 0.0                  ! RPROF(1:NPROF) (km)
1001                  ! NR number of range
 0.01  1.01/          ! R(1:NR )   (km)
1                     ! NSD number of source depth
 10.0 /          ! SD(1:NSD)   (m)
1                     ! NRD number of receiver depth
 40.0 /          ! RD(1:NRD)   (m)
1                     ! NRR = NRD (must be) number of receiver range
 0.0  /          ! RR(1:NRR)   (m) means perfect vertical array
```

2.2.3、Kraken’s Example

Kraken.bat需要两个输入文件:

pekeris_kraken.env和field.flp

主要程序代码:

%==running kraken and producing .mod & .shd files ==

! c:\at\scripts\kraken pekeris_kraken;%（调用kraken.bat）

%==plot modes ==

plotmode(‘pekeris_kraken.mod’);

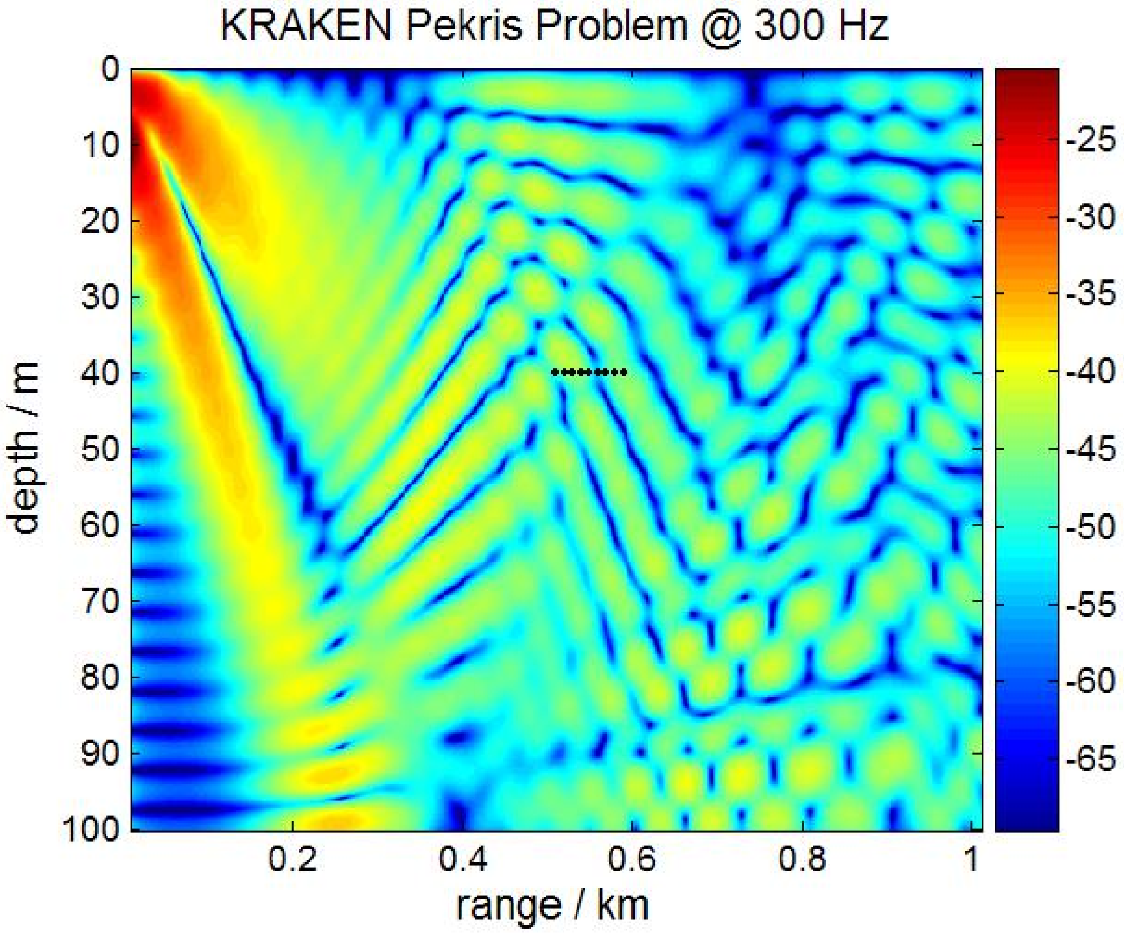
%== reading from the shade file ==

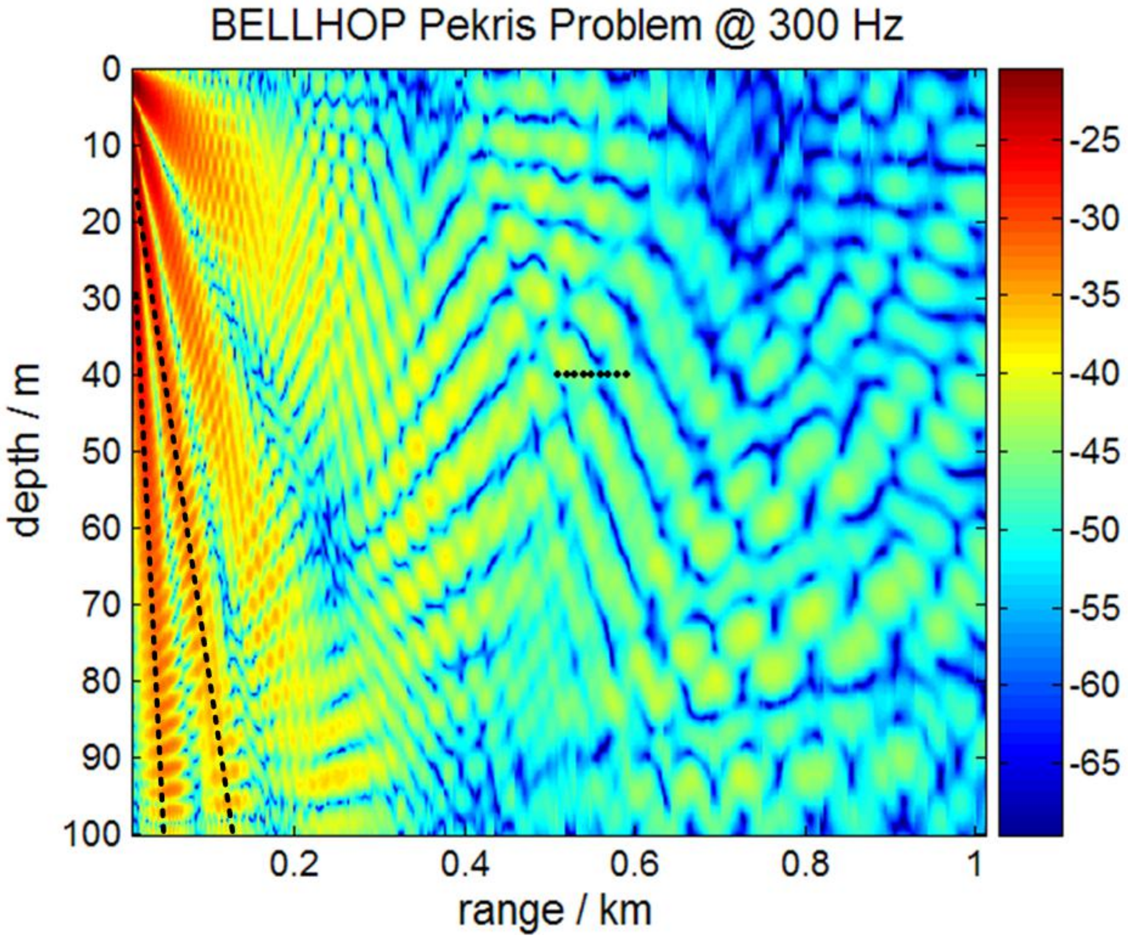
[pltitl,freq,nsd,nrd,nrr,sd,rd,rr,p1] = read_shd((‘pekeris_kraken.shd’);

%==transmission loss ==

tlt(1, :) = 20.0 * log10(abs(p1(ird, :))); % ird – receiver depth

Kraken vs Bellhop





距离 - 深度平面上的声场分布

练习：利用AT进行声场建模仿真

发射信号x(p, t, f)相当于水声信道的输入信号，若视水声信道为线性时不变系统，其冲激响应函数为h(p, t, f)，则接收信号y(p, t, f)相当于信道的输出信号。符号p代表空间位置，t代表时间，f代表频率。

接收声场仿真的原理框图

$$y(p,t,f) = \int_{-\infty}^{T} h(p, t-\tau, f)\, x(p, \tau, f)\, d\tau$$

3、水声传感器

- 水听器Hydrophone for Receiving Sound
- 换能器Transducer for Transmitting Sound
- 传感器阵列 Sensor Array

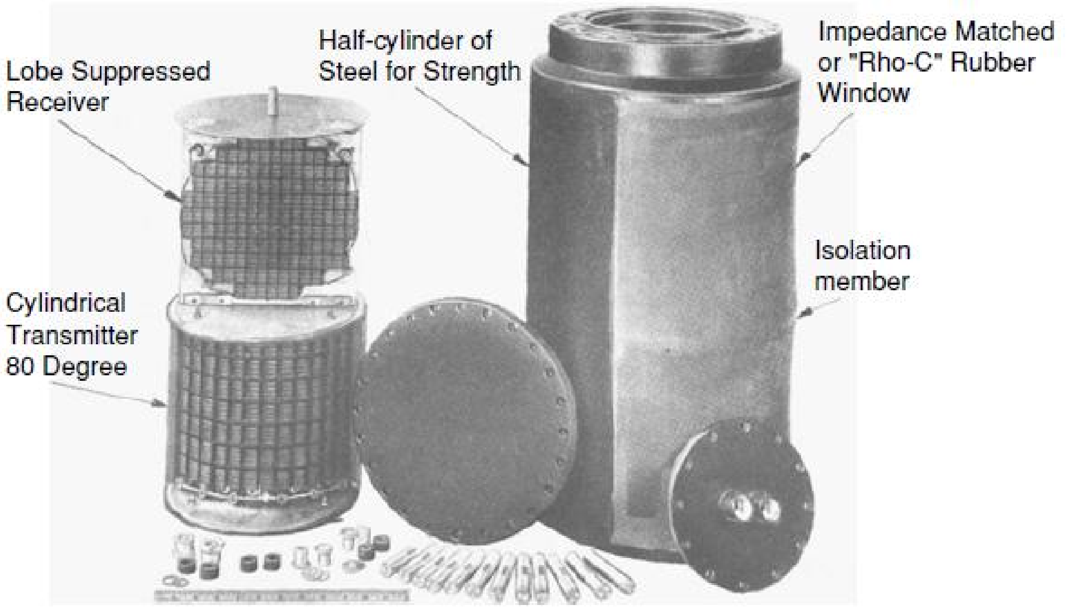
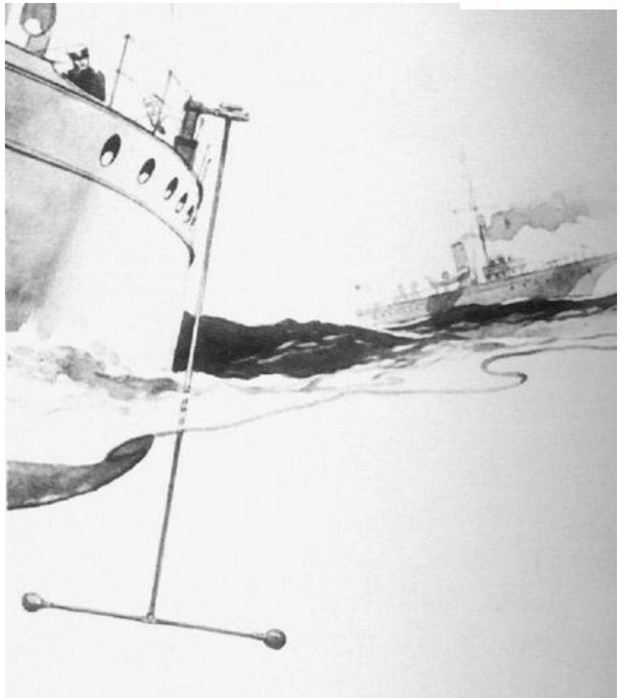


FIGURE 1.7. Early sonar array system with cylindrical transmitter for wide beam pattern and planar array for narrow beam receiving. A baffle between the two minimizes the sound fed from transmitter to receiver [7].



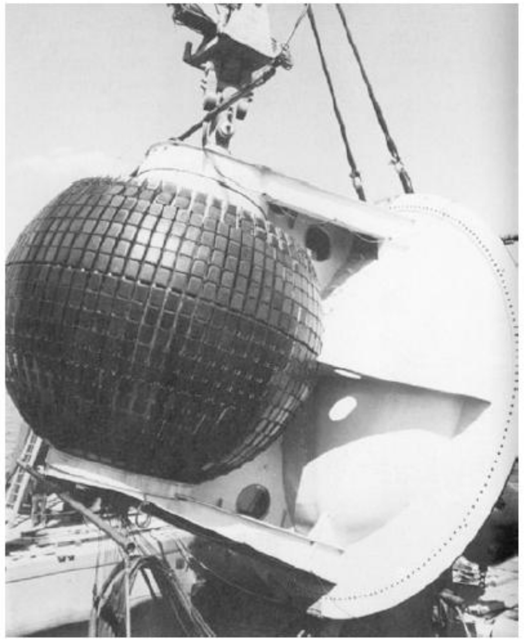
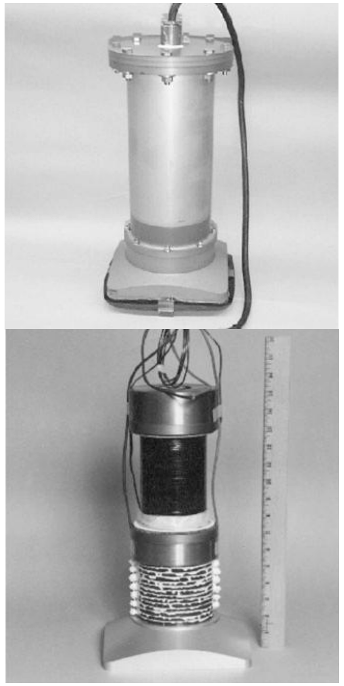


FIGURE 1.15. Submarine sonar spherical array undergoing tests.



3.1、水听器

- 声压灵敏度
- 接收指向性

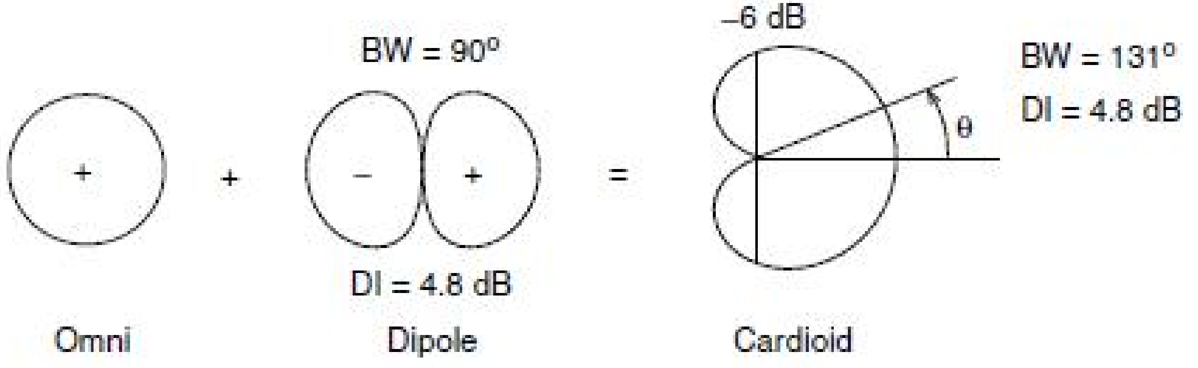


FIGURE 4.30. Synthesis of a cardioid pattern.

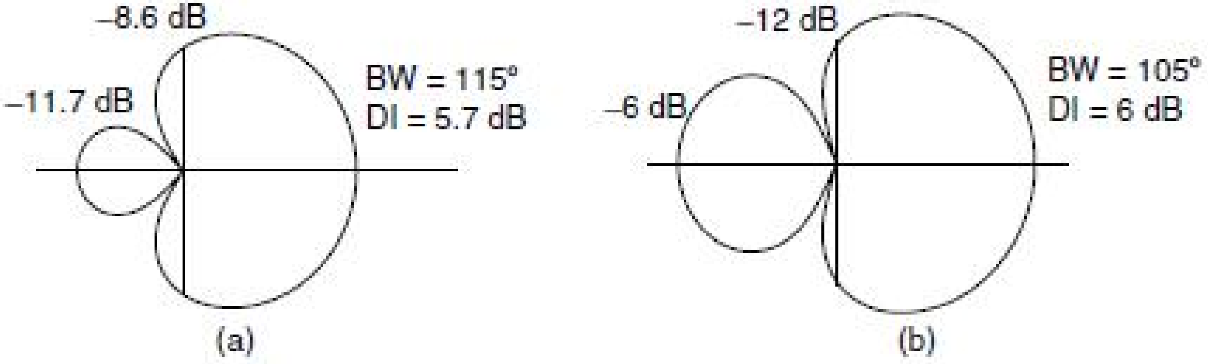


FIGURE 4.31. Super cardioid (a) and hyper cardioid (b) beam patterns.

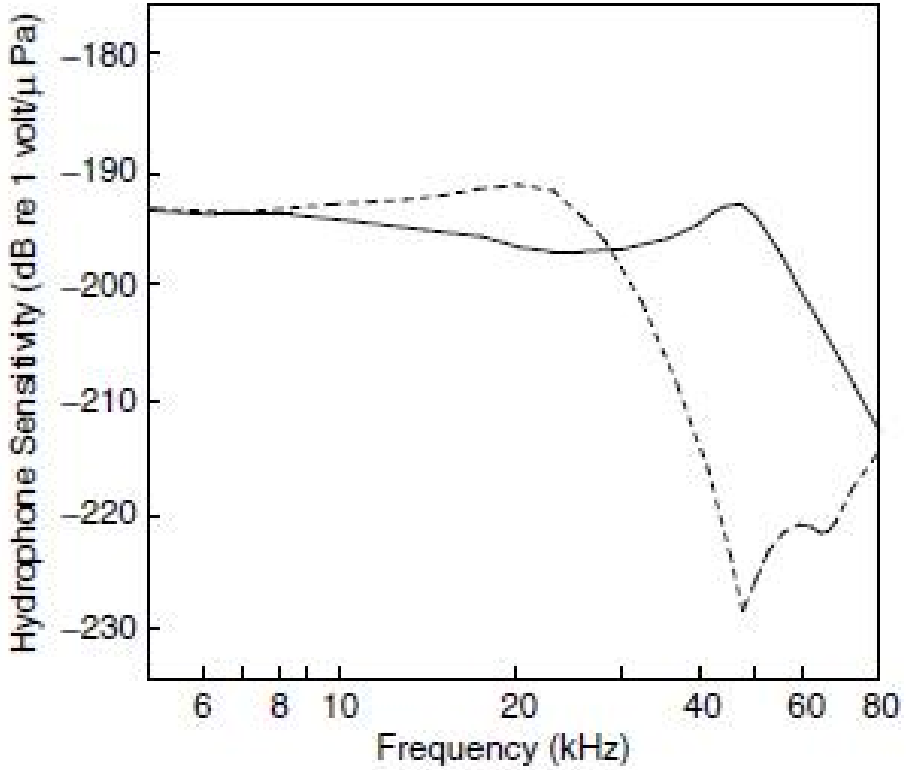


FIGURE 4.11. Comparison of theoretical RVS results for a sphere (—) and a cylinder (- - -) of diameter and height equal to the diameter of the sphere with radius a = 0.0222m [3].

3.2、换能器

- 发射电压响应
- 发射指向性

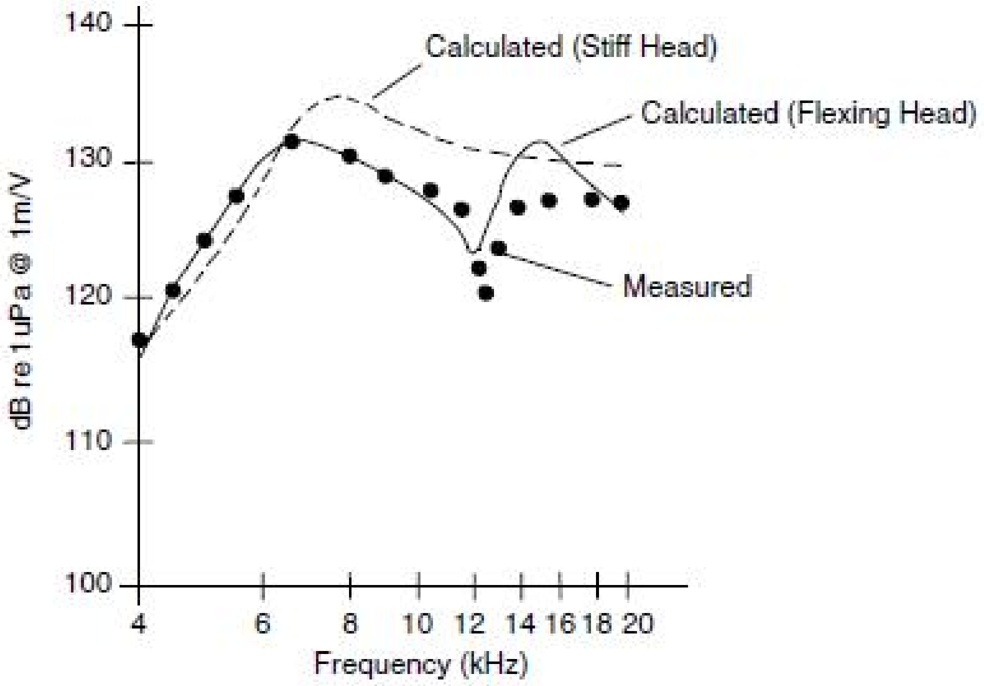


FIGURE 3.21. Comparison of the stiff (– – –) and flexing (—) head calculated responses with the measured (• • •) constant voltage transmitting response of flexing head Tonpilz transducer [23].

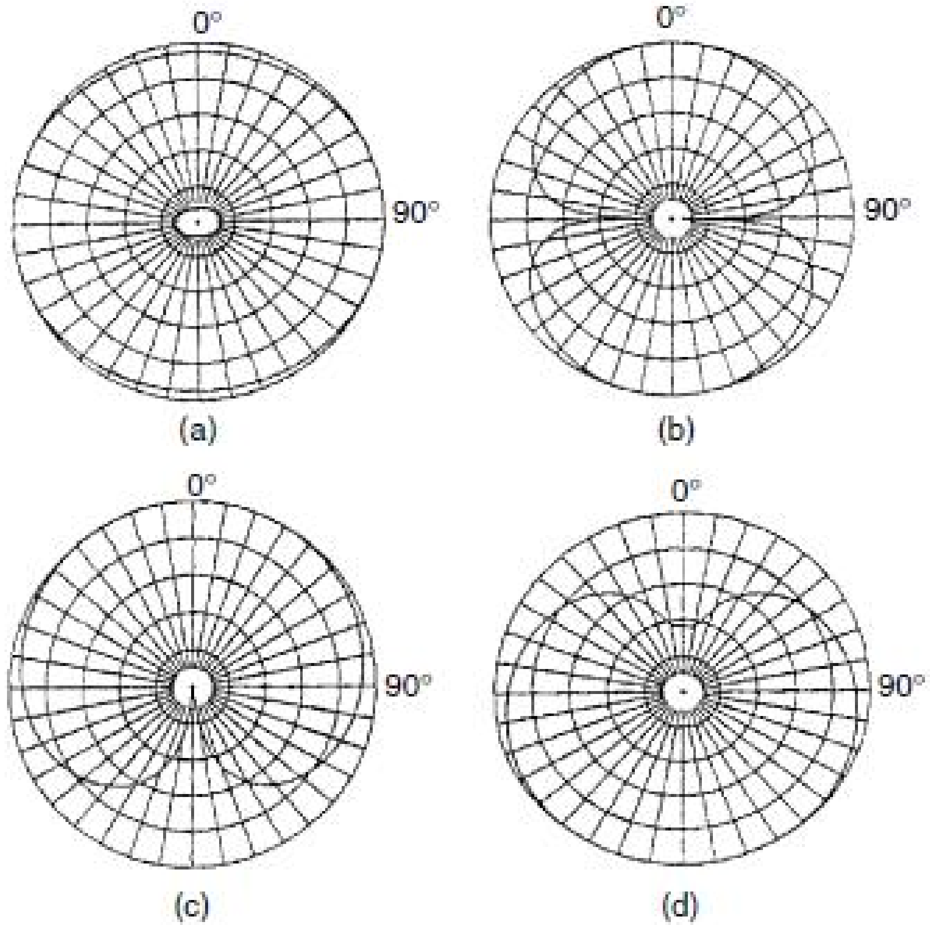


FIGURE 3.42. Measured single element 900 Hz radiation patterns operating in the (a) quadrupole mode, (b) dipole mode, (c) directional mode, and (d) directional mode drive leads reversed (10 dB/division) [56b].

3.3、传感器阵列

矩形面阵

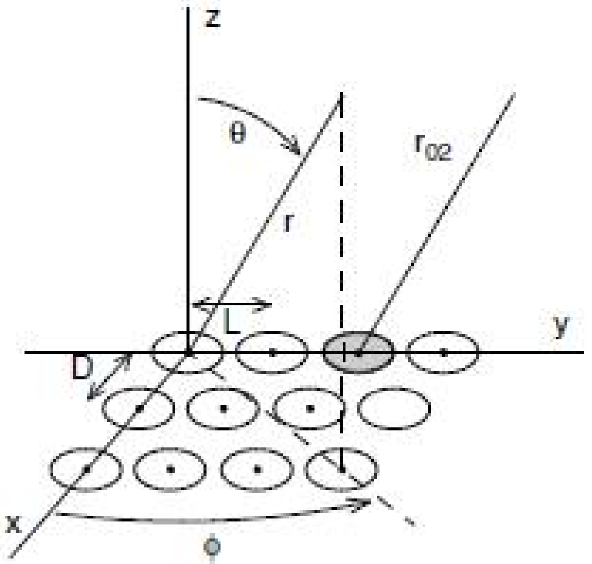


FIGURE 5.4. Coordinates for calculating the far-field of a rectangular array of identical piston transducers. The shaded transducer is located at n = 0, m = 2.

$$p(r,\theta,\phi)=\left[\frac{jNM\rho ckuAf(\theta,\phi)e^{-jkR}}{2\pi r}\right]\times\frac{\sin\left(\frac{1}{2}NkD\sin\theta\cos\phi\right)}{N\sin\left(\frac{1}{2}kD\sin\theta\cos\phi\right)}\,\frac{\sin\left(\frac{1}{2}MkL\sin\theta\sin\phi\right)}{M\sin\left(\frac{1}{2}kL\sin\theta\sin\phi\right)}$$

圆形阵列

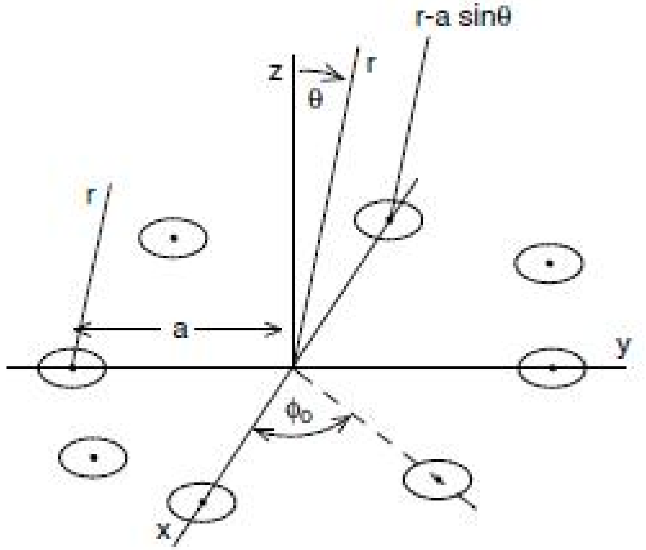


FIGURE 5.5. Coordinates for calculating the far-field in the xz plane of a circular array of identical transducers. The far-field is the same in the xz, yz and other planes passing through two transducers and the center of the array.

$$p(r,\theta)=\frac{j\rho ckuA}{2\pi}f(\theta)\frac{e^{-jkr}}{r}\left[2\cos(ka\sin\theta)+2+4\sum_{n=1}^{\frac{N}{4}-1}\cos(ka\sin\theta\cos n\phi_0)\right]$$

波束形成Beamforming

波束图：主瓣、旁瓣、栅瓣

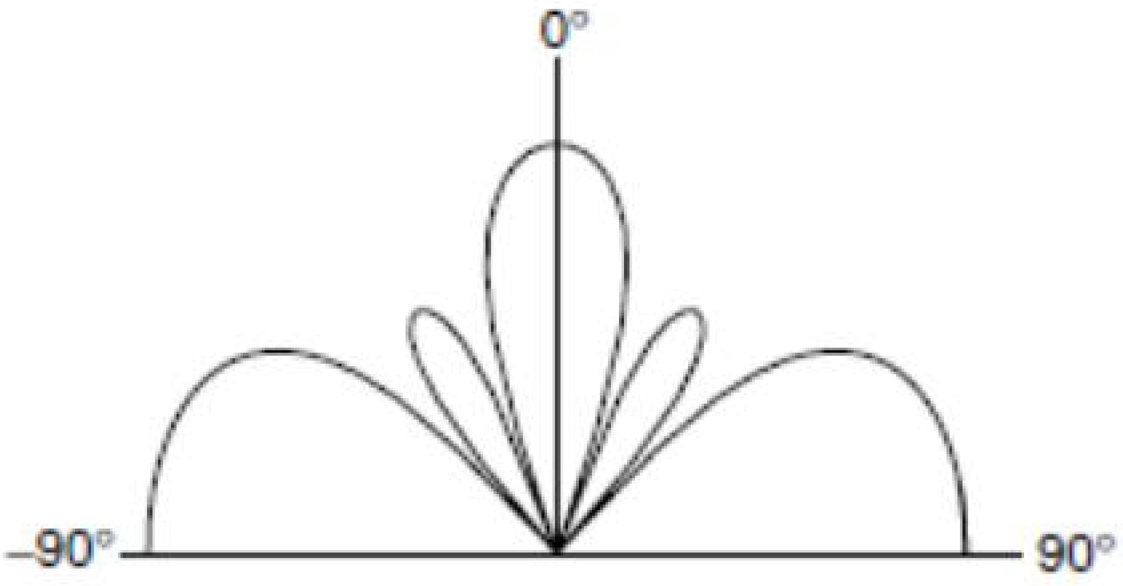


FIGURE 5.6. Example of grating lobes at +/ − 90° for a line array of three transducers with kD = 2π.