# Discovery of Sound in the Sea

# 2022 Webinar Series
# Acoustic Propagation Modeling

THE UNIVERSITY OF RHODE ISLAND

INSPIRE ENVIRONMENTAL

DEPARTMENT OF THE NAVY ONR Science & Technology

NSF

NOAA

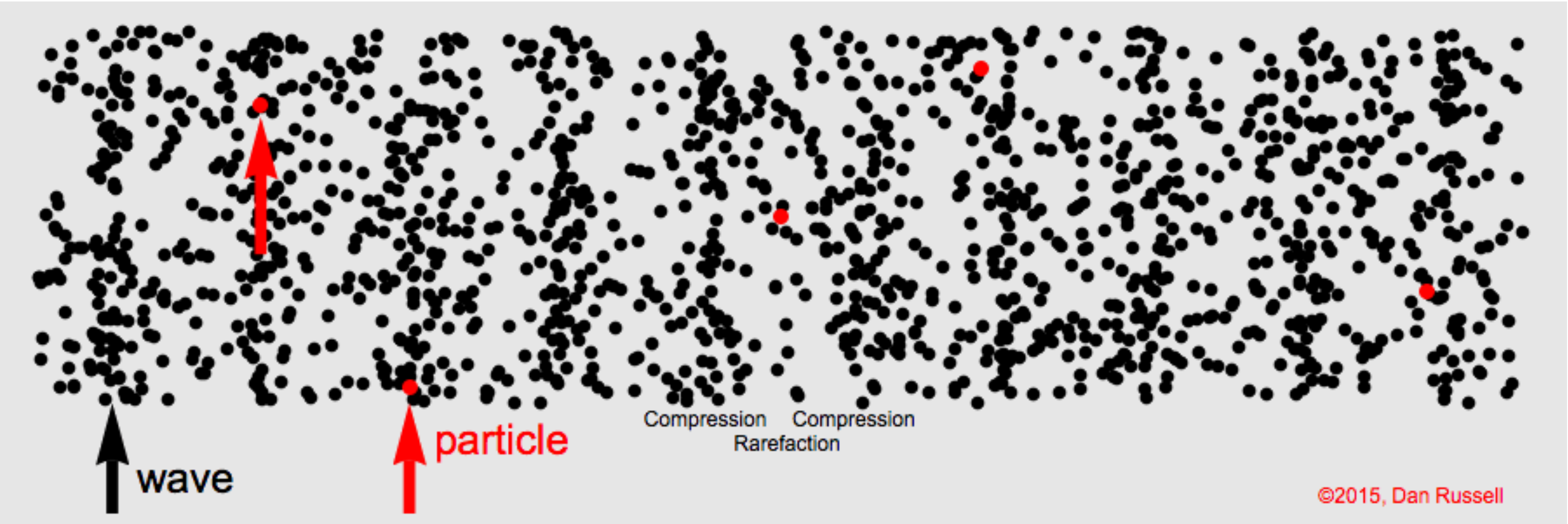
# Who is this for?

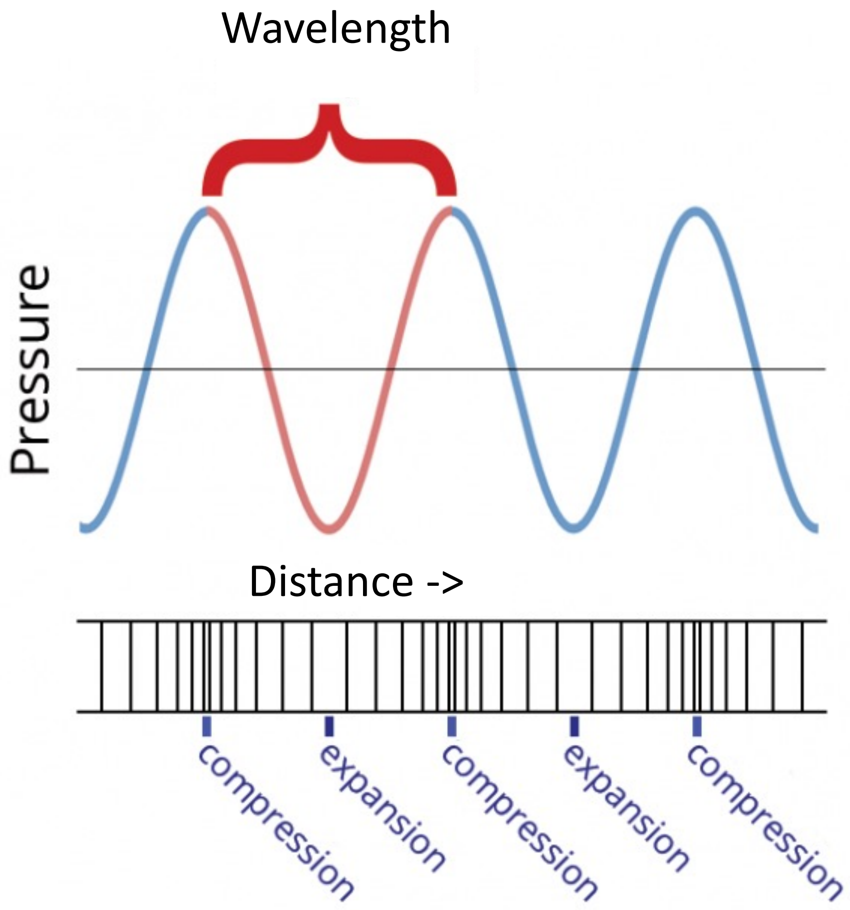
- People trying to understand a report or talk that contains modeling.
- Decision maker trying to evaluate and interpret modeling results.
- Those seeking general introduction and resources for learning more.

# It’s better to be bored than lost

- Preliminaries: review of wavelength and Fourier synthesis.
- Spherical, cylindrical, and “practical” spreading.
- Water and bottom attenuation.
  - Damped cylindrical spreading model for pile driving.
- Information required for more detailed numerical models.
- Three most common “complex” models:
  - Ray tracing
  - Normal Modes
  - Parabolic Equation (PE)
- Source directionality

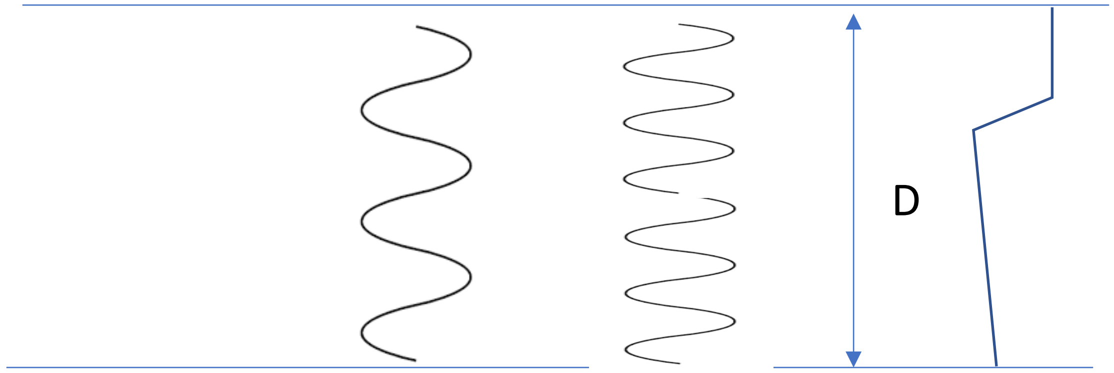
# Review: acoustic wavelength




- Wavelength=sound speed / frequency=1500/$f$
- As frequency increases, wavelength shrinks.
- 1.5 kHz sound has 1 m wavelength in water.
- 150 Hz sound has 10 m wavelength
- 15 kHz has 10 cm (0.1 m) wavelength.

# Wavelength relative to ocean depth determines whether “shallow” or “deep” ocean




- How many acoustic wavelengths fit in your local ocean?
- 10 wavelengths is a good rule of thumb:

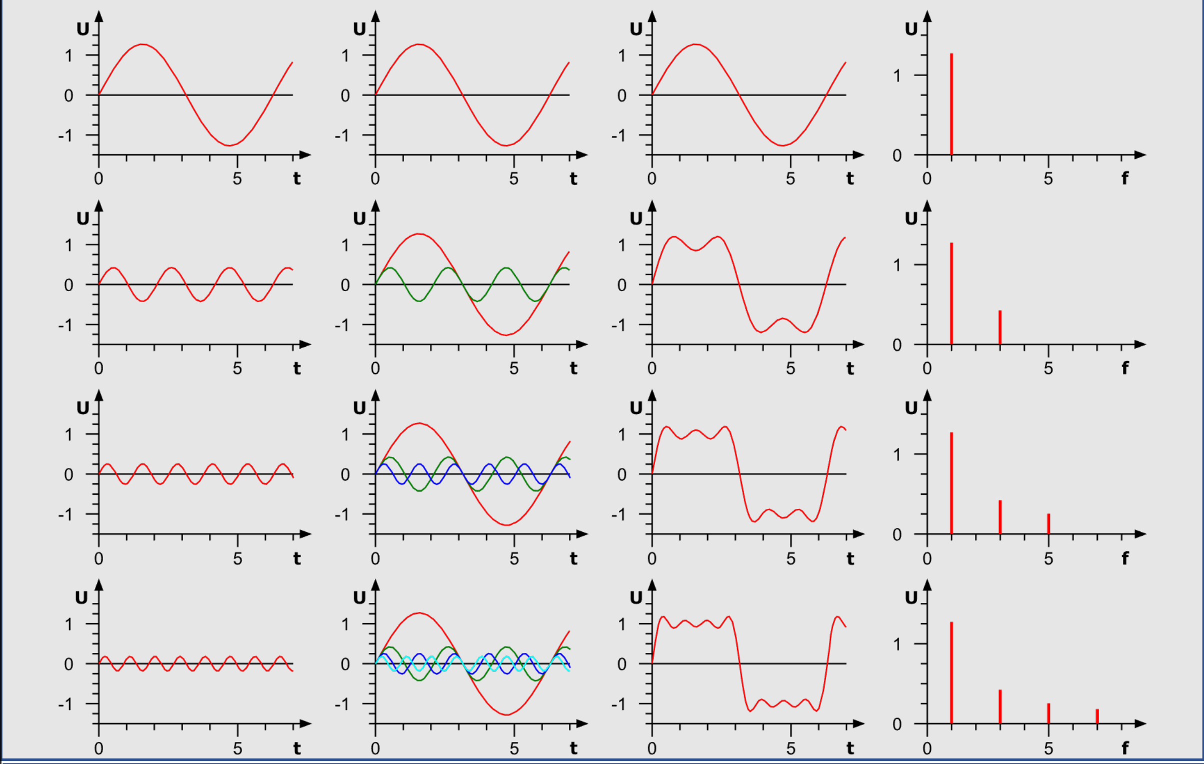
$$D' = 10 * c/f$$

- If *D’>D, “deep water,”* then then frequency and wavelength have less impact on modeling.
- If *D’<D, “shallow water,”* then then frequency and wavelength cannot be ignored, and modeling results strongly depend on frequency.
- Example: for 1.5 kHz, water depth needs to be >10 m in order to discount frequency effects.
- Note: source depth and sound speed profile scale may also cause strong dependence on frequency.

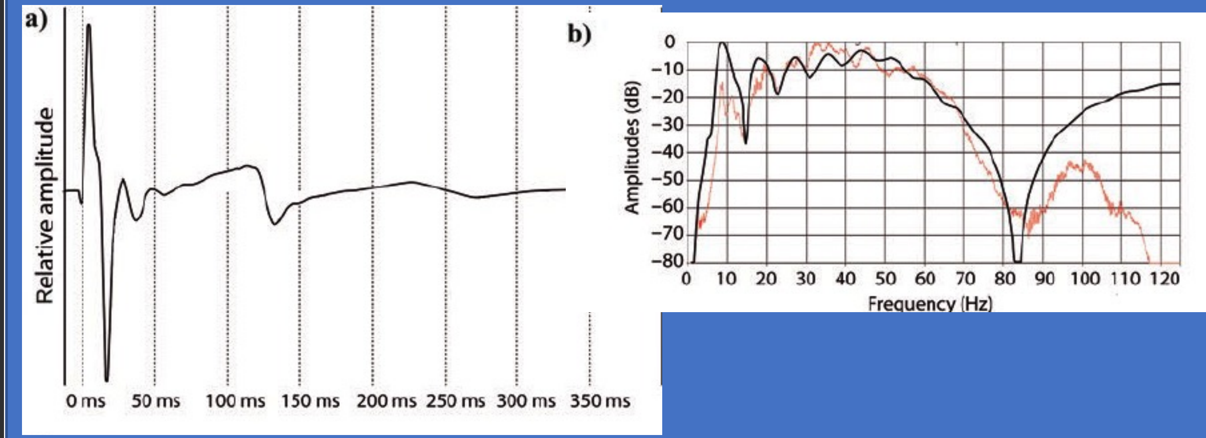
# Fourier Synthesis

- Fourier Synthesis allows us to restrict our modeling to *tones* (sine waves)
- Right: as more tones are added to a time series, we can “build” a square wave.
- Any sound, no matter how complicated in time, can be broken down into a sum of tones of different amplitudes and time delays (phase).
    - Modeled seismic airgun source signal and spectrum (right)
- Therefore, acoustic models only need to model tones.
    - Run the model over a bunch of frequencies, and then conduct a Fourier synthesis.

Square wave synthesis



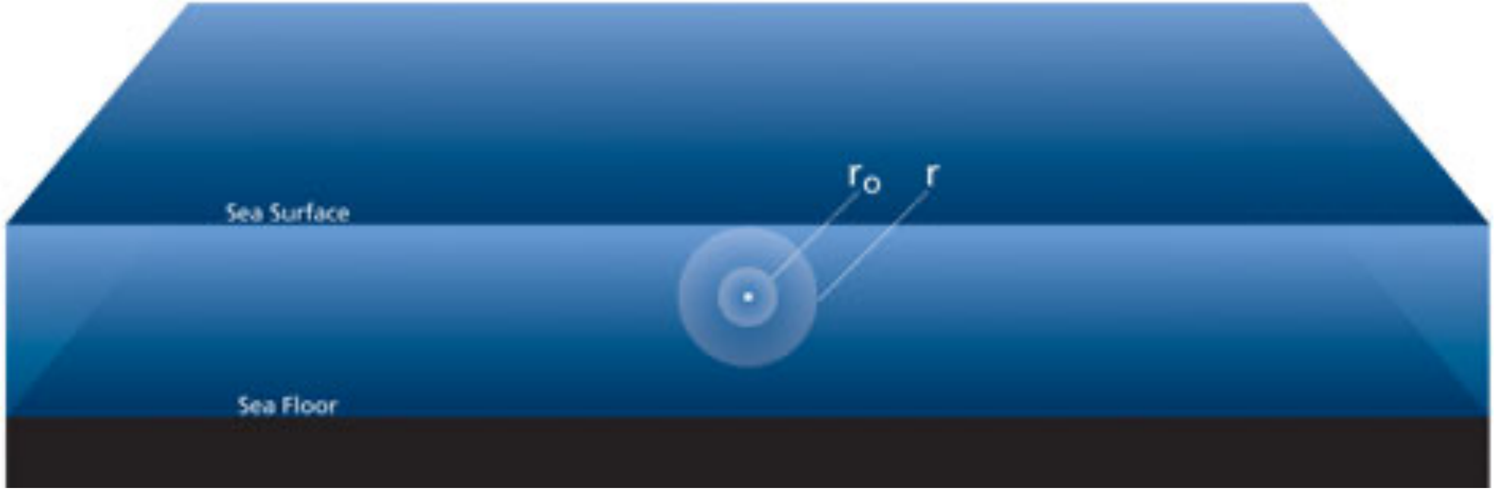

Seismic airgun trace using Gundalf ™



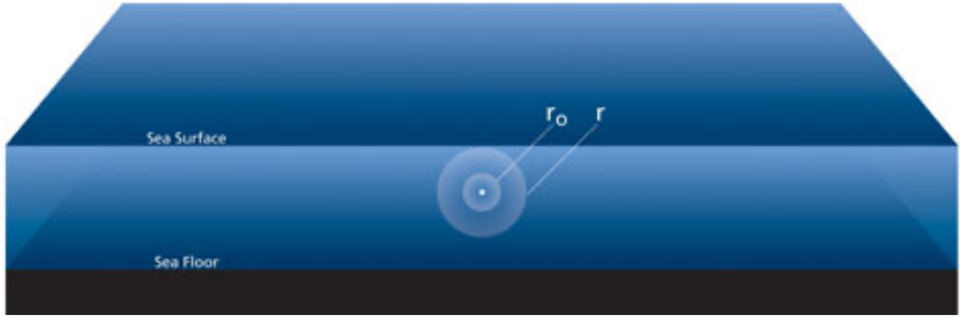
# Simple models of sound propagation can be very useful

- Simple models can accurately represent sound propagation in deep water when far from a boundary (surface, seafloor).
  - Appropriate when water depth *and* source depth greater than 10 wavelengths.

- A valuable "common sense" check for more complicated models.
- Spherical spreading: sound spreads as a sphere in open water.



# Spherical spreading model is simplest propagation model




$$Intensity = \frac{Source\ Power}{4\pi r^2}$$

- The intensity of a sound falls off quickly with increasing range.
- Since acoustic power often can't be measured directly, we define a "reference range" to characterize the power:

$$\text{Intensity} = \left(\frac{Source\ Power}{4\pi r_0^2}\right)\left(\frac{r_0^2}{r^2}\right) \qquad r_0 = 1\ m$$

# Decibel notation and transmission loss

- Intensity $= \left(\frac{Source\ Power}{4\pi r_0^2}\right)\left(\frac{r_0^2}{r^2}\right)$

Source term Propagation term

- Convention is to use *decibels:*

$$10log(\text{Intensity}) = 10log\left(\frac{Source\ Power}{4\pi r_0^2}\right) + 10log\left(\frac{r_0^2}{r^2}\right)$$

RL = SL - 20*log*(r)

Received Level (dB) = Source Level (dB) - Transmission loss (TL)

- Transmission Loss (TL; aka propagation loss) is a positive number.
- The bigger the number, the greater the reduction in source level (attenuation).
- Allows us to model propagation without knowing the source level.

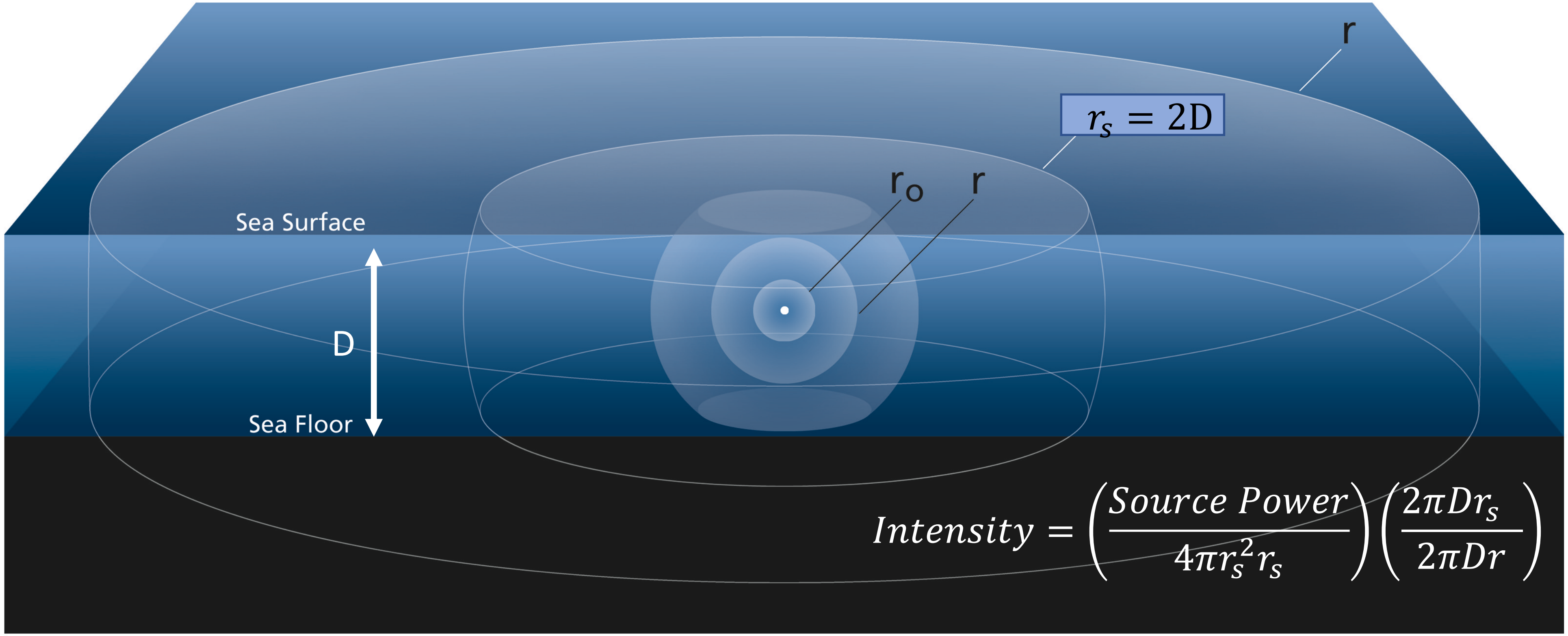
## Spherical spreading TL= 20log(r)

- 2x distance-> 6 dB loss-> 4x smaller
- 3x distance -> 10 dB loss ->10x smaller
- 10x distance-> 20 dB loss-> 100x smaller

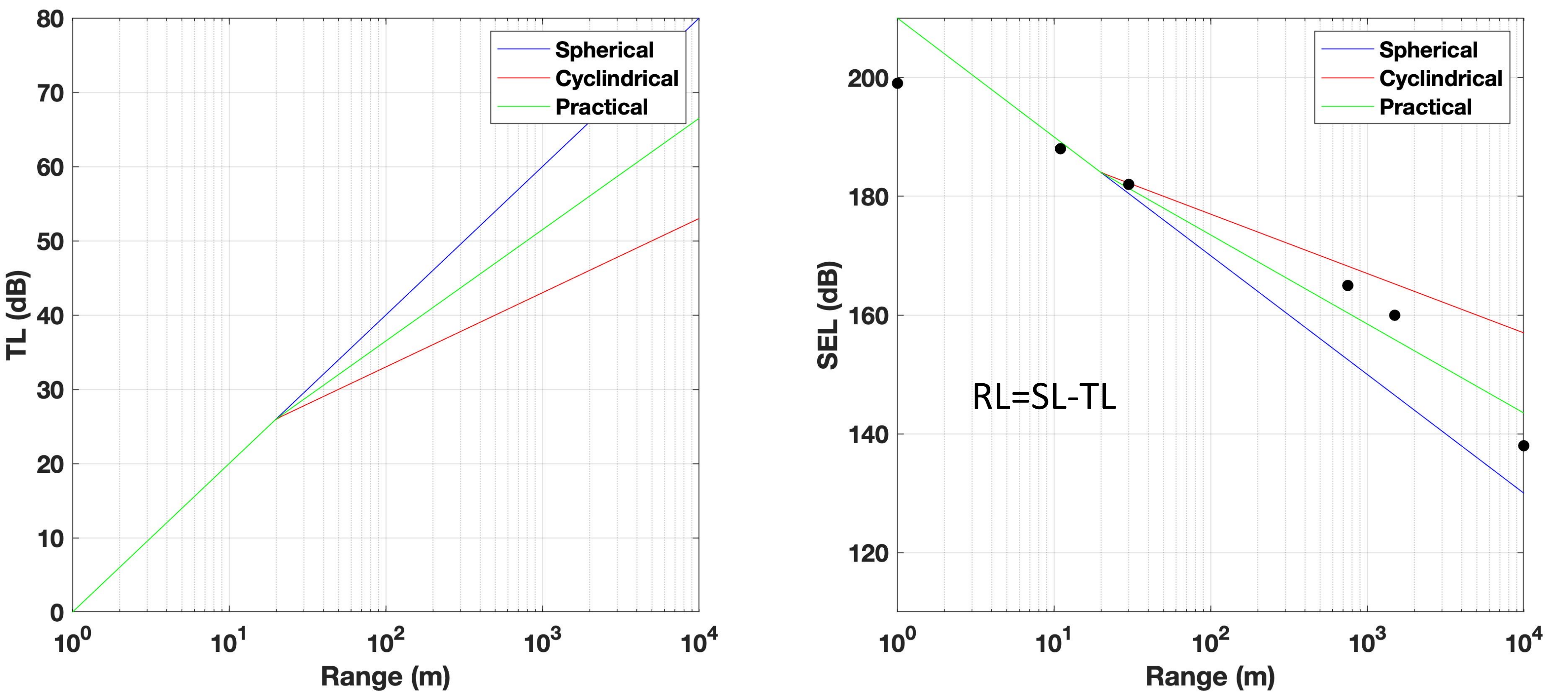
# Cylindrical spreading: sound energy spread across a cylinder, not a sphere

$$RL = SL - \left[20\log(r_s) + 10\log\left({}^{r}/_{r_s}\right)\right]$$

$$TL$$



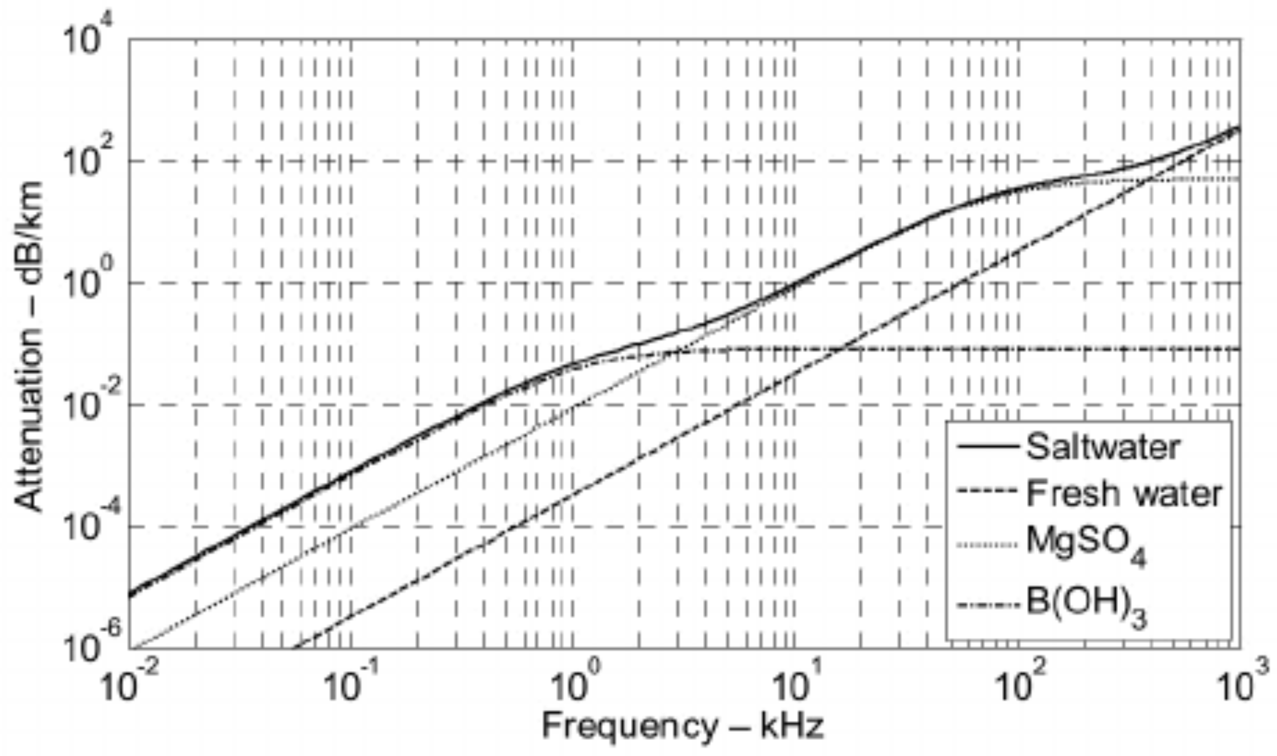
# Example of simple models for a pile driving scenario in 10 m water




- Cylindrical spreading most conservative (yields highest cutoff range)
- True transmission loss typically lies between cylindrical and spherical spreading (see data points).
  - Exception: shallow low frequency source in "deep water".
- 15log(r) often used as a "practical spreading" guide if no information is available besides water depth.
  - Can fit your own coefficient by finding a straight-line least-squares fit to semilog-plotted data.

# Seawater attenuates sound at various rates, depending on frequency

a




TL=20*log*(r)+a*r

- Arises from seawater chemistry
  - Magnesium and boron salts.
- Below 1 kHz: no effect at all.
- 10 kHz and above: essential effect.
  - For beaked whales (25 - 75 kHz), can ignore ocean bottom.

# Bottom loss key factor in shallow water propagation

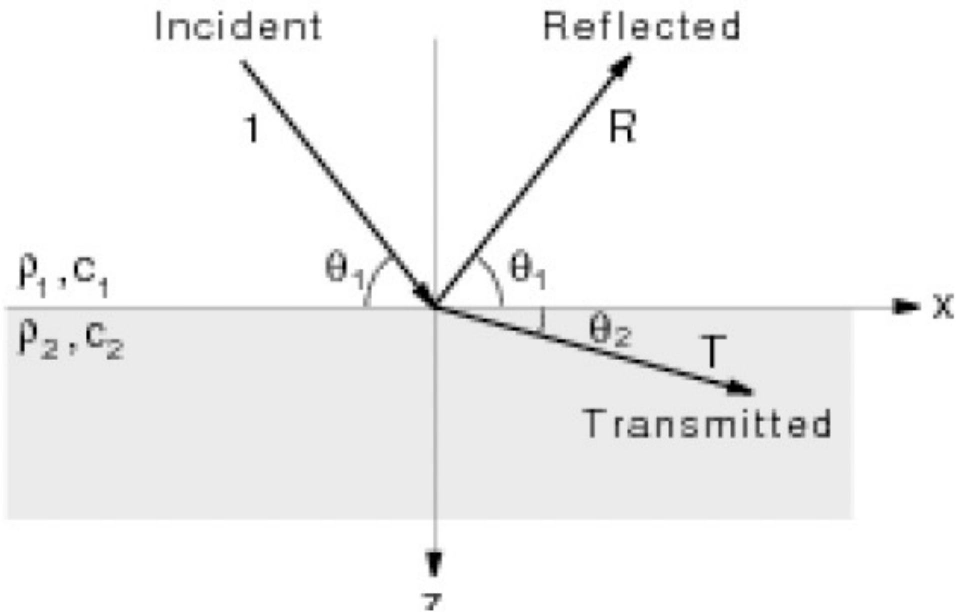



**Table 1.3** Geoacoustic properties of continental shelf and slope environments.

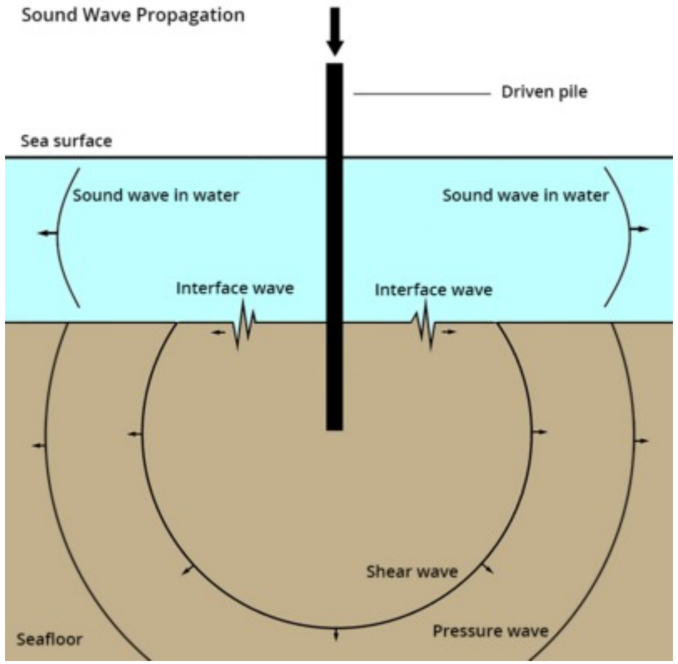
| Bottom type | $p$ (%) | $\rho_b/\rho_w$ - | $c_p/c_w$ - | $c_p$ (m/s) | $c_s$ (m/s) | $\alpha_p$ (dB/$\lambda_p$) | $\alpha_s$ (dB/$\lambda_s$) |
|---|---|---|---|---|---|---|---|
| Clay | 70 | 1.5 | 1.00 | 1500 | $< 100$ | 0.2 | 1.0 |
| Silt | 55 | 1.7 | 1.05 | 1575 | $c_s^{(1)}$ | 1.0 | 1.5 |
| Sand | 45 | 1.9 | 1.1 | 1650 | $c_s^{(2)}$ | 0.8 | 2.5 |
| Gravel | 35 | 2.0 | 1.2 | 1800 | $c_s^{(3)}$ | 0.6 | 1.5 |
| Moraine | 25 | 2.1 | 1.3 | 1950 | 600 | 0.4 | 1.0 |
| Chalk | - | 2.2 | 1.6 | 2400 | 1000 | 0.2 | 0.5 |
| Limestone | - | 2.4 | 2.0 | 3000 | 1500 | 0.1 | 0.2 |
| Basalt | - | 2.7 | 3.5 | 5250 | 2500 | 0.1 | 0.2 |

$c_s^{(1)} = 80\, \tilde{z}^{0.3}$
$c_s^{(2)} = 110\, \tilde{z}^{0.3}$
$c_s^{(3)} = 180\, \tilde{z}^{0.3}$

$c_w$=1500 m/s, $\rho_w$=1000 kg/m$^3$

- Material parameters include bottom density, compressional and shear sound speed, and material attenuation.
  - *Grain size* often allows prediction of other parameters.
  - Combine to specify a *reflection coefficient* that shows effects of incident angle, frequency.
- May have multiple layers of sediments, each with own set of parameters.
- The lower the frequency, the deeper the sound will penetrate into the sediment.
- Scattering from rough surfaces can also add to transmission loss, especially when roughness scale~ wavelength.

# Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient



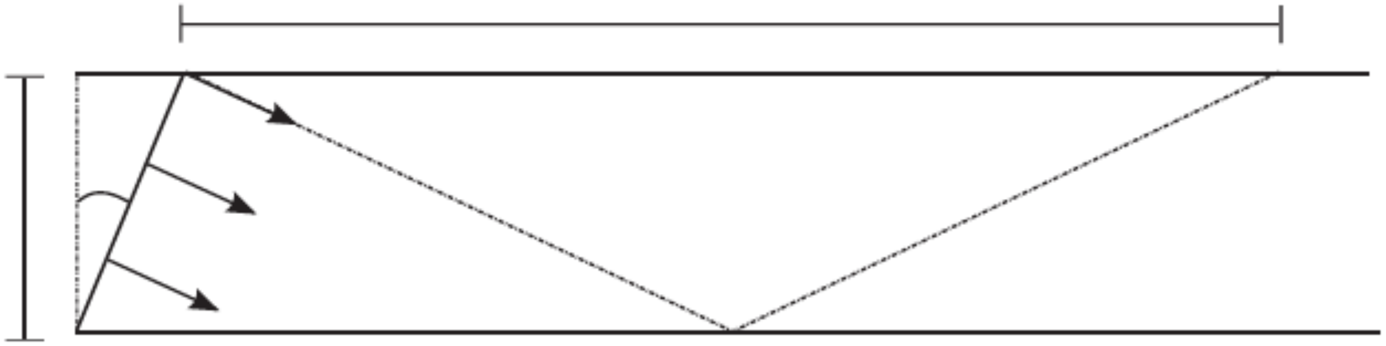
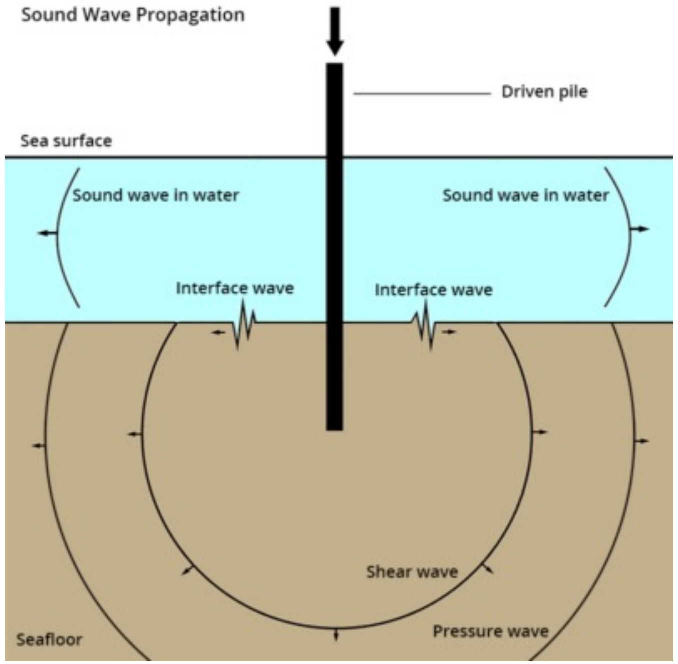



FIG. 1. Schematic sketch of bottom and surface bounce of the Mach cone.

# Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient



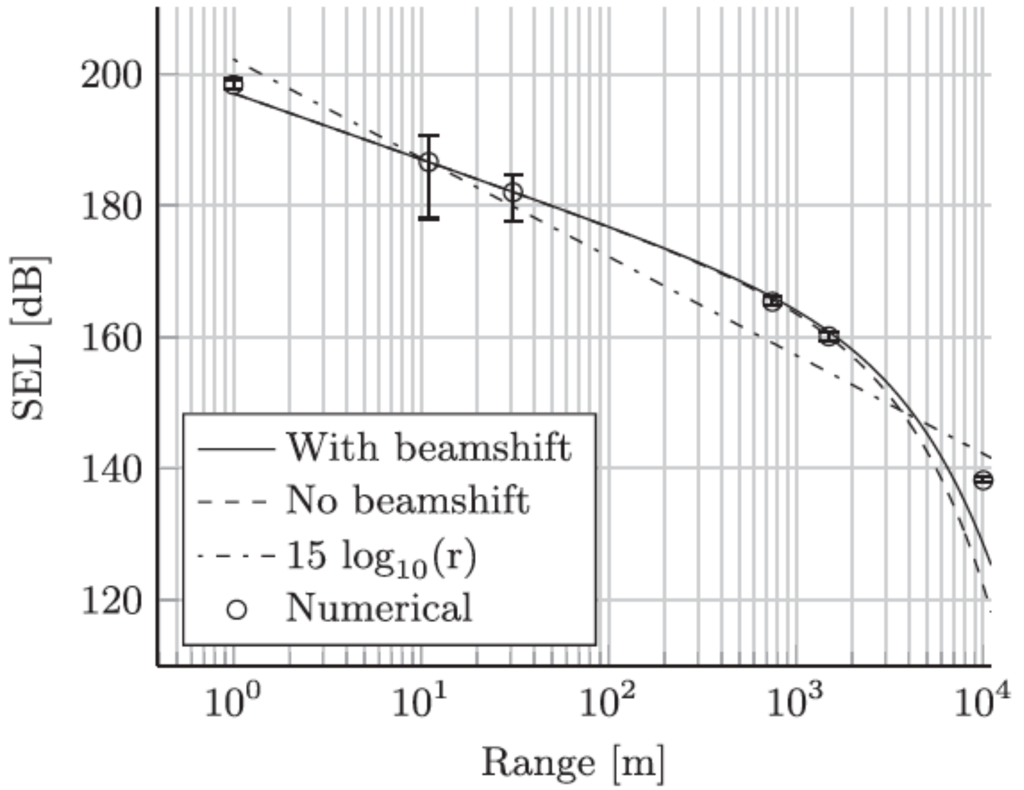
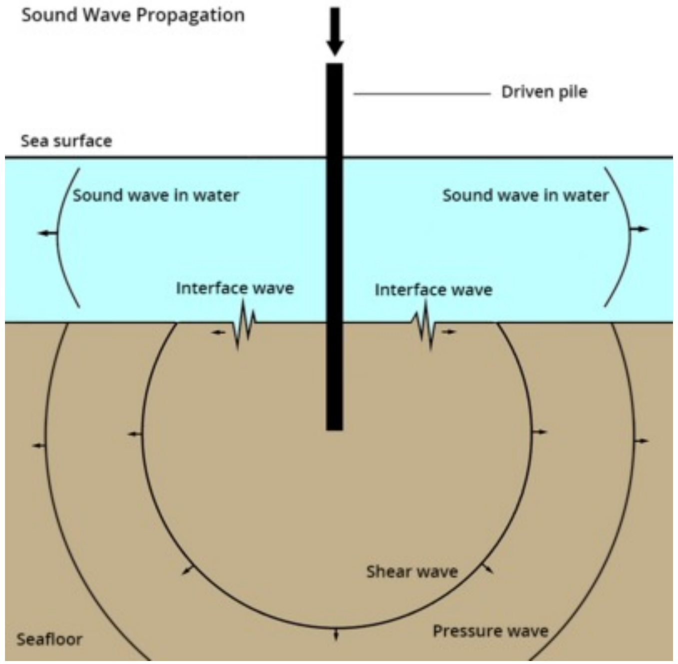




FIG. 3. Comparison of COMPILE results and analytical estimates of damped cylindrical spreading approaches and 15log($r$)-approach scaled at $r = 11$ m (depth-averaged/The vertical bars are not error bars, but indicate the minimum/maximum sound exposure occurring in the water column).

# Damped Cylindrical Spreading Model combines spherical spreading with bottom reflection coefficient



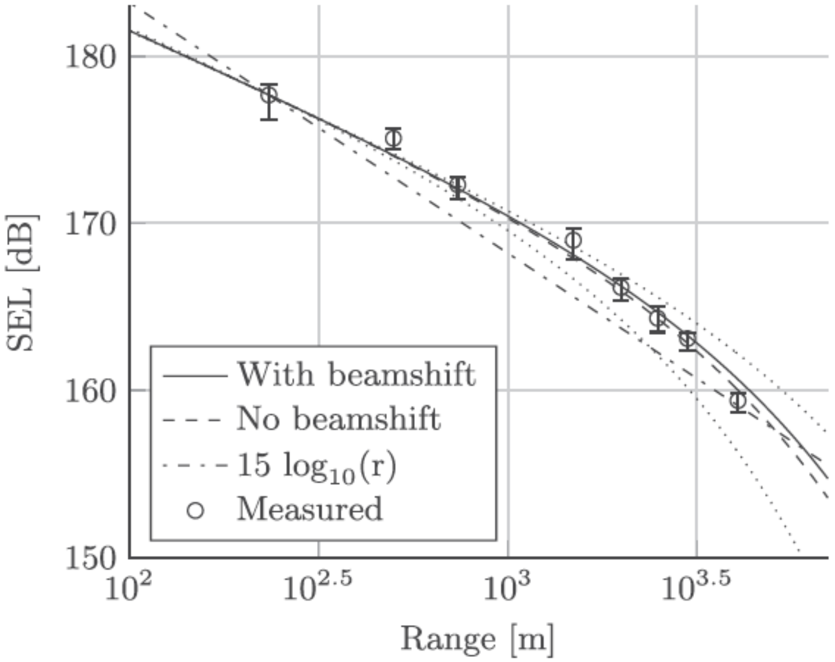




FIG. 4. Comparison of BR1 measurements and analytical estimates of damped cylindrical spreading approaches and 15log($r$)-approach scaled at $r = 234$ m in a depth of $z = 25$ m. Dotted lines indicate limiting cases of a fine sand and a coarse sand half-space, respectively, see Sec. V.

# What information is needed for detailed model?

- Frequency
- Water depth
- Source depth
- Receiver location (depth)
- Bottom composition ( important for low frequency)
- Bathymetric profiles (range independent vs. range dependent)
- Sound speed profile, including range dependence. (high frequency)
- Surface roughness/ice cover and bottom roughness. (high frequency)
- Scatterers in water column (fish): objects the same wavelength

# How do I get this environmental information?

DATABASES

(LIMITED COVERAGE)

DIRECT MEASUREMENTS
(EXPENSIVE)

INVERSION FROM ACOUSTIC DATA

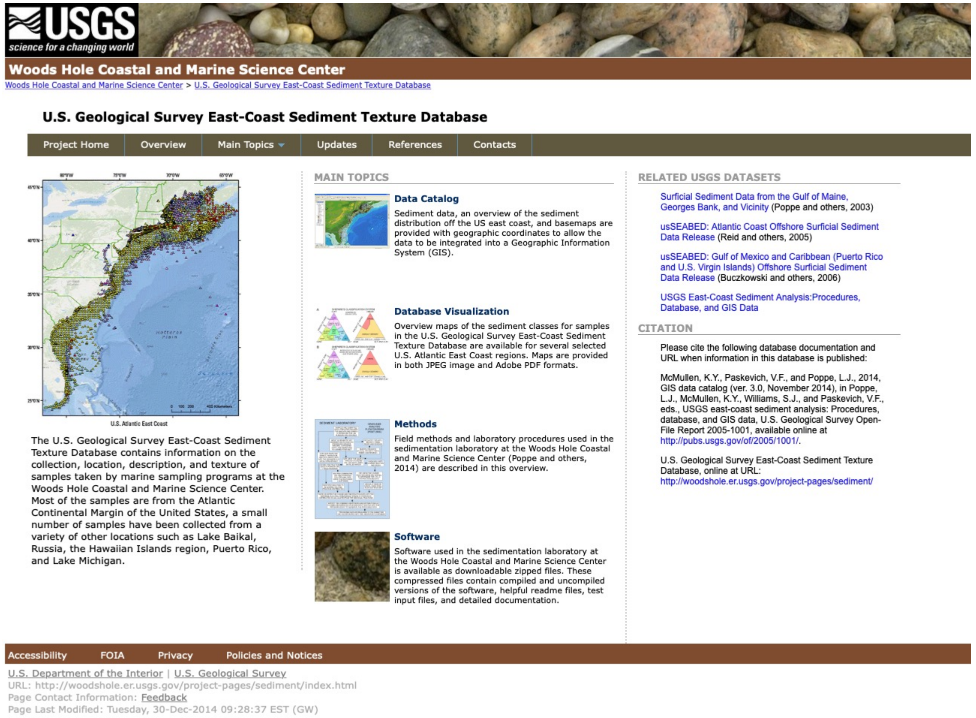
(BECOMING POPULAR)

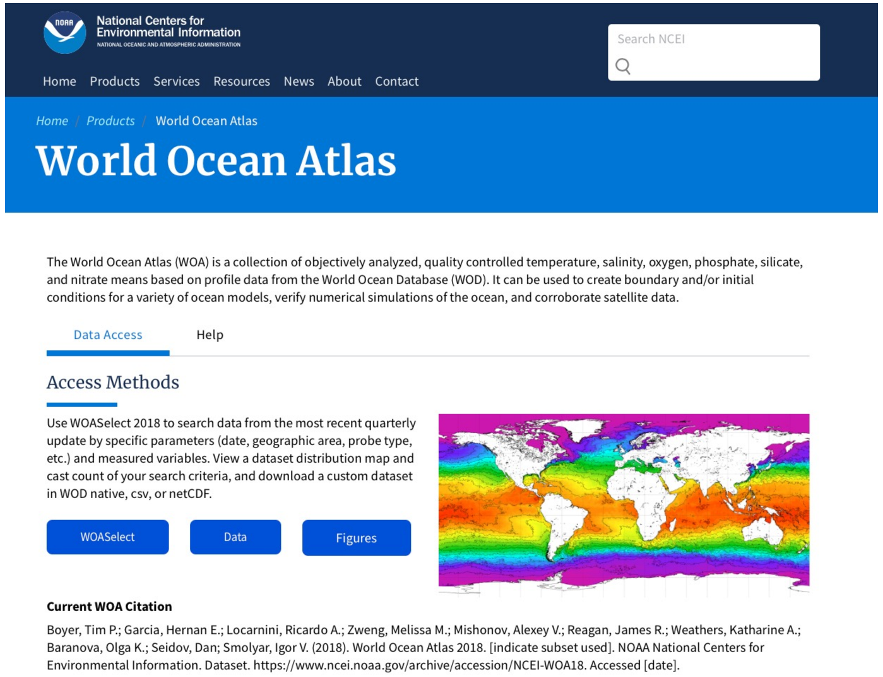

SENSITIVITY ANALYSIS

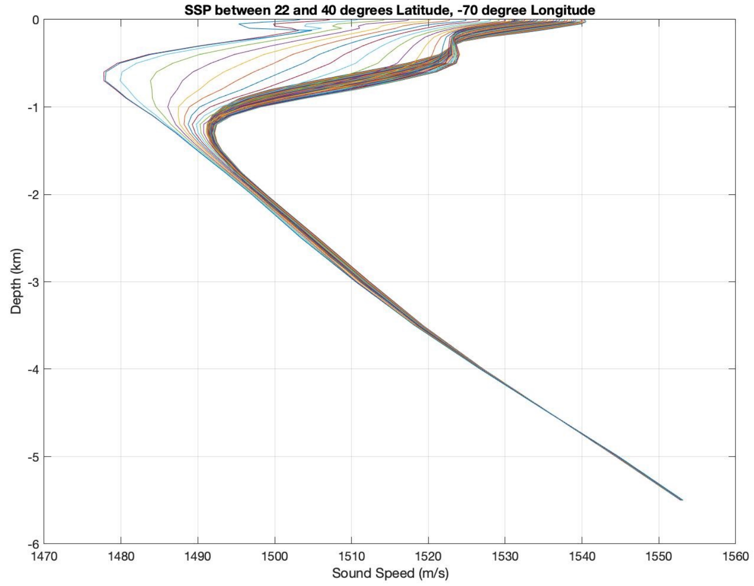
(PLACE BOUNDS ON UNCERTAINTY)

- Pro tip: A great way to appear intelligent when questioning an acoustic modeler!

# Examples of online databases



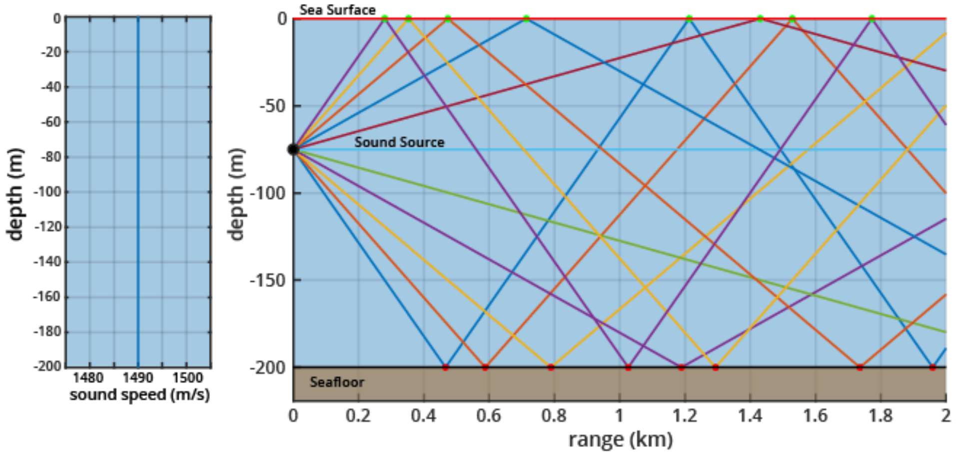



# Three popular types of detailed models

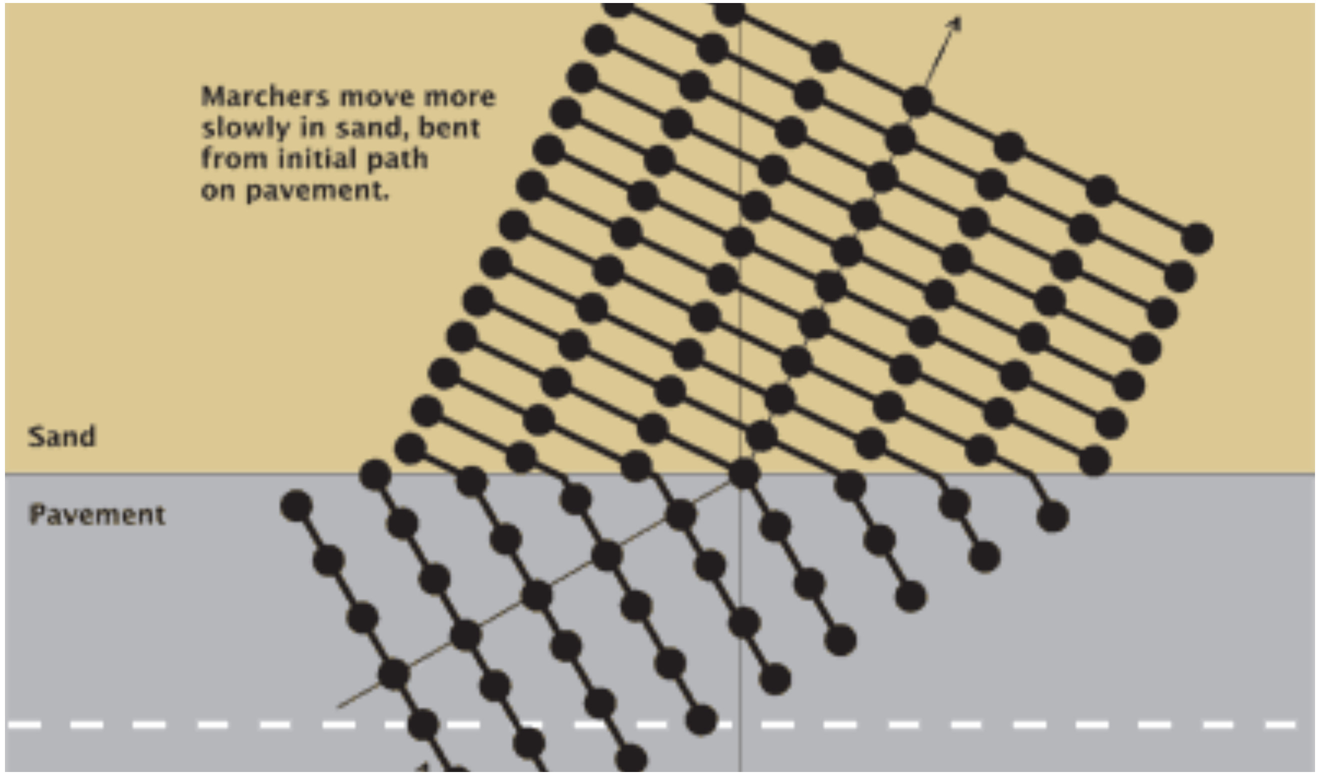
- Each model makes assumptions about acoustic field to speed up computation.
- Ray tracing
  - BELLHOP
- Normal mode propagation
  - KRAKEN
- Parabolic Equation (PE)
  - RAM-GEO
- Not covered:
  - Wavenumber integration
    - best for ice, complex elastic boundaries, exact near field
  - Finite difference or finite element modeling.
    - Exact solution to wave equation
- Ocean Acoustics Library clearinghouse:
  - oalib-acoustics.org

# Ray tracing

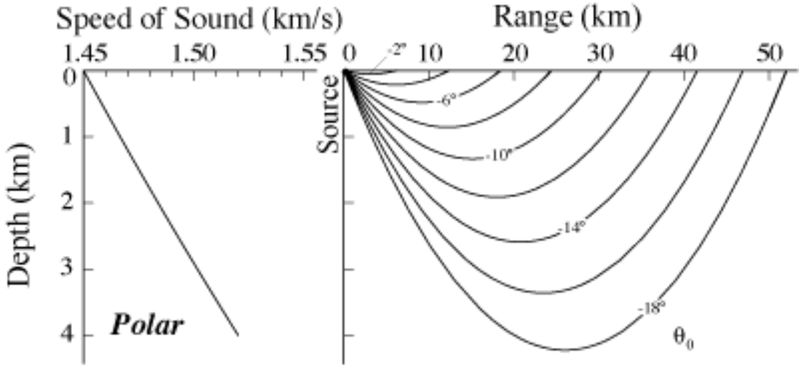
- “Shoot” rays that measure travel time, amplitude
  - “Denser” clusters of rays=more accurate results.
- Eigenrays
  - Rays that connect source and receiver.
- Key assumption: wavelength << ocean depth or features.
- Biggest advantages
  - deep water with little bottom interaction. (in terms of wavelengths)
  - Range-dependent bathymetry or environment.
- Disadvantages
  - Bottom interactions
  - More robust for measuring travel times than transmission loss.
- Common program: BELLHOP (Mike Porter)



# Ray tracing visualizes refraction well, but all advanced models effectively include it

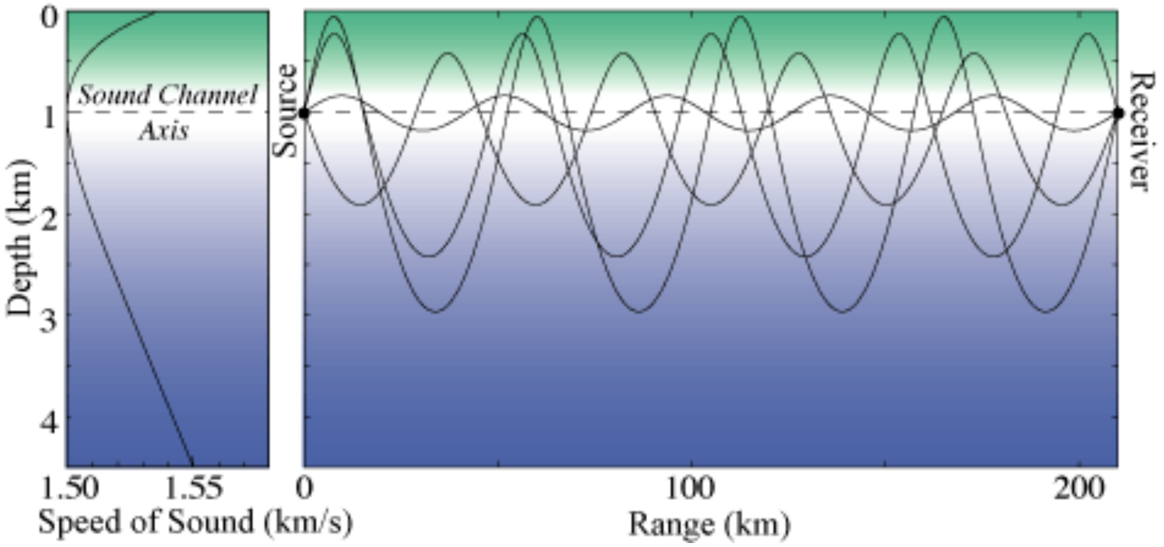



- “Snell’s Law”:  A ray bends toward slower regions.
- Ray tracing codes basically evaluate Snell’s law at every step.

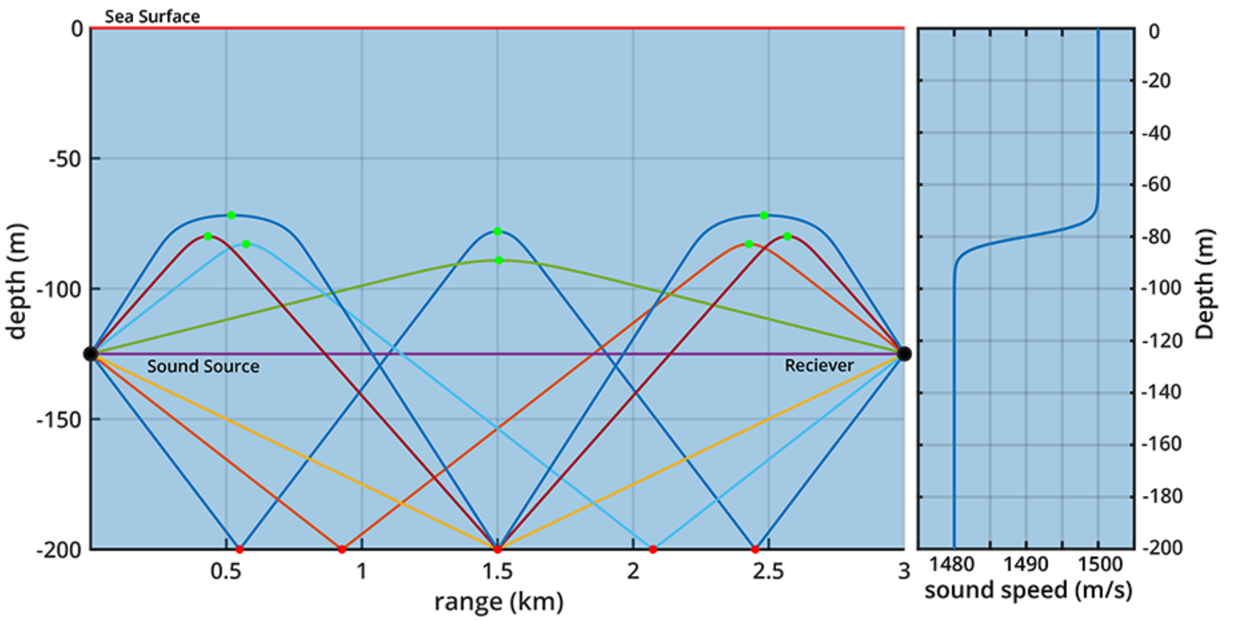


# Two ways of representing ray outputs

- Ray tracing of deep water channel

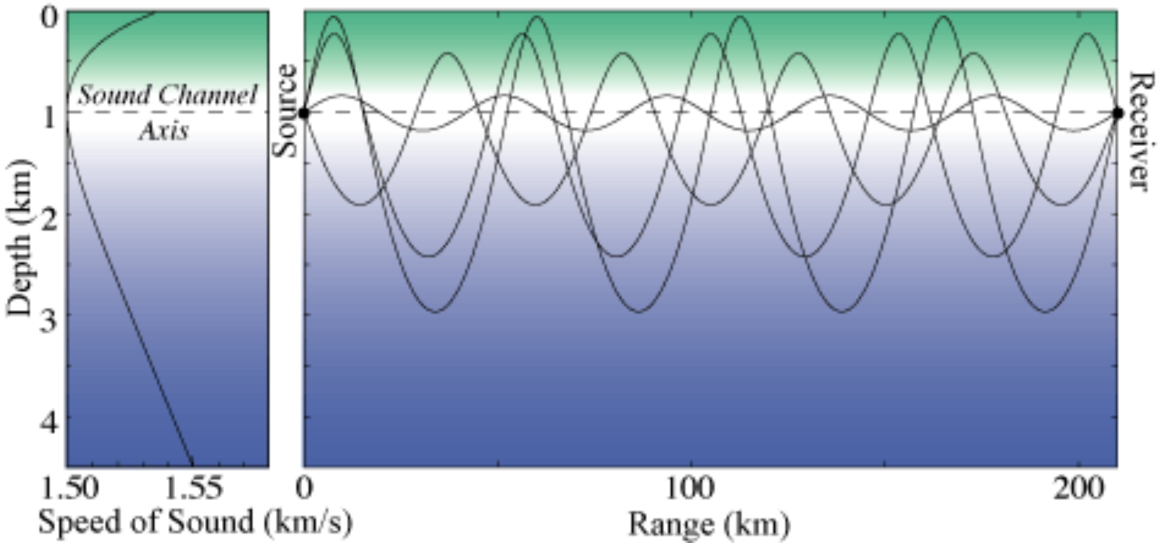



- TL of shallow duct near Hawaii for FKW depredation study (inverted color)

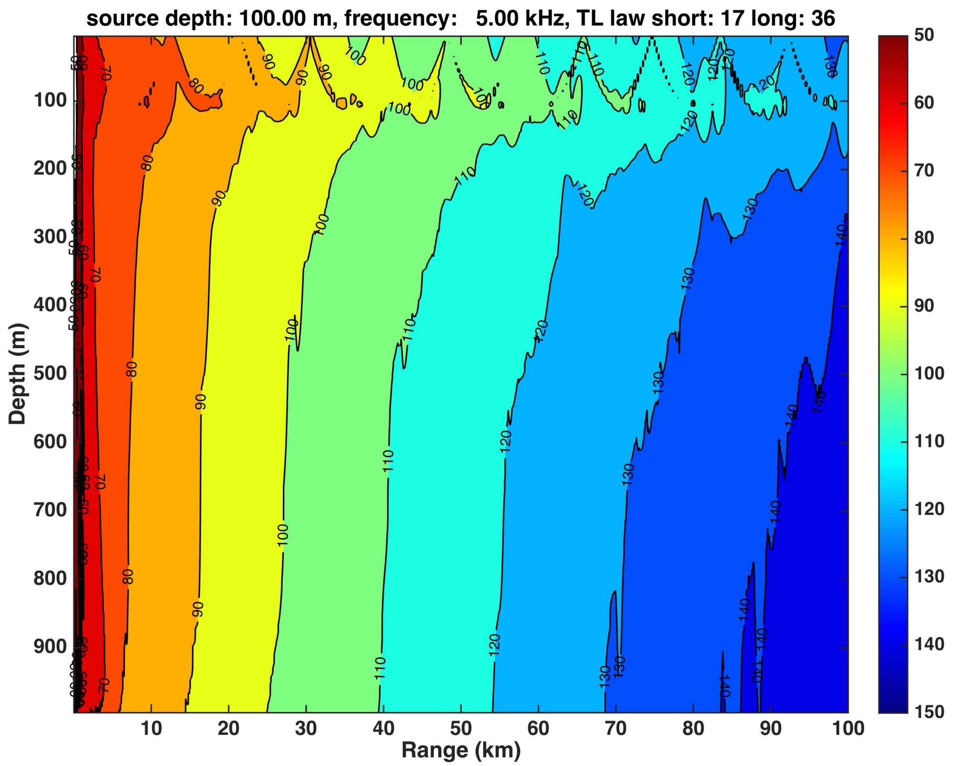


# Two ways of representing ray outputs

- Ray tracing of deep water channel

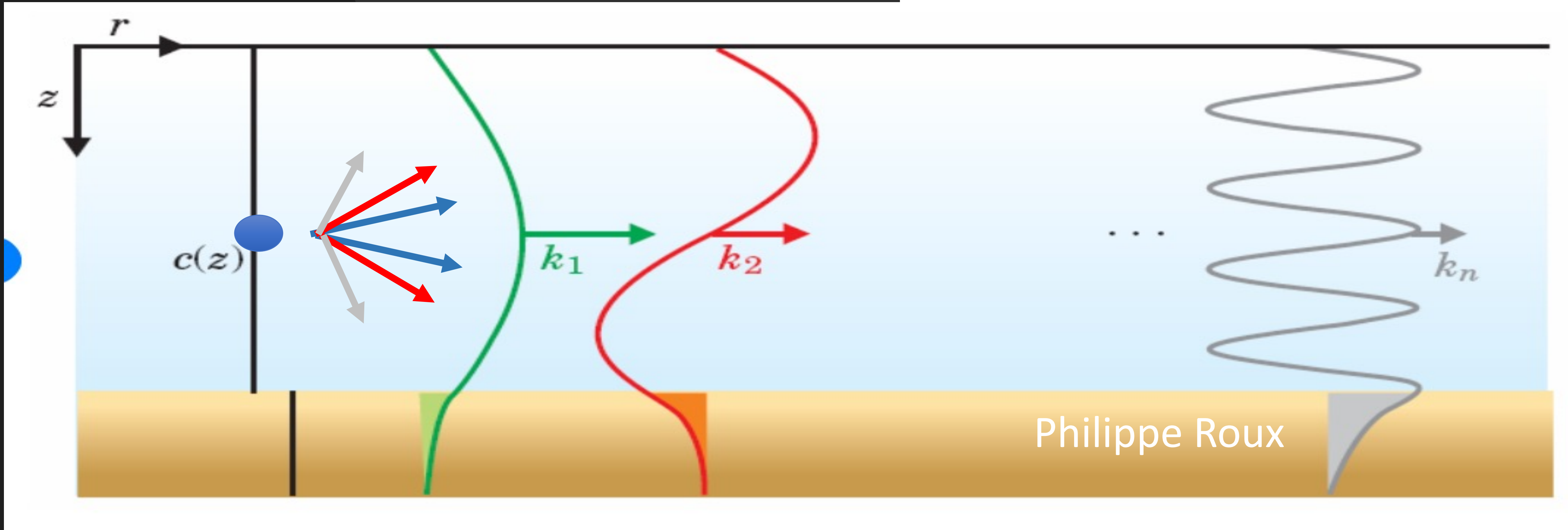



- TL of shallow duct near Hawaii for FKW depredation study (inverted color)



# Normal mode model

- For shallow water where ray paths become "quantized"
- Key assumption: wavelength large vs. ocean bottom or sound speed profile features.

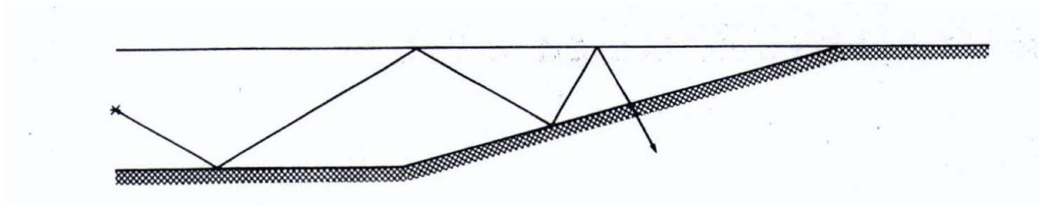


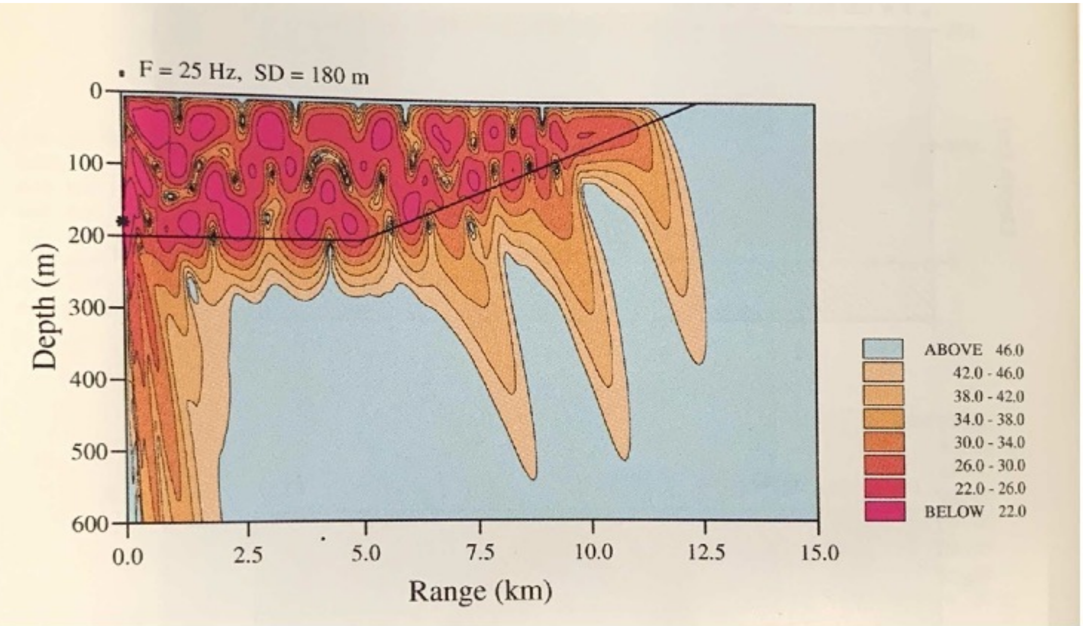
# Normal mode model

- For shallow water where ray paths become "quantized"
- Key assumption: wavelength large vs. ocean bottom or sound speed profile features.
- Biggest advantages
  - Extremely fast
  - Can compute multiple receivers simultaneously.
- Disadvantages
  - Must be a few water depths away.
  - Awkward to implement range dependence.
  - Very shallow water has no modes (cutoff frequency)
- Common program: KRAKEN (Mike Porter)

# Parabolic equation

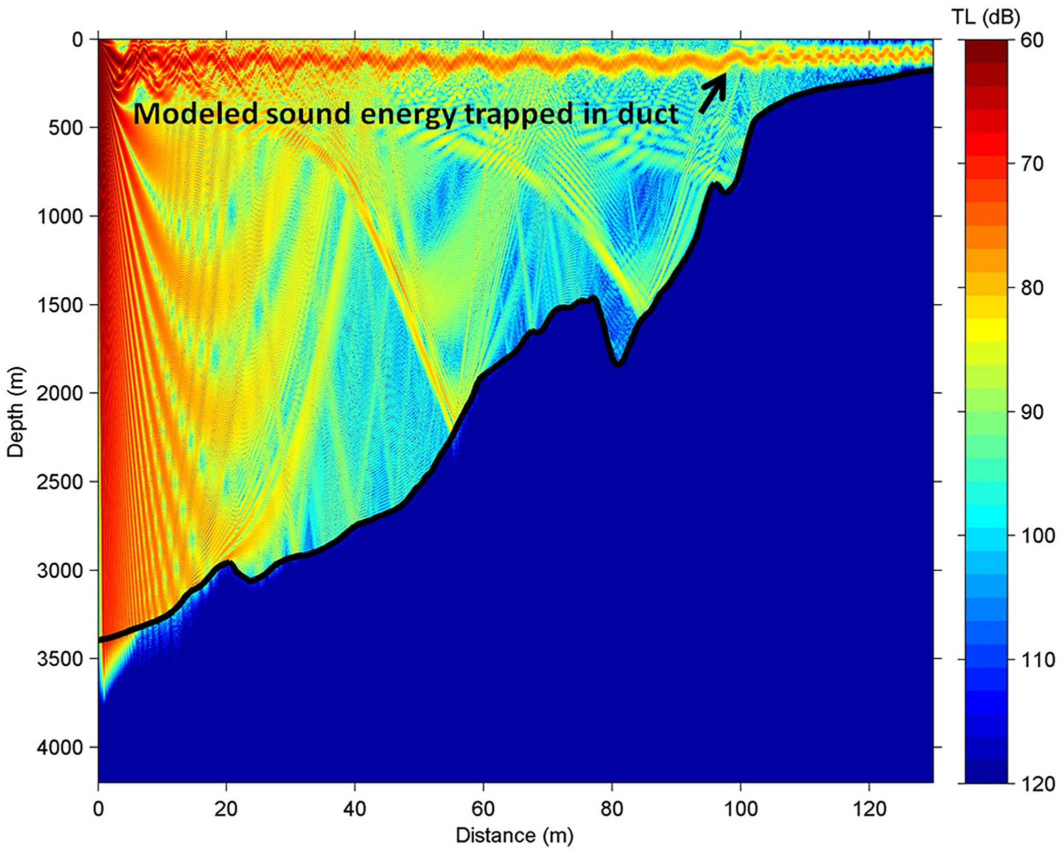
- March a full-wave solution out in range in complex environment.
- Key assumptions:
  - wavelength large compared to ocean depth or ssp features.
  - Direction of propagation is mostly horizontal (small-angle approximation).
    - Getting less restrictive with newer formulations (Pade formulation)
  - No backpropagating (backwards-reflected) energy
- Biggest advantages
  - Fast TL computation in complex range-dependent environments. (See famous “wedge” example on right)
- Disadvantages
  - Propagation of large vertical angles still problematic (Pade approximation best).
- Common programs:
  - RAM-GEO (Mike Collins), wide-angle, navy certified
  - FWRAM (JASCO)
  - Good question to ask: what range of vertical angles is possible?





# Parabolic equation

- March a full-wave solution out in range in complex environment.
- Key assumptions:
  - wavelength large compared to ocean depth or ssp features.
  - Direction of propagation is mostly horizontal (small-angle approximation).
    - Getting less restrictive with newer formulations (Pade formulation)
  - No backpropagating (backwards-reflected) energy
- Biggest advantages
  - Fast TL computation in complex range-dependent environments
- Disadvantages
  - Propagation of large vertical angles still problematic (Pade approximation best).
- Common programs:
  - RAM-GEO (Mike Collins), wide-angle, navy certified
  - FWRAM (JASCO)
  - Good question to ask: what range of vertical angles is possible?



# Summary of models

Advanced Applications for Underwater Acoustic Modeling, Paul C. Etter

| 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)

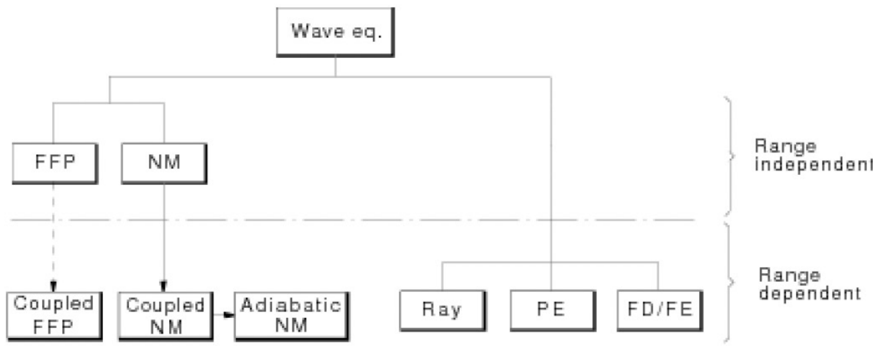
RI: range-independent environment
RD: range-dependent environment

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

◑ Limitations in accuracy or in speed of execution

○ Neither applicable or practical

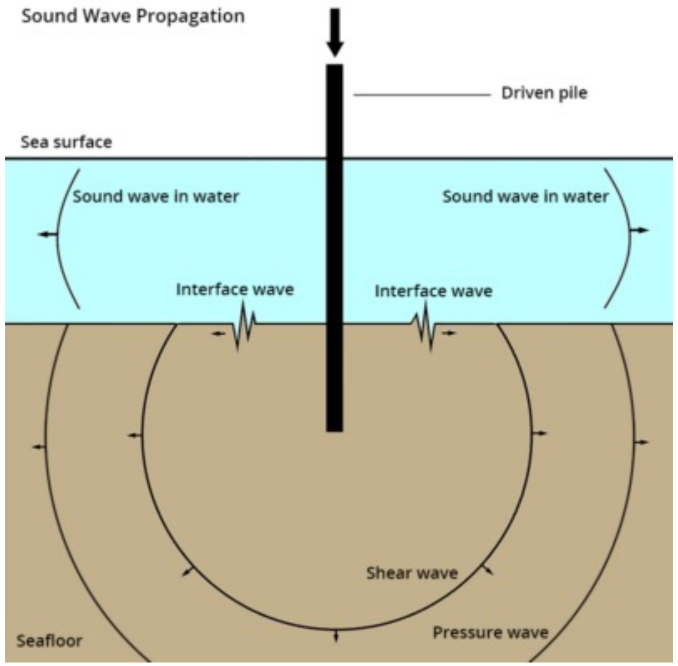
Computational Ocean Acoustics




- Range independent:
    - Normal mode if shallow water (low frequency).
    - Ray tracing if deep water.
- Range dependent:
    - PE if shallow water
    - Ray tracing if deep water

# A comment on directional sources

- Ray tracing: can be weighted by launch angle.
- PE: Directional "starter" or multiple distributed sources
- Normal mode: distributed sources to reproduce source beampattern
- Pro tip: ask how directional sources are modeled!



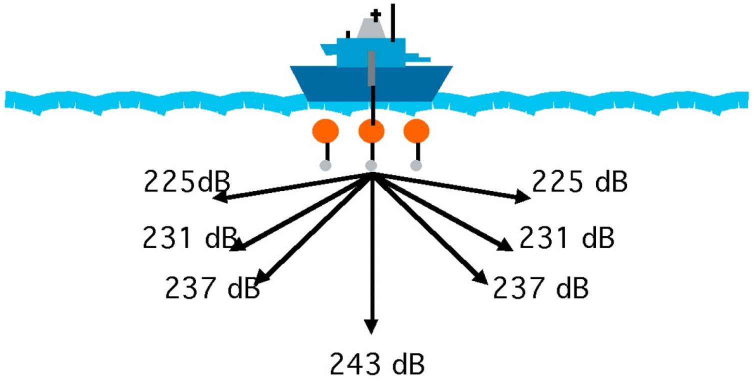




Figure 5. Vertical radiation pattern of typical array. dB levels re 1μPa-m; rms peak-to-peak maximum of 13.4 bars (absolute P-to-P maximum of 19 bars).

Caldwell, Leading Edge, 2000

# Conclusion

- Simple spreading models
    - Transmission loss, DCSM for pile driving
- Input requirements for models
- Ray, Normal Mode, and PE models
- Evidence of good modeling technique
    - Frequency and water depth match the technique.
    - Sources of environmental parameters clearly identified.
    - If environment not known, a range of values are tested.
    - Strategy for directional sources explained.
- Not covered-full 3-D modeling
- Further resources:
    - oalib-acoustics.org
    - P.C. Etter, Underwater Acoustic Modeling (E & FN Spon, London, UK, 1996).
    - Jensen, Kuperman, Porter, Schmidt, Computational Ocean Acoustics

# Examples of other numerical codes





Table 1: Summary of underwater acoustic propagation models. Superscript letters identify those models that have been added to the inventory since 2003.

| Technique | Range independent | | | Range dependent | | | | |
|---|---|---|---|---|---|---|---|---|
| Ray theory | CAPARAY | PLRAY | | ACCURAY | GRAB | LYCH | Pedersen | RAYWAVE |
| | FACT | RANGER | | BELLHOP | GRASS | MEDUSA | PlaneRay[b] | RP-70 |
| | FLIRT | | | Coherent DELTA | HARORAY | MIMIC | PWRC[c] | SHALFACT |
| | GAMARAY | | | FACTEX | HARPO | MPC | Ray5[d] | TRIMAIN |
| | ICERAY | | | FeyRay[a] | HARVEST | MPP | RAYSON[e] | XRAY[f] |
| Normal mode | AP-2/5 | MODELAB | ORCA | ADIAB | COUPLE | KRAKEN | PROSIM | WKBZ |
| | BDRM | NEMESIS | POPP[g] | ASERT | CPMS | MOATL | SHAZAM | WRAP |
| | COMODE | NLNM | PROTEUS | ASTRAL | FELMODE | MOCTESUMA | SNAP/C-SNAP | 3D ocean |
| | DODGE | NORMOD3 | SHEAR2 | CENTRO | IECM[h] | NAUTILUS | SWAMP[i] | |
| | FNMSS | NORM2L | Stickler | CMM3D | Kanabis | PROLOS | WEDGE | |
| Multipath Expansion | FAME | NEPBR | | | | Integrated mode[j] | | |
| | MULE | RAYMODE | | | | | | |
| Fast field or wavenumber integration | FFP | OASES | SAFARI | CORE | RD-OASES | SAFRAN | | |
| | Kutschale FFP | pulse FFP | SCOOTER | OASES-3D[k] | RDOASP | | | |
| | MSPFFP | RPRESS | SPARC | RDFFP | RDOAST | | | |
| Parabolic equation | Use single environmental specification | | | AMPE/CMPE | FEPES | MONM3D[m] | PE-FFRAME | Two-WayPE |
| | | | | Cartesian 3DPE[l] | FOR3D | MOREPE | PESOGEN | ULETA |
| | | | | CCUB/SPLN/CNP1 | HAPE | NSPE[n] | PE-SSF (UMPE/MMPE) | UNIMOD |
| | | | | corrected PE | HYPER | OS2IFD | RAM/RAMS/RAMGEO[p] | 3DPE (NRL-1) |
| | | | | DREP | IFD wide-angle | OWWE[o] | RMPE[q] | 3DPE (NRL-2) |
| | | | | FDHB3D | IMP3D | PAREQ | SNUPE | 3DTDPA |
| | | | | FEPE | LOGPE | PDPE | Spectral PE | 3DWAPE[r] |
| | | | | FEPE-CM | MaCh1 | PECan | TDPE | |