# Presentation at the First Plenary Meeting of the Advisory Committee on Acoustic Impacts on Marine Mammals

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# Basic Physical Properties of Sound and Propagation

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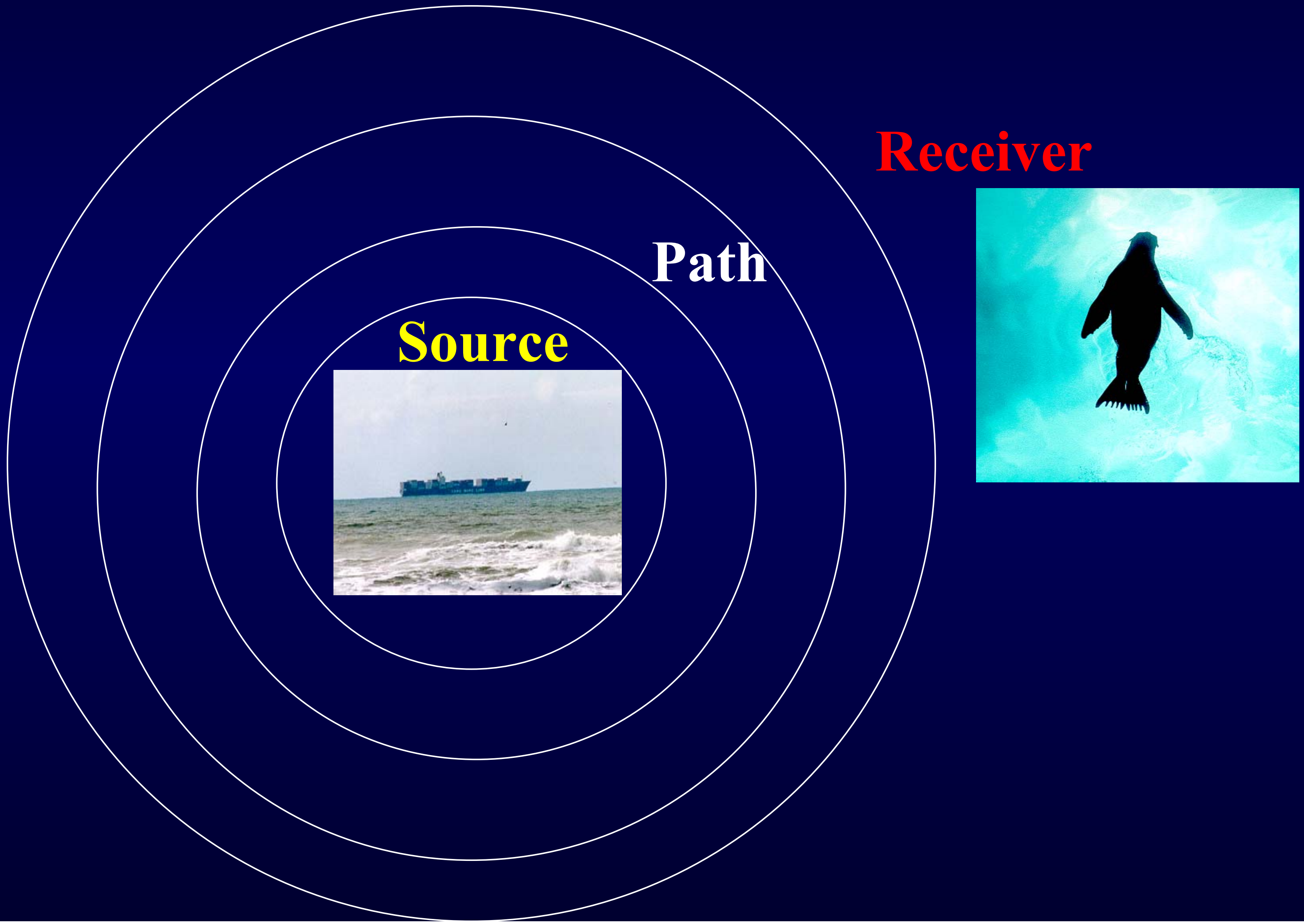
# Source-Path-Receiver Perspective on Estimating Noise Impacts



# Source-Path-Receiver Model for Estimating Noise Impacts

## Source Parameters

- Source Level
- Frequency Characteristics
- Temporal Patterns
- Directivity Patterns
- Geographical Location
- Depth of Source
- Time of Year

## Path Parameters

- Signal Propagation
- Ambient Noise Levels
- Noise Frequencies
- All Envt. Features

## Receiver Parameters

- Absolute Hearing
- Masked Hearing
- Frequency Processing
- TTS & PTS
- Motivational Factors
- Experiential Factors
- All Envt. Features

Effects of noise on marine mammals depend (at a minimum) on sound **frequency**, exposure **level**, and **duration** as well as **range** from an animal and its **hearing ability**, not simply source level!

Assigning a single received level as the general onset of behavioral disturbance or injury is too simplistic

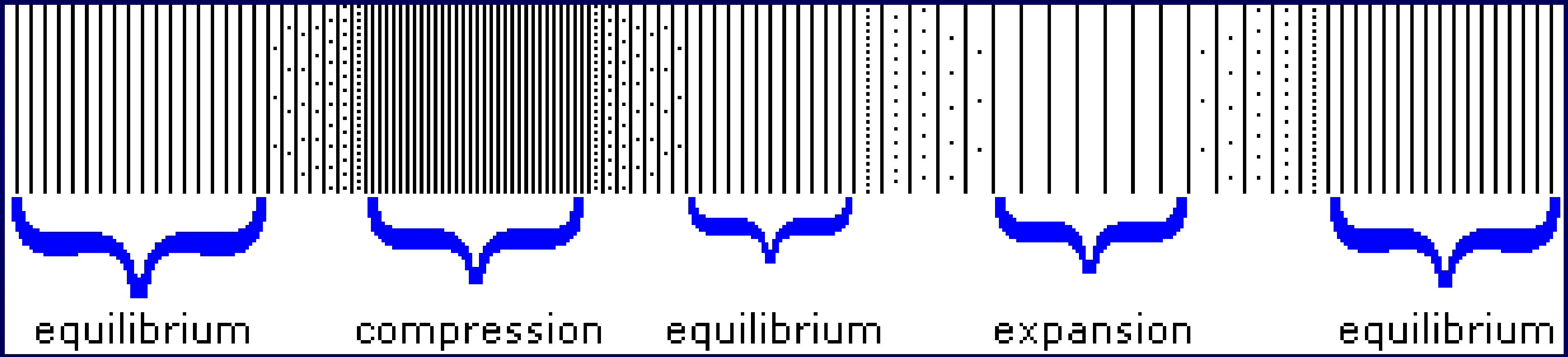
# Acoustics Primer Outline

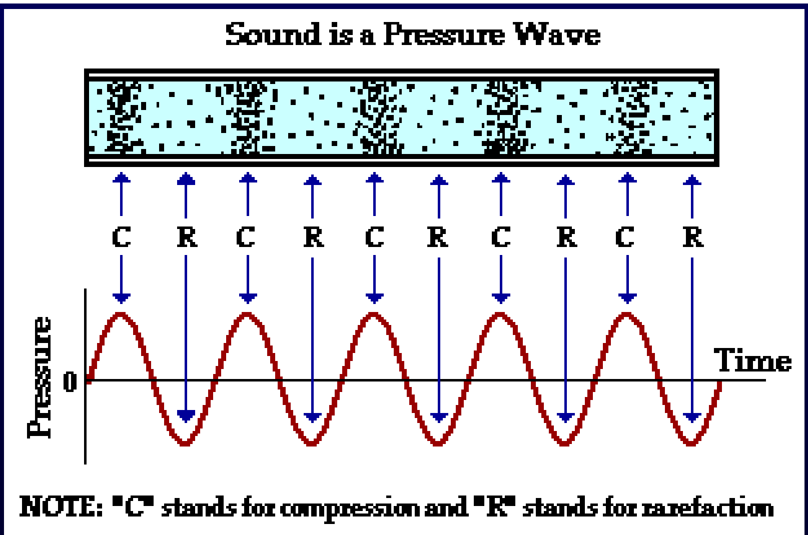
- Basic Physical Acoustics, and **Source** Characteristics
- **Path** Characteristics
  - esp. Sound Propagation

**Receiver** Characteristics (other presentations)

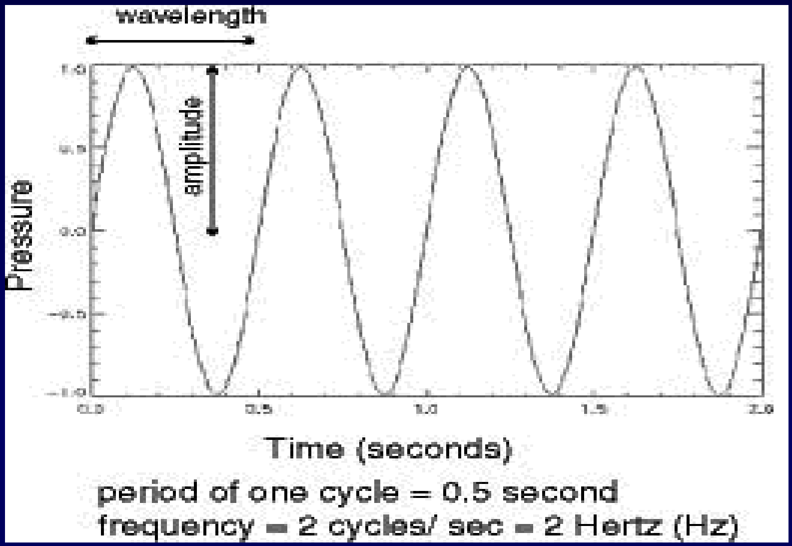
# Basic Physical Acoustics:
# What is sound?

Sound is a mechanical wave created by a vibrating object that moves through an elastic medium and results in hearing



# Basic Physical Acoustics: Wavelength, Frequency, and Amplitude




- Wavelength (λ): distance between waves (m)
- Frequency (f): rate of oscillation (Hz)
- Speed of sound (c): depends on density (m/s)

$$\lambda = c/f$$

- Amplitude: pressure measurement (Pa) – can be converted to a sound pressure level (dB)

# Basic Physical Acoustics: Pressure, Energy, and Intensity

- **Pressure** = force per unit area (F/A), which means that some **Work** has been done
- **Energy**: the ability to do work
- **Power**: rate at which work is done
- **Intensity**: sound power per unit area ($W/m^2$)

  **$I = p^2/\rho c$ [where p = pressure, $\rho c$ = medium impedance)**

# Acoustic Units: What's with these *%#$ logarithms?

- In describing relative sound magnitude, acousticians realized that the human ear responds over a tremendously large range and in a non-linear manner (same for other mammals).
- Solution to handle both of these issues is to use a logarithmic function, the decibel (dB) scale to describe the aspect of sound that we perceive as "loudness"

# Acoustic Units: Calculating Sound Levels (or, what is a dB?)

- Sound levels are a factor of the logarithm of a ratio, which includes a reference value as the denominator
- Sound pressure level: **20 log ($P/P_o$)**

  ($P_o$ in water = 1 $\mu$Pa, $P_o$ in air = 20 $\mu$Pa)

  Air/water difference: 20 log(20) = 26 dB

- Sound intensity level: **10 log ($I/I_o$)**

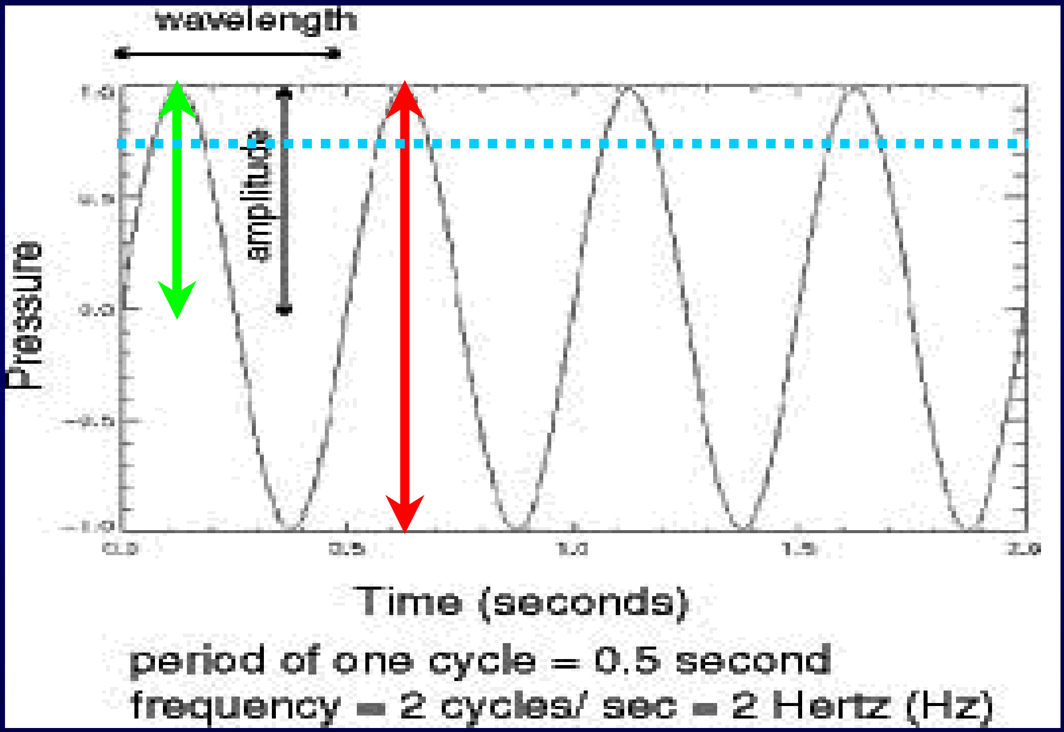
  ($I_o$ in water = $6.7 \times 10^{-19}$ $W/m^2$, $I_o$ in air = $1 \times 10^{-12}$ $W/m^2$) ***

  Air/water difference: pressure difference (26 dB) + impedance difference (37 dB) = 63 dB

# Acoustic Units: Wait, there's more... Peak, Peak-to-Peak, and RMS

Peak Pressure

Peak-to-Peak Pressure




RMS Pressure

For non-transients:

$$dB_{rms} + 3 = dB_{peak} + 6 = dB_{peak\text{-}to\text{-}peak}$$

# Acoustic Units: Another wrinkle… Energy Flux Density

- For brief sounds (*e.g.*, explosions), appropriate measurements include both pressure and duration
- Energy measurements are also useful in considering cumulative effects on longer sounds
- Proportional to time integral of pressure squared; may be described as: 10 log [(pressure)$^2$*time(s)] with units in dB re: 1 (or 20) $\mu$Pa$^2$*s

# Acoustic Units: And finally… Analysis Bandwidth

- Both natural and artificial receivers of sound perform some type of frequency filtering analysis
- Important to know the analysis bandwidth

  Broadband (across spectrum)

  1-octave

  1/3rd-octave

  1/12th-octave

  1 Hz (spectral density level)

# Source Characteristics: Natural and Human Underwater Sounds

| Sound Source | Typical Source Level ($dB_{rms}$ re: $1\mu Pa$) | Frequency Range (kHz) |
|---|---|---|
| Weddell Seal | 155 - 190 | 0.1 - 12.8 |
| Cetacean Sonar | 135 - 225 | 10 - 200 |
| Humpback Whale | 145 - 190 | 0.4 - 4.0 |
| Large Ship | 170 - 190 | 0.01 - 1.0 |
| Airgun Array | 235 - 255 | 0.01 - 1.0 |
| LFA Sonar | 210 - 220 | 0.1 - 0.5 |

# Path Characteristics: Ambient Noise

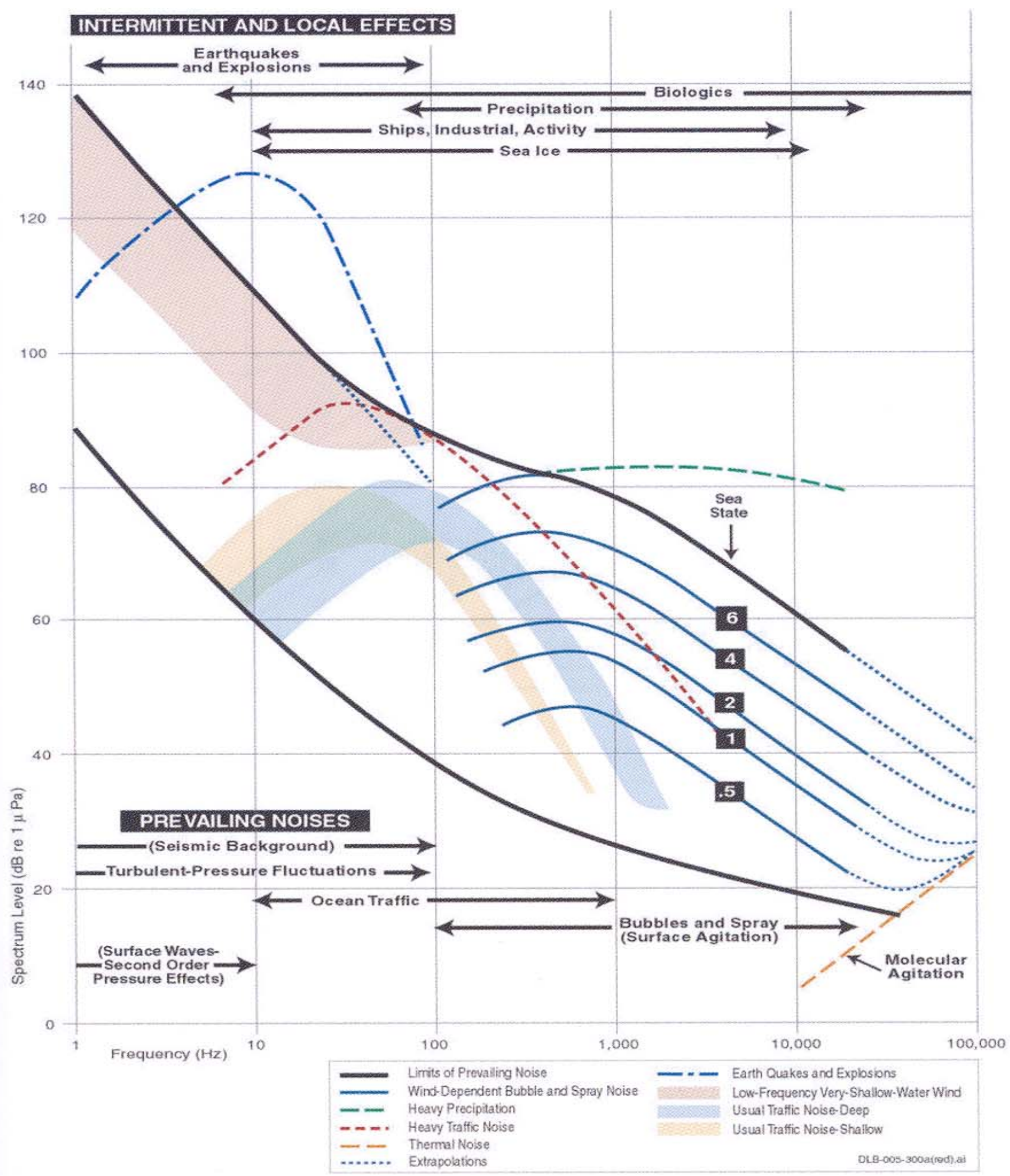



PLATE 1 Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping. (Adapted from Wenz, 1962.)

Source: NRC, 2002 (adapted from Wenz, 1962)

# Received Noise Levels Depend on Many Factors

Misleading comparisons frequently made between source and received levels

- **Source Characteristics (including level)**
- **Propagation (Path) Characteristics**
  - Frequency of Sound: low frequencies travel farthest
  - Range: levels drop rapidly with distance
  - Depth of Source and Receiver in Water Column

# Path Characteristics: Sound Propagation

Sound Propagation is Highly Variable Depending on Environmental Features

- Source level, frequency, duration, directionality (beam pattern), depth
- Geographical location and time of year
- Sound speed profiles with depth
- Presence and characteristics of boundaries

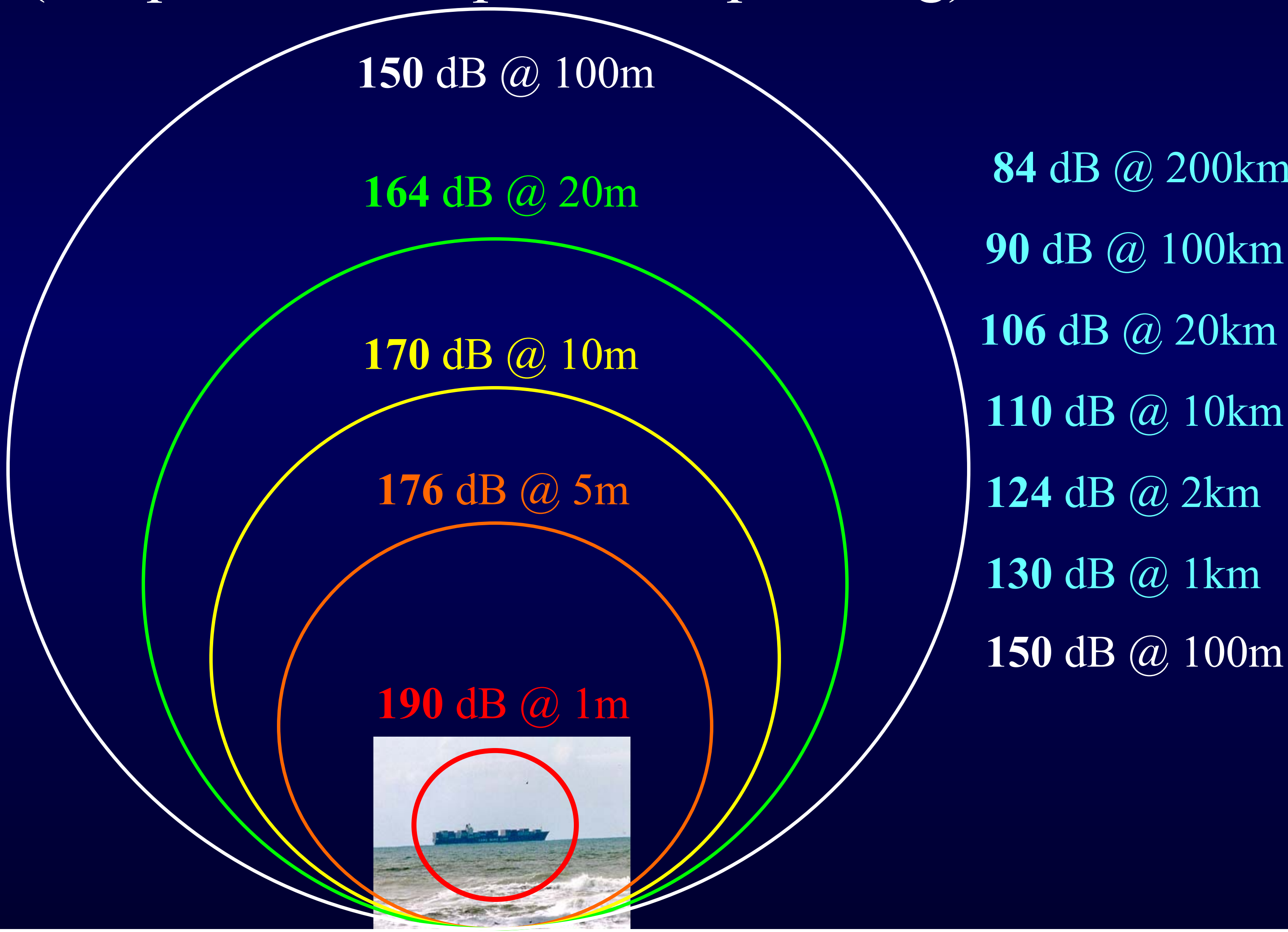
# Path Characteristics: Predicting Propagation Loss

Sound propagation loss with range (R) may be predicted by the following equations

- **Spherical Spreading**: Received Level (RL) = Source Level (SL) - 20 logR- αR
- **Cylindrical Spreading**: RL = SL - 10 logR - αR

# Sound Levels Drop Rapidly as Sound Waves Spread Over an Increasingly Large Area

(Simple Model: Spherical Spreading)




Not to Scale

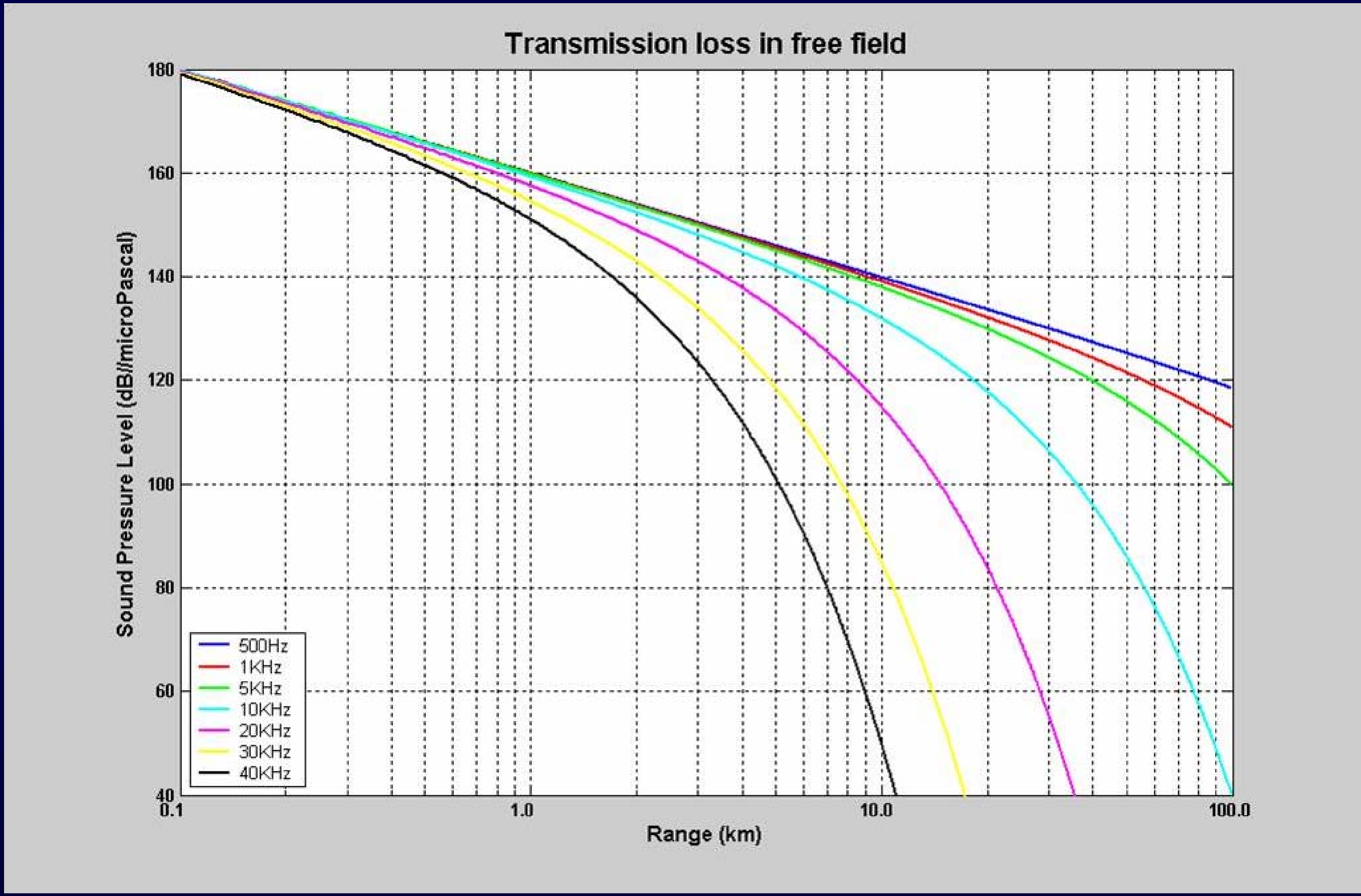
# Sound Levels are Also Reduced as Sound Energy is Absorbed by Water

(Sound Frequency is Critical)

Absorption Loss at Variable Range

| | **1 km** | **10 km** | **100 km** |
|---|---|---|---|
| **0.1 kHz** | - 0.001 dB | - 0.01 dB | - 0.1 dB |
| **1 kHz** | - 0.1 dB | - 1 dB | - 10 dB |
| **40 kHz** | -10 dB | -100 dB | n/a |

# Geometrical spreading and absorption effects in sound propagation loss

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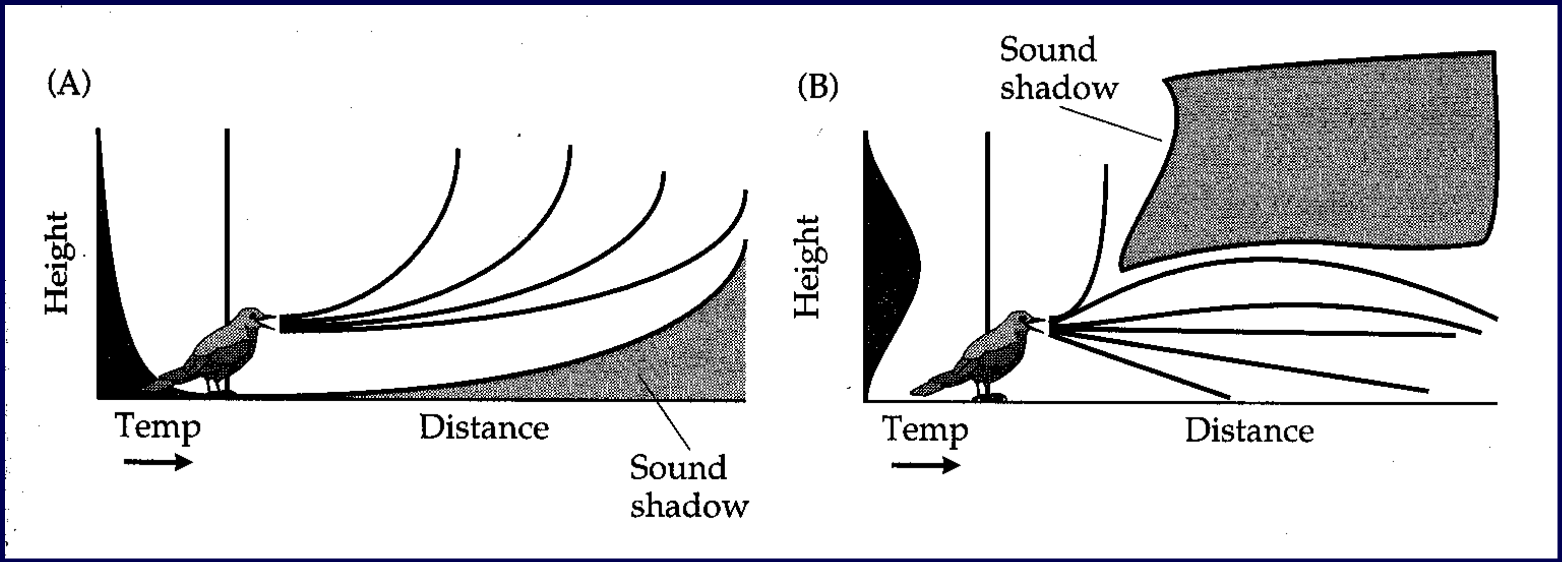
# Refraction Can Cause Sound Propagation to be Very Different than Theoretical Models (Aerial Example)

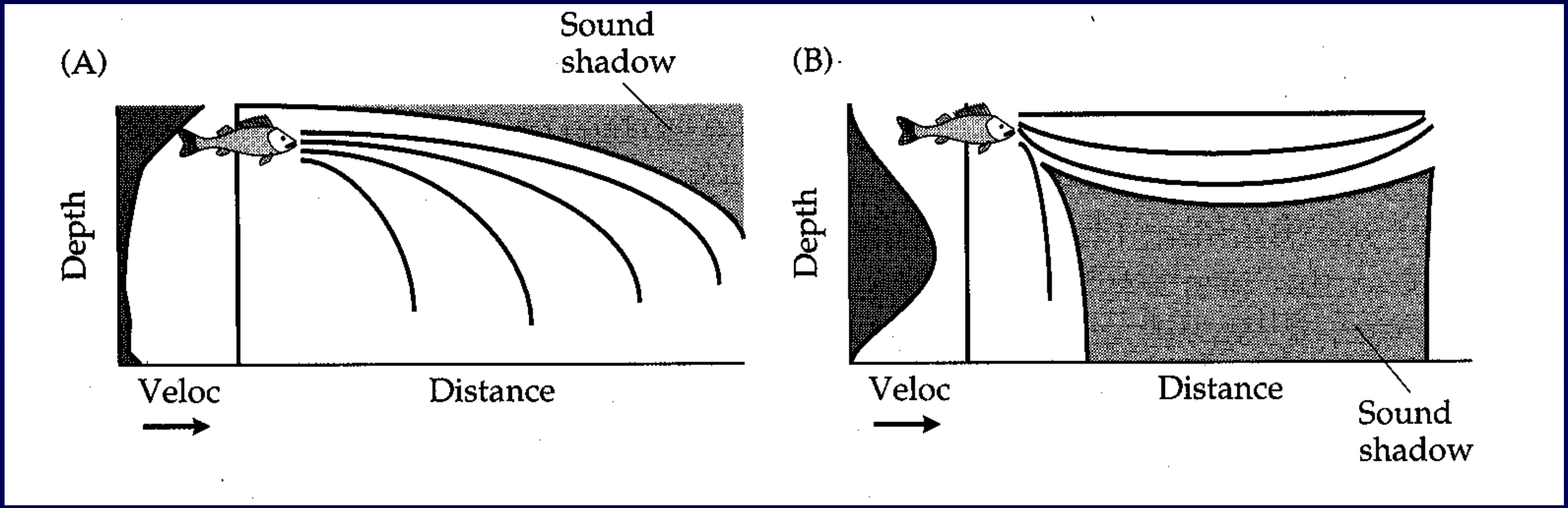



**(A)** Air near ground warmest, sounds refracted upwards

**(B)** Warmest air above ground, sounds refracted downwards

Source: Bradbury and Vehrencamp, 1998

# Refraction Can Cause Sound Propagation to be Very Different than Theoretical Models (Underwater Example)

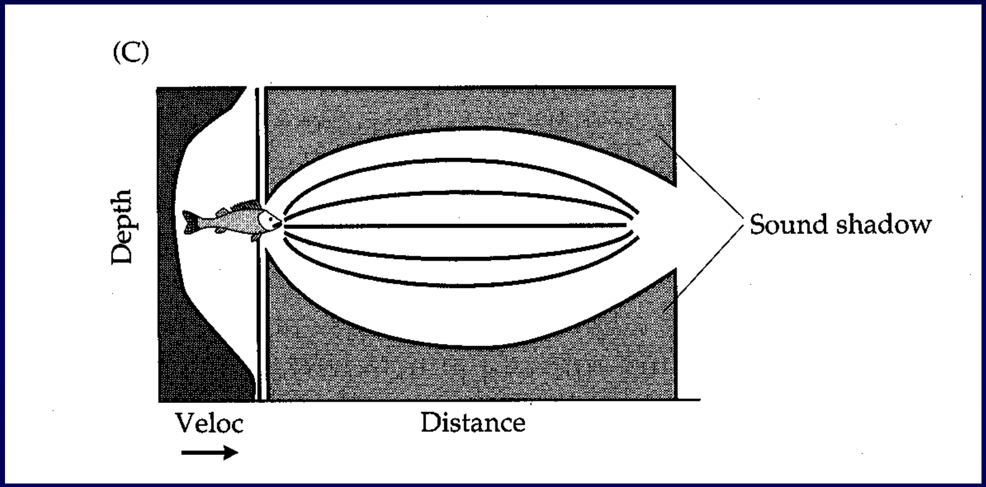


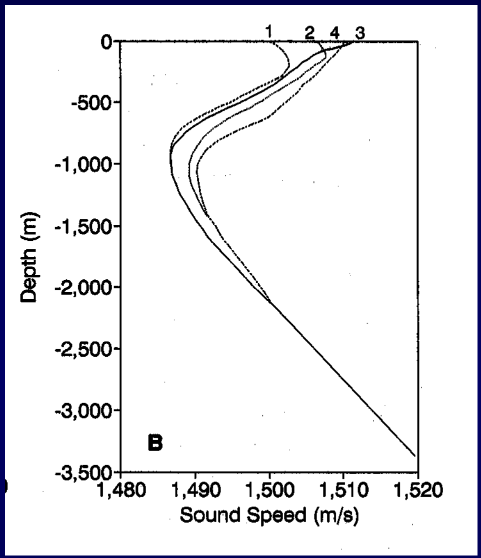

**(A)** Surface layer warm - sound refracted away from surface

**(B)** Surface cold - sound refracted toward surface

Source: Bradbury and Vehrencamp, 1998

# In Certain Conditions, Refraction can Cause Sound to Travel Long Distances by "Ducting"

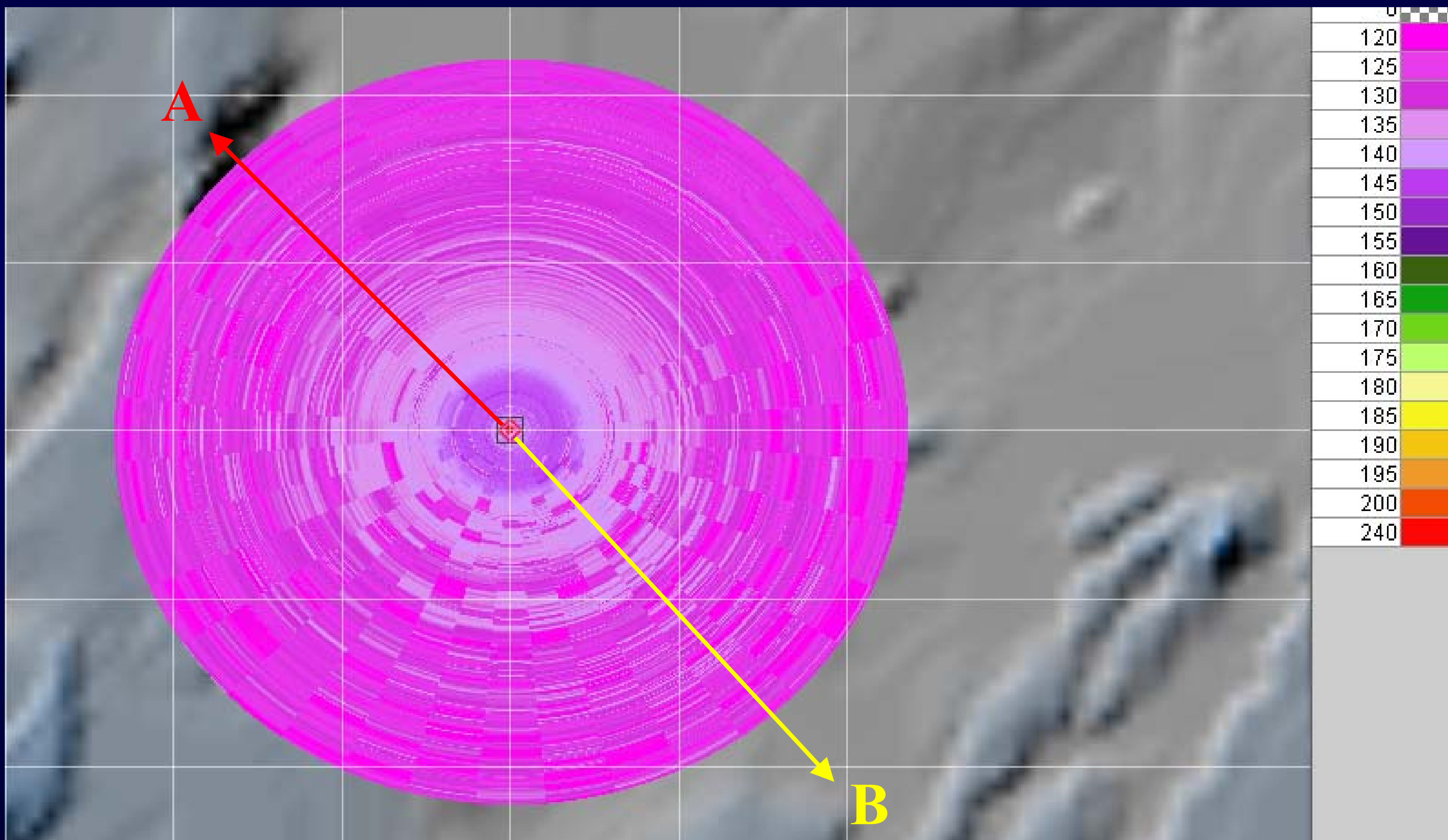


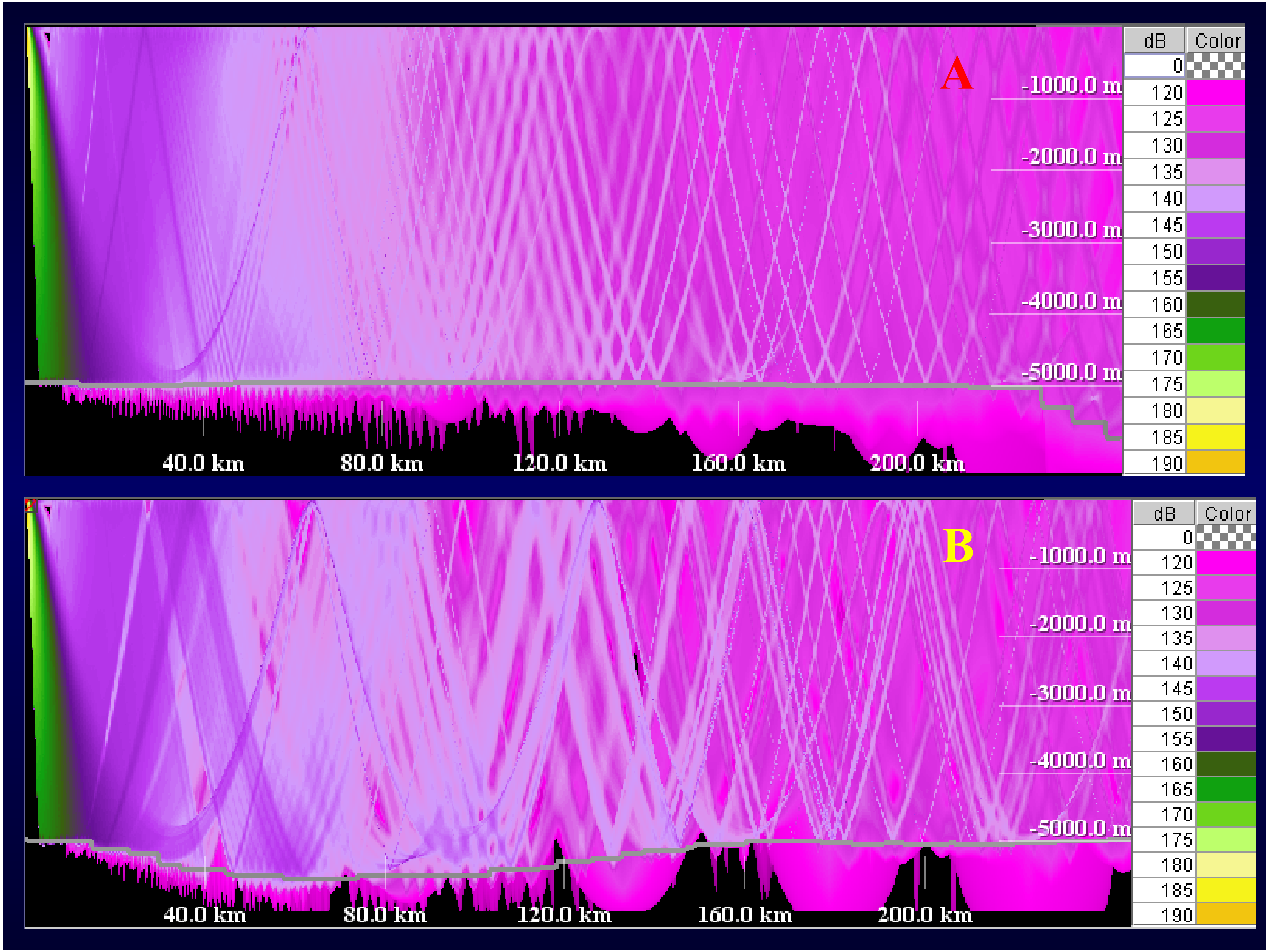




Sound produced within a zone of minimum sound speed can be trapped or "ducted" and travel very long distances in the sound fixing and ranging (SOFAR) channel.

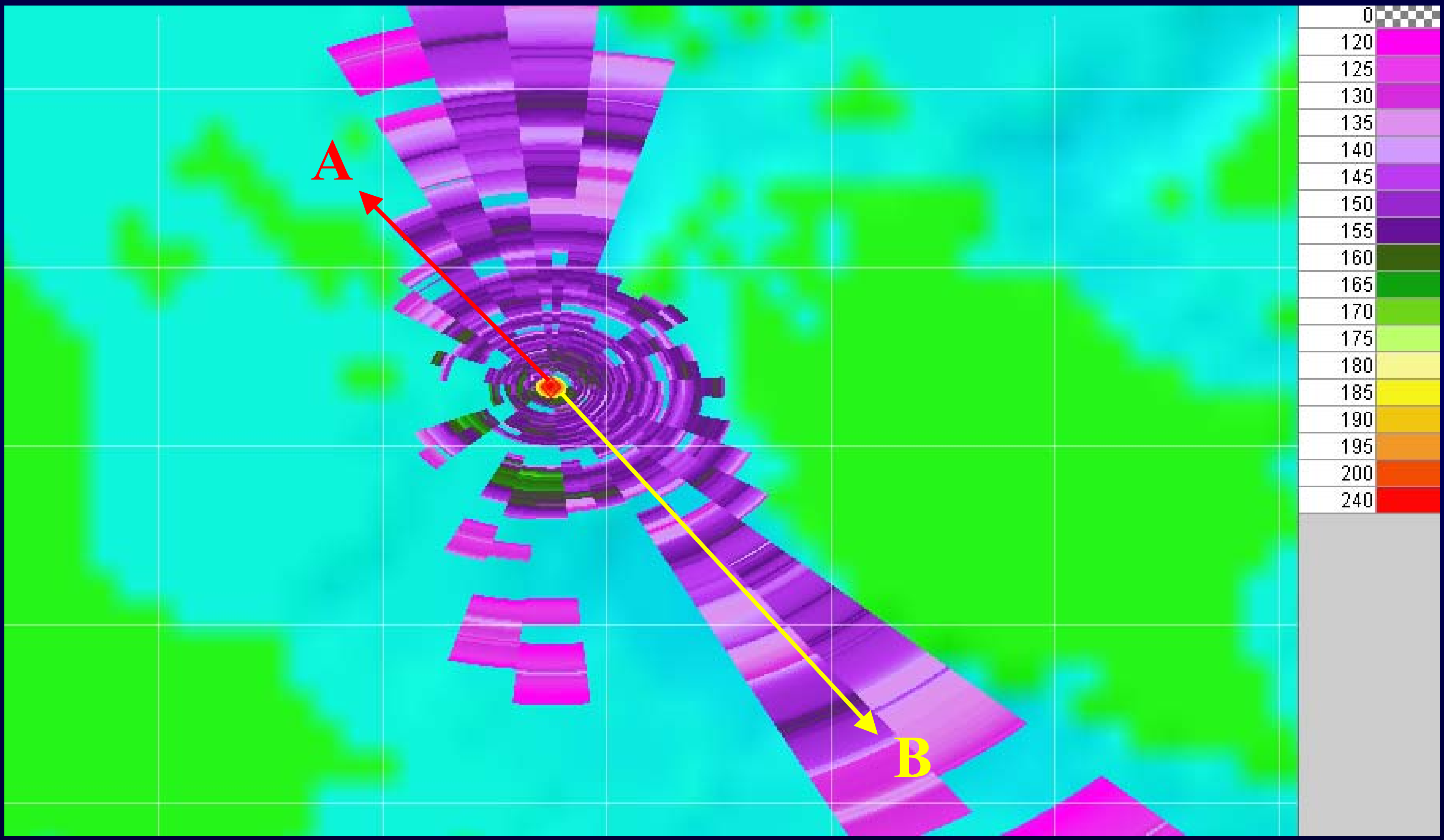
Sources: Bradbury and Vehrencamp, 1998; Richardson *et al*., 1995

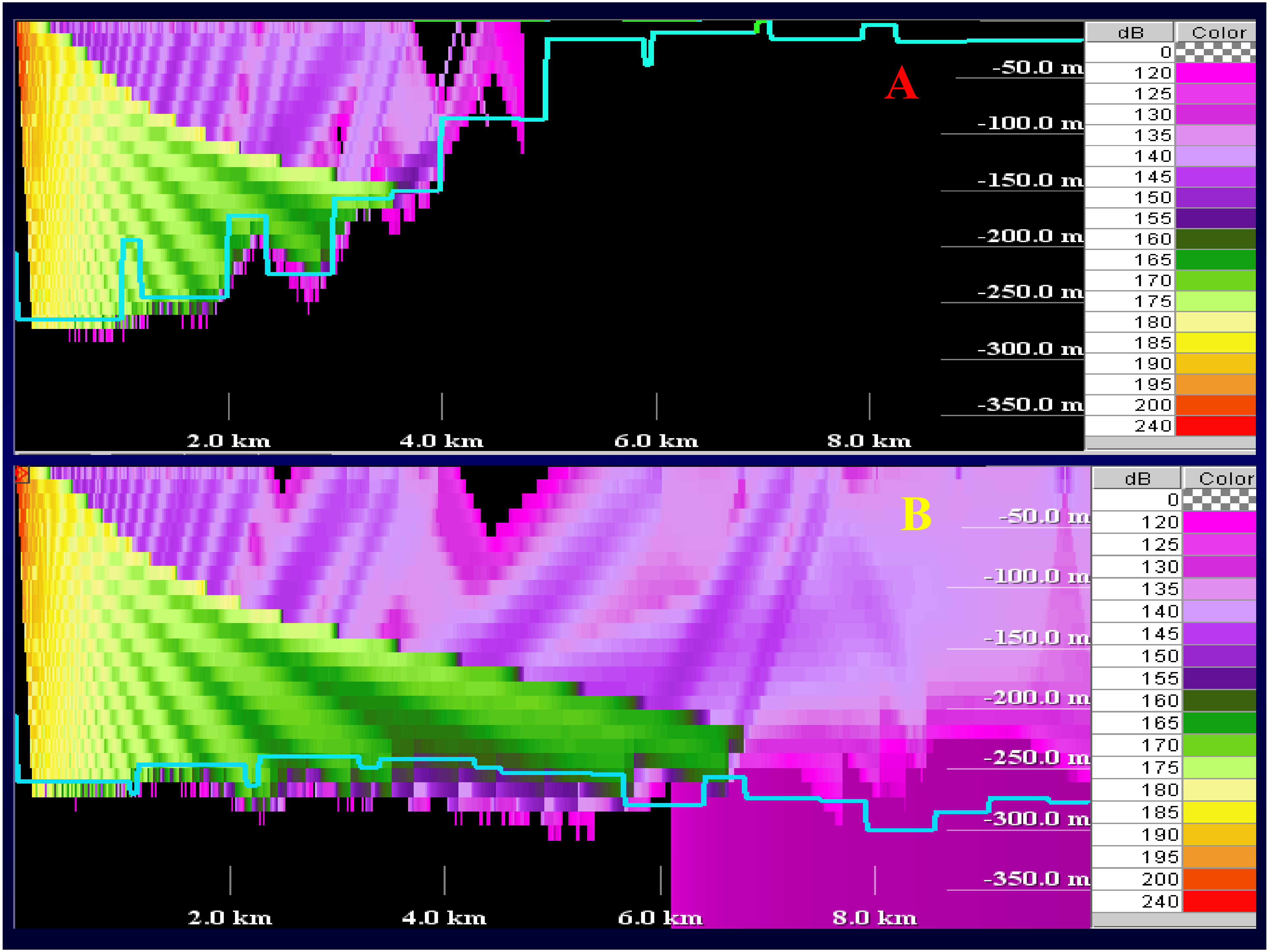
# Sound Propagation Example:
## Deep water/low environmental variability




A
-1000.0 m
-2000.0 m
-3000.0 m
-4000.0 m
-5000.0 m
40.0 km
80.0 km
120.0 km
160.0 km
200.0 km
dB
Color
0
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
B
-1000.0 m
-2000.0 m
-3000.0 m
-4000.0 m
-5000.0 m
40.0 km
80.0 km
120.0 km
160.0 km
200.0 km
dB
Color
0
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190

# Sound Propagation Example:
## Shallow water/high environmental variability




A
-50.0 m
-100.0 m
-150.0 m
-200.0 m
-250.0 m
-300.0 m
-350.0 m
2.0 km
4.0 km
6.0 km
8.0 km
dB
Color
0
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
240
B
-50.0 m
-100.0 m
-150.0 m
-200.0 m
-250.0 m
-300.0 m
-350.0 m
2.0 km
4.0 km
6.0 km
8.0 km
dB
Color
0
120
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180
185
190
195
200
240

# Conclusions

- Many physical variables determine noise conditions experienced by an animal and the effects they may have. Our understanding of certain factors is limited.
- However, we can and should use the information available to make decisions about noise impacts that reflect these complexities.
- There are certain principles of physics (*e.g.*, spreading loss) involved in these issues for which no opinion or interpretation is warranted.

*** Clarification ***

Separate reference intensity values were given for water (6.67 x $10^{-19}$ W/$m^2$) and air (1 x $10^{-12}$ W/$m^2$). The value for water represents the intensity calculated as the underwater reference pressure (1 μPa) squared divided by the medium impedance. However, the appropriate reference intensity for both media based on ANSI (1994) standards is (1 x $10^{-12}$ W/$m^2$, which is also referred to a 1 pW/$m^2$). Thus the appropriate calculation for sound intensity levels in either media, making the assumption that what is being measured is a free plane wave, based on the calculation given in the presentation is 10 log (intensity/(1 pW/$m^2$)).]