Underwater Acoustics:

Noise and the Effects on Marine Mammals

A Pocket Handbook
3rd Edition

Compiled by
Christine Erbe

JASCO APPLIED SCIENCES

www.jasco.com   info@jasco.com

2101 – 4464 Markham St. Victoria, British Columbia V8Z 7X8 Canada Tel: +1.250.483.3300 Fax: +1.250.483.3301 Victoria@jasco.com	301 – 32 Troop Ave. Dartmouth, Nova Scotia B3B 1Z1 Canada Tel: +1.902.405.3336 Fax: +1.902.405.3337 Halifax@jasco.com
Brisbane Technology Park 1 Clunies Ross Court PO Box 4037, Eight Mile Plains QLD 4113 Australia Tel: +61.7.3853.5218 Fax: +61.7.3853.5211 Australia@jasco.com	The Roundel, St Clair's Farm Wickham Road Droxford, Hampshire SO32 3PW United Kingdom Tel/Fax: +44.1489.878439 Europe@jasco.com

Part A: Fundamentals of Underwater Acoustics

Units: This book uses the International System of Units (SI).

Quantity	**Unit Name**	**Symbol**
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Luminous intensity	Candela	cd
Amount of substance	Mole	mol

Table 1: SI Units.

Other quantities and their units are derived from these base quantities via quantity equations.

Multiplier Prefixes:

Prefix	**Symbol**	**Factor**		**Prefix**	**Symbol**	**Factor**
deci	d	10^{-1}		deka	da	10^{1}
centi	c	10^{-2}		hecto	h	10^{2}
milli	m	10^{-3}		kilo	k	10^{3}
micro	µ	10^{-6}		mega	M	10^{6}
nano	n	10^{-9}		giga	G	10^{9}
pico	p	10^{-12}		tera	T	10^{12}

Table 2: SI Multiplier Prefixes.

1. Terminology

Sound:
- a mechanical wave
- travels through a medium by oscillation of its particles

in water and air:
- travels as longitudinal (pressure, *P*) wave
- alternating compressions and rarefactions

in rock:
- travels as both longitudinal and transverse (shear, *S*) waves
- *P* waves travel faster than *S* waves => *P* arrive before *S*
- *P*: primary; *S*: secondary

Frequency:
- rate of oscillation
- number of cycles per second
- f [Hz: Hertz]; 1 Hz = 1/s

Harmonics: integer multiples of the fundamental f : $2f$, $3f$, $4f$, ...

Period:
- duration of 1 cycle : $T = 1/f$ [s]

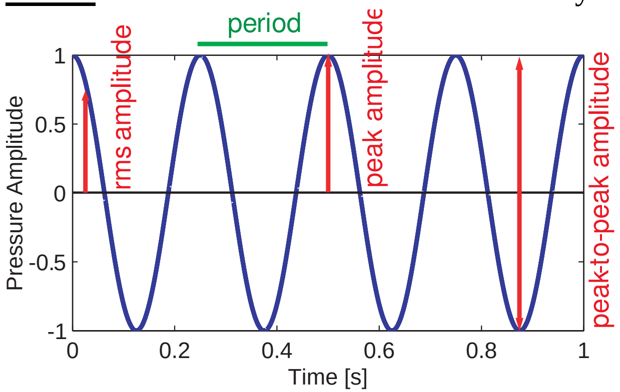


Figure 1: A cosine wave having a peak amplitude of 1, a peak-to-peak amplitude of 2, an rms amplitude of 0.7, a period of 0.25s, and a frequency of 4 Hz.

Wavelength: • the spatial distance between two successive 'peaks' in a propagating wave: λ [m]

Speed:
- the ratio of distance travelled per time
- $c = \lambda / T = \lambda \times f$ [m/s]

Medium	c_P [m/s]	c_S [m/s]
Air, 20°C	343	
Fresh water, 25°C	1,497	
Salt water, 25°C, S=33 ppt, D=1m	1,532	
Sand	800 – 2,200	
Clay	1,000 – 2,500	
Sandstone	1,400 – 4,300	700 – 2,800
Granite	5,500 – 5,900	2,800 – 3,000
Limestone	5,900 – 6,100	2,800 – 3,000

Table 3: P-wave and S-wave speeds of certain Earth materials.

Particle Velocity: • a vector (having direction): u [m/s]

- the speed at, and the direction in which the water particles move (vibrate)

Pressure: • force per area

- *Hydrostatic* pressure at any given depth in a *static* liquid is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid.
- *Acoustic* pressure is due to a deviation from the ambient hydrostatic pressure caused by a sound wave.
- measured with a *microphone* in air
- measured with a *hydrophone* under water
- P [1 bar = 10^5 Pa = 10^6 dyn/cm^2]
- $\vec{\nabla} P = -\rho \frac{\partial \vec{u}}{\partial t}$ (Newton's 2nd Law)
- $P = \rho c u$ in the far-field, or for plane waves

Acoustic Impedance: • $Z = \rho c$, ρ: density, c: sound speed

- in air, 0°C: ρ = 1.3 kg/m^3, c = 331 m/s => Z = 430 kg/m^{2}s
- in fresh water, 15°C: ρ = 1,000 kg/m^3, c = 1,481 m/s => Z = 1,481,000 kg/m^{2}s
- in sea water, 15°C, 3.5% salinity, 1m deep: ρ = 1,035 kg/m^3, c = 1,507 m/s => Z = 1,559,745 kg/m^{2}s

Examples of Underwater Sound Levels	dB re 1 µPa
Peak P of 1 GI airgun (45 in^3 generator) @ 1m [31]	228
Peak P of sperm whale click [36]	223
Peak P of pile driving (75cm diameter, 13mm wall thickness, 180 kJ hammer) @ 14m [15]	207
Source level (rms) of a zodiac with twin 175 hp outboard motors travelling @ 55 km/h [12]	169
Source level (rms) of a zodiac with twin 175 hp outboard motors travelling @ 10 km/h [12]	147
Source level of killer whale whistle [35]	140
Beluga hearing threshold @ 500 Hz [16]	107
Snapping shrimp spectrum @ 4 kHz [15]	72
Beluga hearing threshold @ 10 kHz [16]	64
Ambient noise, SS 2, @ 1 kHz [12]	59

Table 4: Examples of pressure levels.

Acoustic Energy: • energy of an acoustic wave
• E [J: Joules]; 1 J = 1 kg m^2/s^2

• sum of kinetic E (contained in particle movement) and potential E (= work done by elastic pressure forces)
• proportional to squared pressure P^2 and time T in plane waves

Acoustic Intensity: • acoustic energy E flowing through a unit area A perpendicular to the direction of propagation, per unit time T

• $I = E / AT = Pwr / A$
• $I = P^2/Z = P^2/(\rho c)$ for plane waves

Acoustic Power: • the amount of sonic energy E transferred (radiated) within a certain time T

• $Pwr = E / T = I \text{ x } A$
• Pwr [W: Watts]; 1 W = 1 J/s = 1 kg m^2/s^3

Decibel: [dB]

- quantifies variables with large dynamic ranges on a logarithmic scale
- quantities expressed in dB are referred to as "levels"
- $20 \log_{10}(P/P_{ref})$, P_{ref} = 1 µPa under water

- $10 \log_{10}(I/I_{ref})$, $I_{ref} = 6.5\text{x}10^{-19}$ W/m^2 for a plane wave with $P_{rms} = 1$ µPa

Levels in Air vs. Water:

- Standard reference level in air: P_{ref} =20 µPa, under water: P_{ref} =1 µPa.
- 0 dB re 20 µPa = 26 dB re 1 µPa, because 20 $\log_{10}20 = 26$
- For 2 sources of equal intensity in air and under water, the pressure under water is 36 dB greater than the pressure in air:
  $I_a = I_w \Leftrightarrow P_a^2/Z_a = P_w^2/Z_w \Leftrightarrow P_w/P_a = \sqrt{(Z_w/Z_a)}$
  $$20\log_{10}\sqrt{\rho_w c_w/\rho_a c_a} = 36$$

Some dB Mathematics:

- How to convert from dB to linear scale:
  e.g., 120 dB re 1µPa = 20 $\log_{10}(x$ /µPa)
  What is x? $x = 10^{120/20}$ µPa = 10^6 µPa
- Addition of dB (e.g. amplifier gains):
  120 dB re 1µPa + 120 dB = 240 dB re 1µPa
- Addition of dB referenced to absolute values:
  120 dB re 1µPa + 120 dB re 1µPa = 126 dB re 1µPa, because
  120 dB re 1µPa = 1 x 10^6 µPa
  1 x 10^6 µPa + 1 x 10^6 µPa = 2 x 10^6 µPa = 126 dB re 1µPa; absolute values need to be added in linear space.
- A doubling in pressure adds 6 dB:
  $20 \log_{10}(2P/P_{ref}) = 20 \log_{10}(2) + 20 \log_{10}(P/P_{ref})$
  $= 6 \text{ dB} + 20 \log_{10}(P/P_{ref})$
- A doubling in intensity adds 3 dB:
  $10 \log_{10}(2I/I_{ref}) = 10 \log_{10}(2) + 10 \log_{10}(I/I_{ref}) = 3 \text{ dB} + 10 \log_{10}(I/I_{ref})$
- A 10-fold increase in intensity adds 10 dB:
  $10 \log_{10}(10I/I_{ref}) = 10 \log_{10}(10) + 10 \log_{10}(I/I_{ref})$
  $= 10 \text{ dB} + 10 \log_{10}(I/I_{ref})$
- Inversion of reference units changes the sign:
  -180 dB re 1V/µPa = + 180 dB re 1µPa/V
- Addition of dB with differing reference units:
  -180 dB re 1V/µPa – 20 dB re *FS*/V = -200 dB re *FS*/µPa

Peak Pressure:

- maximum absolute value of the amplitude of a pressure time series $P(t)$
- also called zero-to-peak pressure (Figure 1)

Peak Pressure Level: [dB re 1 µPa]

$$SPL_{Pk} = 20\log_{10}(\max(|P(t)|))$$

Peak-to-peak Pressure Level: [dB re 1 µPa]

$$SPL_{Pk-Pk} = 20\log_{10}(\max(P(t)) - \min(P(t)))$$

RMS Pressure:

- root-mean-square of the time series $P(t)$
- useful for continuous sound (as opposed to pulsed)

RMS Pressure Level: [dB re 1 µPa]

$$SPL_{rms} = 20\log_{10}\left(\sqrt{\frac{1}{T}\int_T P(t)^2\, dt}\right)$$

Source Level:

- acoustic pressure at 1m distance from a point source
- *SL* [dB re 1 µPa @ 1m]
- For sources that are physically larger than a few cm (ship propellers, airguns etc.), the pressure is measured at some range, and a sound propagation model applied to compute what the pressure would have been at 1m range if the source could have been collapsed into a point-source.
- If *Pwr* is the total radiated source power in Watts, ρ= 1000kg/m^3 the water density, and c = 1500 m/s the sound speed, then
  $SL = 10\log_{10}(10^{12}\, \rho c\, Pwr / 4\pi) = 170.77 \text{ dB} + 10\log_{10}(Pwr)$
- A 1 Watt source has a *SL* of 170.77 dB re 1µPa @ 1m.
- *SL* can also be expressed in terms of sound exposure [dB re 1µPa^{2}s].

Sound Exposure Level:

- proportional to the total energy of a signal
- for plane waves:

$$SEL = 10\log_{10}\left(\int_T P(t)^2\, dt\right)$$

$$SEL = SPL_{rms} + 10\log_{10}T$$

- [dB re 1 µPa^2•s]

In the presence of significant ambient noise $P_n(t)$, noise energy needs to be subtracted to compute sound exposure from the signal alone. In praxis, the noise energy is computed from a time section preceding or succeeding the signal:

$$SEL = 10\log_{10}\left(\int_0^T P(t)^2\,dt - \int_{Tn}^{Tn+T} P_n(t)^2\,dt\right)$$

Pulse Length: For pulsed sound (e.g. airguns, pile driving), the pulse length $T_{90\%}$ is taken as the time between the 5% and the 95% points on the cumulative energy curve. $SPL_{rms90\%}$ is computed by integrating P^2 from $T_{5\%}$ to $T_{95\%}$.

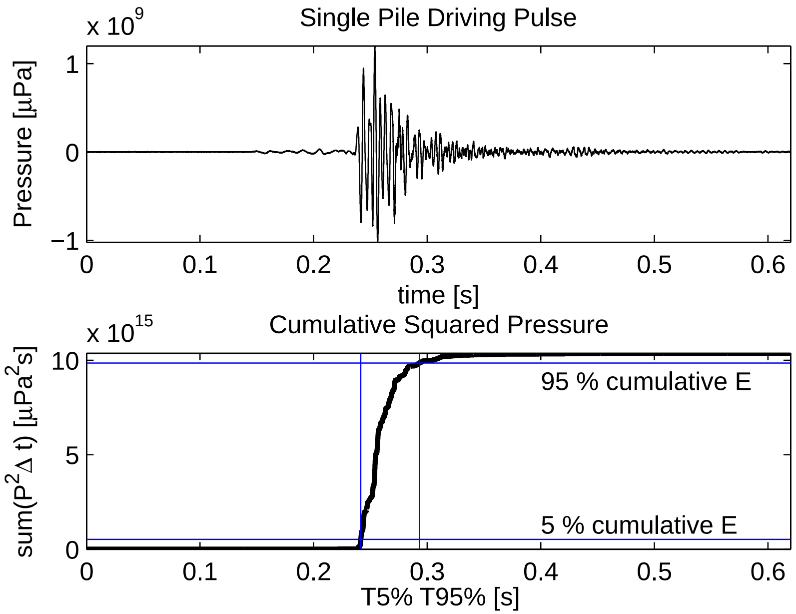


Figure 2: Pile driving waveform (top) and cumulative energy curve (bottom); horizontal lines mark the 5% and 95% cumulative energy; vertical lines mark the corresponding times.

Duty Cycle: The fraction of time that a source is 'on'. E.g., a source transmitting for 2h per day has a duty cycle of 2/24 = 0.08 = 8%.

Fourier Transform:

- computes the spectral (frequency) content of a signal

$$H(f) = \int_{-\infty}^{\infty} h(t)e^{-2\pi i f t}\,dt$$

$$h(t) = \int_{-\infty}^{\infty} H(f)e^{2\pi i f t}\,df \qquad \text{inverse transform}$$

Power Spectrum Density:

- describes how the power of a signal is distributed with f
- 1. read the signal time series [µPa] in windows of length T [s]; 2. compute the Fourier Transform [µPa/Hz]; 3. square the amplitudes, discard negative f, double remaining amplitudes [µPa^2/Hz^2]; 4. divide by T [=> µPa^2/Hz]
- If T=1s, then the power is computed in bands of constant 1Hz width.

Power Spectrum Density Level: [dB re 1 µPa^2/Hz]

- 10 $\log_{10}$ of squared sound pressure in 1 Hz bands ("1 Hz band level")

Frequency Bands:

- The spectrum of a sound can be split into a series of adjacent frequency bands.
- *Constant bandwidth*: All bands are equally wide, e.g. 1 Hz => power spectrum density.
- *Proportional bandwidths*: The ratio of upper to lower frequency remains constant. Bands become wider with increasing f. Common examples are octave and 1/3 octave bands.
- Bandwidth is computed as the difference between upper and lower band-edge frequency: $\Delta f = f_{up} - f_{low}$
- Centre frequencies of proportional bands are computed as the geometric mean (not the arithmetic mean): $f_C = \sqrt{f_{low} \times f_{up}}$

Octave Bands:

- o Series of adjacent pass bands that are 1 octave wide.
- o From one octave to the next, frequency doubles: $f_{up} = 2\, f_{low}$

1/3 Octave Bands:

- o Series of adjacent pass bands that are 1/3 of an octave wide.
- o Every octave is split into 3 adjacent bands, not linearly but logarithmically.

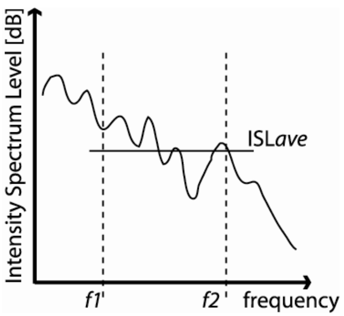
- Centre frequencies f_C of adjacent 1/3 octave bands are computed as $f_C(n) = 10^{n/10}$, where n counts the 1/3 octave bands
- The lower and upper frequencies of band n are:

$$f_{low}(n) = 10^{-1/20} \times f_c(n) \qquad f_{up}(n) = 10^{1/20} \times f_c(n)$$

10	12.5	16
20	25	31.5
40	50	63
80	100	125
160	200	250
315	400	500
630	800	1000
1250	1600	2000
2500	3150	4000
5000	6300	8000
10000	12500	16000
20000	31500	31500

Table 5: Centre frequencies of adjacent 1/3 octave bands [Hz] [2; 28].

Band Levels:



Consider the sketched intensity spectrum. The band level BL in the band f_1-f_2 is the total intensity in this band: $BL = 10 \log_{10}(I_{tot}/I_{ref})$.

Let I_{1Hz} be the intensity spectral density, i.e. the intensity in 1Hz bands [intensity per Hz], and I_{ave} the average intensity per Hz, then:

$$I_{tot} = \int_{f_1}^{f_2} I_{1Hz}\, df = I_{ave} \times (f_2 - f_1).$$

The band level thus becomes:
$BL = 10 \log_{10}(I_{ave} \times \Delta f) = ISL_{ave} + 10 \log_{10}(\Delta f / \text{Hz})$,
where ISL_{ave} is the average intensity spectrum level.

1/3 Octave Band Levels:

- pressure or energy levels in bands that are 1/3 of an octave wide

- easily computed by integrating power density spectrum into 1/3 octave bands
- can be SPL [dB re 1 µPa] or SEL [dB re 1 µPa^{2}s]

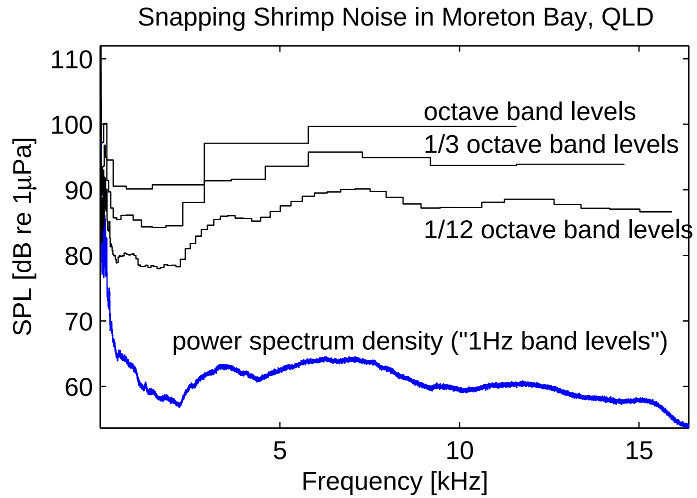


Figure 3: Illustration of band levels versus power spectrum density levels, for the example of snapping shrimp noise [15]. The spectrum density level drops with increasing frequency up to 2kHz; the increase between 2-16kHz is attributable to snapping shrimp. Band levels are at least as high as the underlying spectrum density levels. There are twelve 1/12-octave bands in each octave, and three 1/3-octave bands. The wider the band, the higher the level, because more power gets integrated.

Percentile Levels:

- useful if the measured sound changes with time
- 50th percentile = median sound level
- The nth percentile gives the level that is exceeded n% of the time (note: in engineering, the definition is reversed).

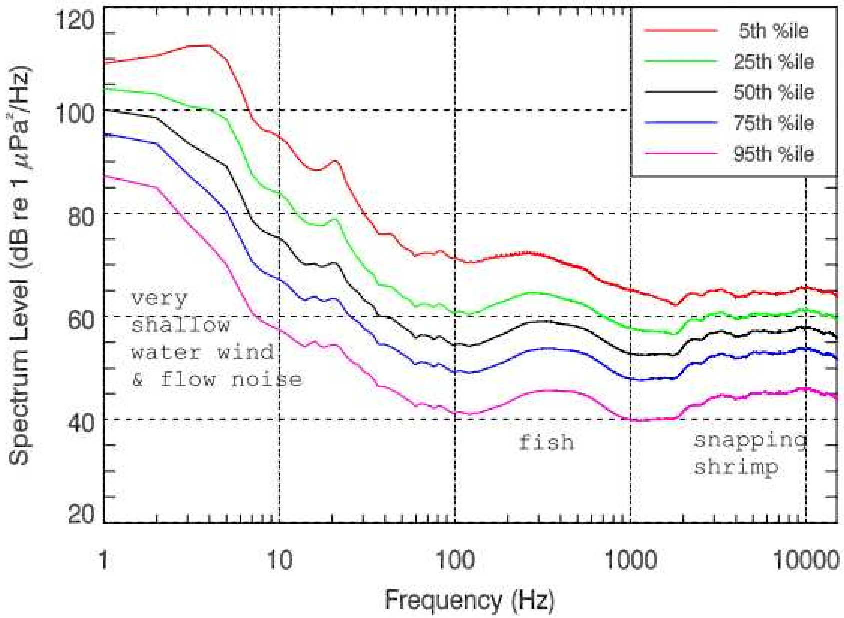


Figure 4: Percentiles of ambient noise power spectrum densities measured in tropical water over a 2 month period. Lines from top to bottom correspond to the 5th, 25th, 50th, 75th and 95th percentiles.

2. Sound Sources

a. Natural Sound Sources

Ambient Noise Spectra ("Wenz Curves"):

Figure 5 was adapted from Wenz [52]. While the often cited "Wenz curves" show sea state dependent noise spectra only above 200 Hz, with a peak at about 500 Hz, Wenz himself showed measurements at lower frequencies [52]. Spectrum levels exhibited a local minimum at about 100-200 Hz and rose for f < 100 Hz. A similar relationship was observed by Cato [4] around Australia. The "Cato curves" were joined to the "Wenz curves" in Figure 5.

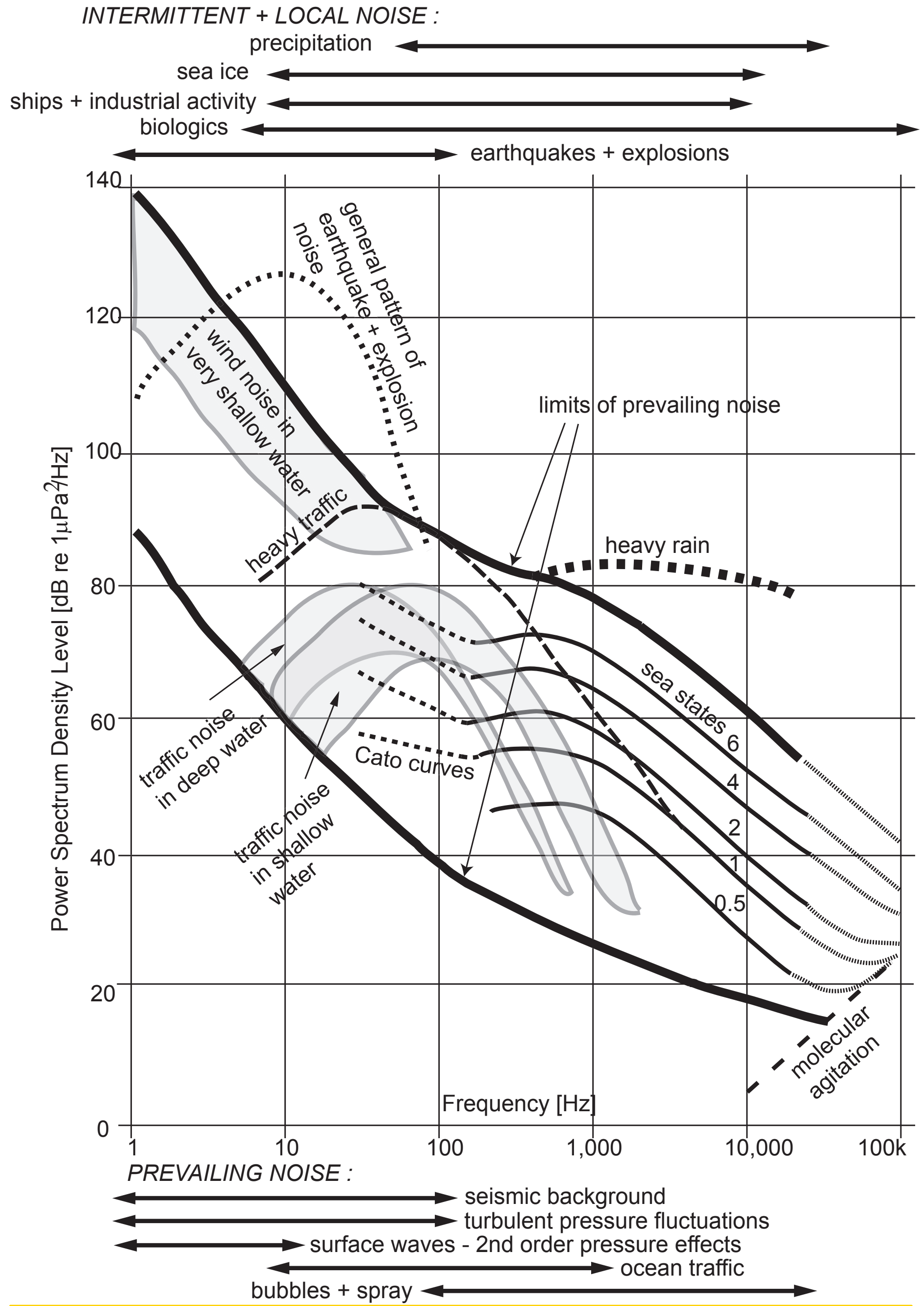


Figure 5: Ambient noise spectra after Wenz [52]; wind dependent noise < 100 Hz from Cato [4].

Beaufort Scale:

Wind Speed [kn]	Beau-fort Scale	Sea State (SS)	Wave Height [m]	WMO Meteoro-logical Terms	Description
< 1	0	0	0	Calm	Flat, glassy
1-2	1	0.5	0.1	Light air	Ripples without crests
3-6	2	1	0.2	Light breeze	Small wavelets, glassy crests
7-10	3	2	0.6	Gentle breeze	Large wavelets, crests begin to break
11-15	4	3	1	Moderate breeze	Small waves, whitecaps
16-20	5	4	2	Fresh breeze	Moderate waves, some foam + spray
21-26	6	5	3	Strong breeze	Large waves with foam crests
27-33	7	6	4	Near gale	Sea heaps up, foam begins to be blown
34-40	8	6	5.5	Gale	High waves, breaking crests form spindrift, streaks of foam
41-47	9	6	7	Strong gale	High waves with dense foam, crests roll over
48-55	10	7	9	Storm	Considerable tumbling of waves with heavy impact, large amounts of airborne spray reduce visibility
56-63	11	8	11.5	Violent storm	Very large patches of foam driven before the wind cover much of the sea surface
> 64	12	9	> 14	Hurri-cane	Sea completely white with foam, air filled with spray

Table 6: Beaufort Scale + Sea State. WMO: World Meteorological Organization.

Deep Ocean Ship Noise: Since Wenz' studies in the 1960s, the number of commercial vessels has approximately doubled, and the gross tonnage quadrupled, with a corresponding increase in horsepower. Deep ocean ambient noise west of California rose by 10-12 dB in 40 years (spectrum levels 10-12 dB higher than in Figure 5), and was attributed to shipping [34].

b. Anthropogenic Sound Sources

- ships, small to large: whale-watching boats; coast guard vessels; support vessels for construction & exploration; naval ships; fishing vessels; cargo vessels
- seismic exploration: oil & gas industry; research
- sonars: fish-finding, echo-ranging, military
- scientific sources; acoustic communication & navigation
- construction & industrial activities: drilling, trawling, dredging, pile driving, renewable energies (wind turbines, tidal power plants)
- explosions: dynamite fishing; military; decommissioning
- aquaculture noise including acoustic deterrent and harassment devices
- low-flying aircraft

Ship Noise:

- consists of machinery noise (main engines, auxiliary machinery, gears) and hydrodynamic noise (flow past the hull, appendages + cavities; blade rate tones; propeller singing; cavitation);
- all machinery on a ship radiates sound through the hull into the water;
- noise increases with ship size, power, load, and speed;
- ships with propellers are generally louder than ships with jet propulsion;
- propeller cavitation is the loudest component for speeds greater than the cavitation inception speed;
- tones at low frequencies correspond to *propeller blade rate* and harmonics: f [Hz] = number of blades x rpm/60 ;
- small vessels have small propellers turning at higher speeds resulting in higher frequency blade-rate tones;
- at low frequency (< a few 100 Hz), the ship spectrum also has tonal components from engines and gears; these spectral lines form the *acoustic signature* of the ship and allow acoustic identification;
- for f >100Hz the spectrum falls as $-20\log_{10}f$.

Doppler Shift:

- The frequency of tones shifts up if a source moves towards a receiver, and down if a source moves away from a receiver. If f_r: received frequency [Hz]; f_o: fundamental frequency [Hz]; c: velocity of sound [m/s]; u: velocity of the source towards (+) or away (-) from the receiver [m/s]; v: velocity of the receiver towards (-) or away (+) from the source [m/s], then

$$f_r = f_0\left(\frac{c+u}{c+v}\right)$$

- E.g. boat approaching at u = 55km/h (30kn, 15m/s); f_O = 200 Hz blade rate frequency; receiving hydrophone stationary (v = 0): f_r = 202 Hz.
- The Doppler Shift increases with increasing speed of the source and receiver towards each other. It plays an import role in active sonar detection, e.g. anti-submarine warfare.

Cavitation: Rotating propellers create regions of low pressure behind the blades. If the pressure drops below the vapour pressure, the water vaporizes, creating bubbles, which become unstable and collapse. Analogy: boiling. Boiling is a result of increasing temperature; cavitation is a result of decreasing pressure.

Ross [45] derived an average ship spectrum (Figure 6) relative to a reference level *L*.

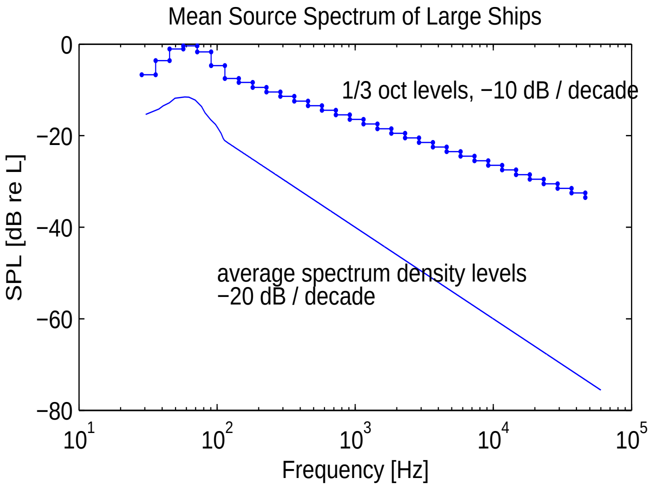


Figure 6: Relative spectrum density levels of large ships [45]. The spectrum follows -20log*f* above 100Hz. Spectral lines at *f*<500Hz (not shown) supersede this average spectrum and differ from ship to ship.

$L = 175 + 60 \log(u/25) + 10 \log(B/4)$,

where u: propeller tip speed [m/s], B: number of blades.

With an 'average' u = 37.5 m/s and B = 4, Scrimger & Heitmeyer [46] computed the predicted Ross spectrum and compared this to 50 measurements of large merchant ships. The measured mean fitted the Ross curve very well, with a maximum deviation of 4dB (below the predicted level, up to 700 Hz). Hamson [26] used the same measured mean spectrum ($SV(f)$) and derived an equation for the source spectrum SL as a function of vessel speed V [knots] and vessel length Le [feet]:

$$SL = SV(f) + 60 \log(V/12) + 20 \log(Le/300)$$

Noise spectra of other vessels can be found in [12] for zodiacs and [18] for icebreakers.

Seismic Exploration:

- most commonly done with arrays of airguns as the acoustic source
- survey vessel (e.g. travelling at 5 knots) tows airgun array
- array fired every few (e.g. 10) seconds
- pulsed pressure waveform sent into the ground
- reflections from various geological layers at various depths are received by the receivers
- receivers can be streamers (hydrophone arrays) towed behind the source array or hydrophones along ocean bottom cables

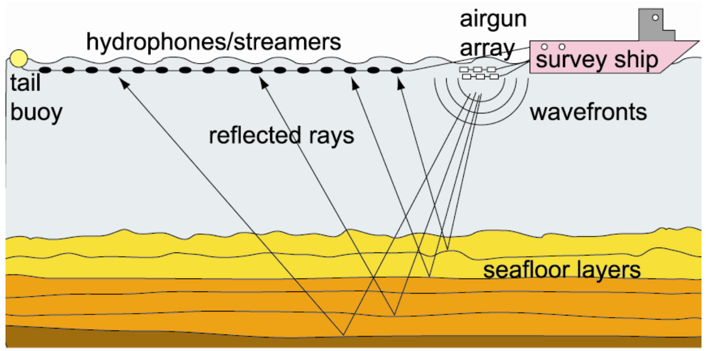


Figure 7: Sketch of a seismic survey. The survey ship tows both the airgun array and the receiving hydrophone streamers.

Airgun:
- underwater chamber of compressed air
- rapidly released air creates oscillating bubble in the water

⇨ omni-directional propagating pressure wave

- waveform shows a primary peak (the desired signal for geophysical profiling) followed by a series of decaying bubble pulses (Figure 8)
- GI guns consist of 2 chambers: a generator and an injector. The generator is fired first producing the primary peak; the injector is fired at half the bubble period (Figure 8); this reduces the unwanted bubble pulse. The spectrum of a GI gun is smoother than that of a sleeve airgun.

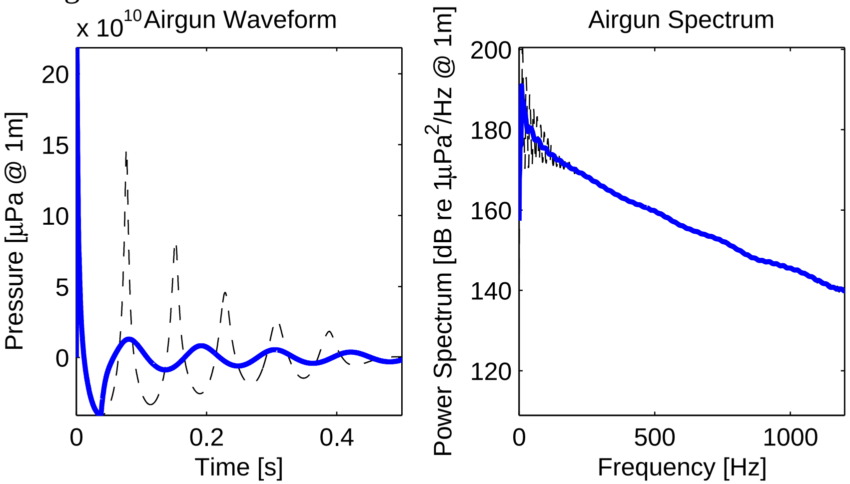


Figure 8: Waveform and spectrum of a 'normal' single-chamber airgun (- -), and of a GI gun (solid line) [31].

Airgun Arrays: • Airguns arranged in arrays are tuned to focus sharply pulsed pressure downward into the ground. Energy emission and propagation in the horizontal is reduced.

• Airgun arrays exhibit a frequency-dependent directivity pattern in the horizontal. At low frequencies, they appear omni-directional. They go through a dipolar and quadrupolar pattern at a few hundred Hz and become more multipolar with higher frequency.

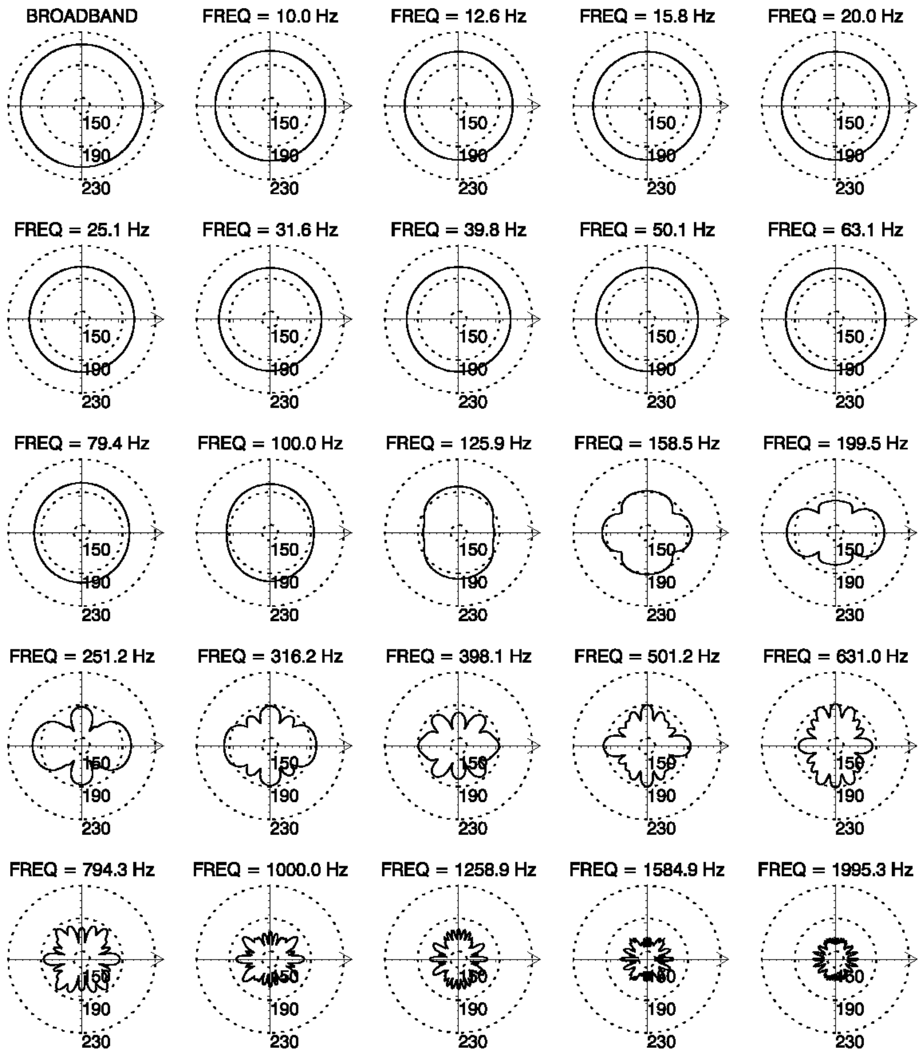


Figure 9: Horizontal directivity pattern of an airgun array. Dotted circular axes indicate source level in dB re 1 µPa [31].

Explosions: • produce a shock wave travelling in all directions underwater
- waveform shows an 'infinitely' steep front, high peak pressure, and rapid decay
- W: charge weight or TNT mass [kg]; R: range [m]

$P(t) = P_p \times e^{-t/t0}$: pressure waveform

$P_p = 5.24 \times 10^{13} (W^{1/3} / R)^{1.13}$: peak pressure [μPa]

$t_0 = 92.5\ W^{1/3} (W^{1/3} / R)^{-0.22}$: decay constant [μs]
[Aarons *et al.* via [49]]

Pile Driving:

Vibratory pile driving:

- vibratory pile driver sits on top of pile
- consists of counter-rotating eccentric weights, arranged such that horizontal vibrations cancel out while vertical vibrations get transmitted into the pile
- less noisy than impact pile driving

Impact pile driving:

- weight hammers pile into the ground
- different methods for lifting the weight: hydraulic, steam or diesel
- acoustic energy is created upon impact; travels into the water along different paths:
  1. from the top of the pile where the hammer hits, through the air, into the water; 2. from the top of the pile, down the pile, radiating into the air while travelling down the pile, from air into water; 3. from the top of the pile, down the pile, radiating directly into the water from the length of pile below the waterline; 4. ... down the pile radiating into the ground, travelling through the ground and radiating back into the water
- In the water, sound is reflected and refracted.
- Near the pile, acoustic energy arriving from different paths with different phase and time lags creates a pattern of destructive and constructive interference.
- Further away from the pile, water and ground borne energy prevails.
- Noise increases with pile size (diameter and wall thickness), hammer energy, and ground hardness. Figure 10 shows how the level increases as one pile is driven from start to end.

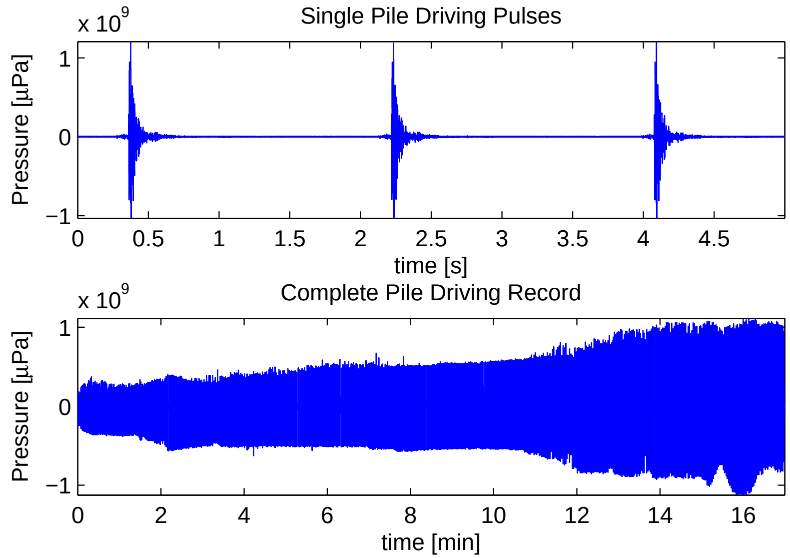


Figure 10: Waveform of impact pile driving recorded at 320m range. Water depth 3m, hollow steel pile, diameter 0.8 m, wall thickness 1.3cm, driven to 25m below ground, into sandstone bedrock, hydraulic hammer of 12t weight and 180 kJ energy rating [15].

Figure 11 gives power spectra for a number of anthropogenic sources: airgun array 2900 in^3 volume, measured broadside [JASCO]; pile driving 1.5m diameter hollow steel pile, 280 kJ hydraulic hammer [15]; icebreaker propeller cavitation during ridge ramming [18]; large vessels [45; 46; 49]; mean of five dredges dredging and dumping [JASCO]; a drilling caisson [JASCO] and mean whale-watching zodiacs [12]. Spectra of the pulsed sources (airgun array and pile driving) were computed over the *pulse length* $T_{90\%}$ (see p. 7) comprising 90% of the total energy. All spectra were measured at some range and back-propagated to 1m to compute source levels. This method assumes a point source and thus over-estimates levels that can be measured close to physically large sources. E.g., in the *near field* (see Figure 17) of an airgun array, waveforms from individual airguns superpose constructively and deconstructively creating spatially variable received levels (an interference pattern) that are always less than estimated by back-propagating long-range levels. In other words, reported source levels are useful to predict received levels at long ranges, but overpredict near-field levels.

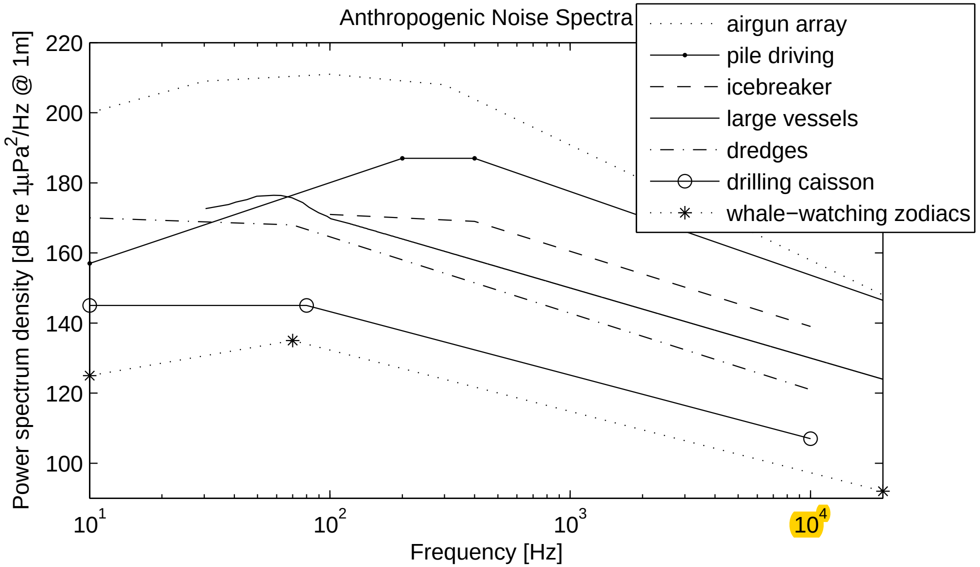


Figure 11: Source spectra of anthropogenic sources.

3. Sound Propagation

a. Overview

To model sound propagation, one needs to solve the wave equation under appropriate boundary conditions.

Wave Equation: $$\nabla^2 \Phi = \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2}$$

- c: speed of sound; t: time

Harmonic Solution: $\Phi = \phi \times e^{-i\omega t}$

- ϕ: amplitude; $\omega = 2\pi f$: angular frequency
- inserting the harmonic solution into the wave equation yields the:

Helmholtz Equation: $\nabla^2 \phi + k^2 \phi = 0$

- $k = \omega/c = 2\pi/\lambda$: wavenumber

Solutions to the Helmholtz Equation:

1. $\phi = F(x,y,z)e^{i\varphi(x,y,z)}$

F: amplitude function; φ: phase function
range-dependent => **Ray Theory**

2. $\phi = F(z)G(r)$

F: depth function => Normal Mode equation => Green's function
G: range function => Bessel equation => Hankel function
range-independent => **Normal Mode Models, Multipath Expansion Models,** and **Fast Field Models**

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

F => Parabolic equation
G => Bessel equation => Hankel function
range-dependent => **Parabolic Equation (PE) Models**

Phase-coherence:
- The propagation model considers phase.
- Models that ignore phase are called incoherent.

b. Sonar Equation

- equation of energy conservation
- originally developed to assess sonar performance
- summation of terms that are all expressed in dB

Source Parameters	Symbol	Definition
Source Level	SL	$10\log_{10}$(source intensity / reference intensity)
Source Directivity Index	DIs	$10\log_{10}$(intensity of a directional source in the source-to-target direction / intensity of an omni-directional source of equal power)

Medium Parameters		
Transmission Loss	TL	$10\log_{10}$(signal intensity @ source / signal intensity @ target or receiver)
Noise Level	NL	$10\log_{10}$(noise intensity / reference intensity)
Target Parameters		
Target Strength	TS	$10\log_{10}$(echo intensity / incident intensity)
Receiver Parameters		
Received Level	RL	$10\log_{10}$(received intensity / reference intensity)
Receiver Directivity Index	DIr	$10\log_{10}$(intensity measured by an omni-directional receiver / intensity of a directional receiver in the same isotropic sound field)
Detection Threshold (signal-to-noise ratio)	DT	$10\log_{10}$(signal intensity / noise intensity) @ threshold

Table 7: Terms in the sonar equation. Further terms exist.

One-way Sonar Equation:
For the signal of an omni-directional source to be detected at a directional receiver, the following equation has to be satisfied.
$SL - TL - NL + DIr > DT$

Two-way Sonar Equation:
For a signal from an omni-directional source to be detected at a directional receiver at the source location after reflection off a target, the following equation has to be satisfied.
$SL - 2\ TL + TS - NL + DIr > DT$

Transmission Loss:
$RL = SL - TL$
The following equations can be used as a fast and rough estimate for how sound energy dissipates as a function of range R from the source.

Geometric Spreading:

Spherical Spreading Loss:
near the source, where sound can propagate uniformly in all directions: $TL = 20\log_{10}(R/1\text{m})$

Cylindrical Spreading Loss:
In very shallow water, sound cannot propagate as a spherical wave in all directions, but only as a cylindrical wave bound by the sea floor and the sea surface. $TL = 10\log_{10}(R/1\text{m})$

Combined Spreading Loss:
In general, sound will propagate spherically near the source. At some range H, the spherical wave hits the sea floor, from here on, sound propagates cylindrically. At a range R greater than the water depth H, the TL is:
$TL = 20\log_{10}(H/1\text{m}) + 10\log_{10}(R/H) = 10\log_{10}(H/1\text{m}) + 10\log_{10}(R/1\text{m})$

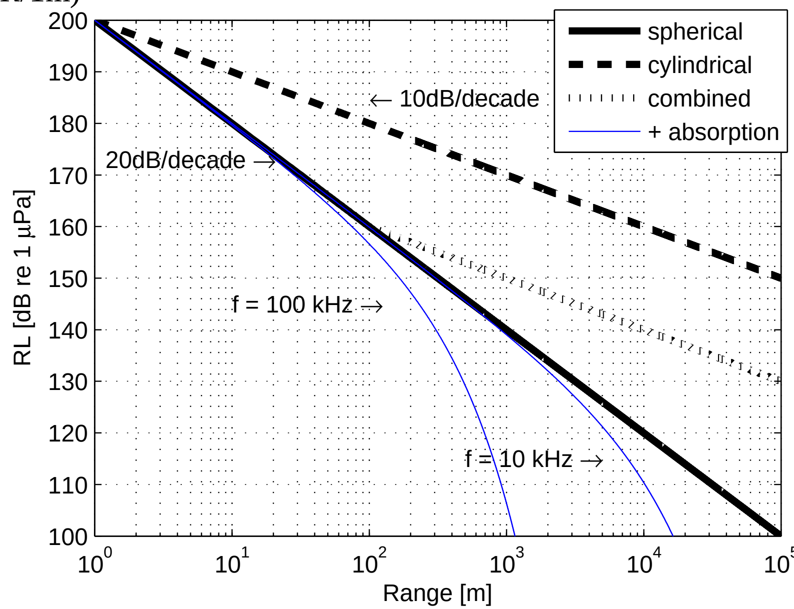


Figure 12: Geometrical transmission loss for a source of 200 dB re 1μPa @ 1m. In the combined case, the sound spreads spherically until $R = H$ = 100m, and cylindrically thereafter. Spreading loss is f-independent. Thin lines: Spherical spreading + f-dependent absorption for f = 10kHz and f = 100kHz.

Molecular Relaxation (Absorption) Loss:

- due to the relaxation of boric acid $B(OH)_3$ and magnesium sulphate $MgSO_4$ molecules, and the shear & bulk viscosity of pure water
- $TL = \alpha R$

$$\alpha = 0.106 \frac{f_1 f^2}{f_1^2 + f^2} e^{(pH-8)/0.56} + 0.52(1+\frac{T}{43})\frac{S}{35}\frac{f_2 f^2}{f_2^2 + f^2} e^{-z/6}$$
$$+ 4.9\times10^{-4} f^2 e^{-(T/27+z/17)}$$

with $f_1=0.78(S/35)^{1/2}e^{T/26}$ and $f_2=42e^{T/17}$; f [kHz], α[dB/km]

valid for $-6 < T < 35$°C (S=35ppt, pH=8, z=0)
$7.7 < pH < 8.3$ (T=10°C, S=35ppt, z=0)
$5 < S < 50$ppt (T=10°C, pH=8, z=0)
$0 < z < 7$km (T=10°C, S=35ppt, pH=8) [1; 24; 25]

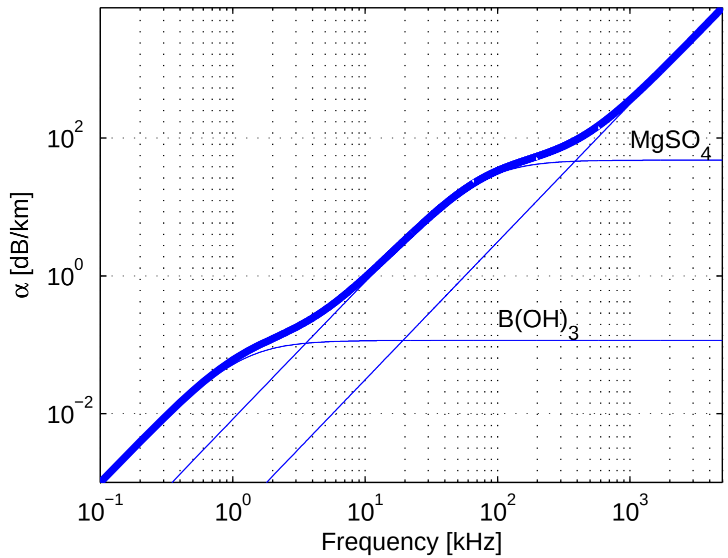


Figure 13: Absorption loss dominated by $B(OH)_3$ for f < 5 kHz, by $MgSO_4$ for 5 < f < 500 kHz, and by viscosity above. T = 10°C, S = 35ppt, z = 0, pH = 8.

Additional Losses:

- scattering at the sea floor and at the sea surface
- scattering off particles, biologics and bubbles
- transmission loss into the sea floor

Reverberation:

- unwanted echoes that limit signal detection or sonar performance
- originates from reflection and scattering off the seafloor, sea surface and volume inhomogeneities
- can lead to continuous background noise or discrete interferences

The change in the speed of sound with depth distorts the spherical and cylindrical wave fronts. This effect is treated by more sophisticated propagation models.

c. RAY Propagation

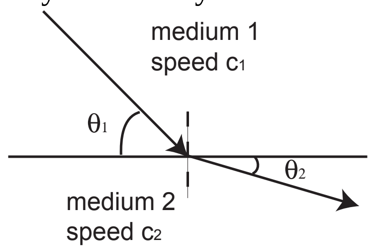
Reflection: • is the change in direction of a wave at an interface between two different media so that the wave returns into the medium from which it originated

• In specular (mirror-like) reflection, the angles of incidence and reflection are equal: $\theta_1 = \theta_2$

Refraction: • is the change in direction of a wave due to a change in its speed

A **ray** is the normal vector of a wavefront, pointing in the direction of propagation. Ray models trace rays by repeatedly applying:

Snell's Law: • For layered media (layers of ocean water of differing properties), Snell's Law relates the angles of incidence and refraction at a layer boundary.



$$\frac{\cos\theta_1}{c_1} = \frac{\cos\theta_2}{c_2}$$

Rays bend towards the horizontal if $c_2 > c_1$, and away from the horizontal if $c_1 > c_2$.

Sound Speed Profiles:
The speed of sound in sea water depends on the temperature T [°C], salinity S [ppt], and depth D [m].

$$c\ [\mathrm{m/s}] = 1448.96 + 4.591\ T - 5.304 \times 10^{-2}\ T^2 + 2.374 \times 10^{-4}\ T^3 + 1.340\ (S-35) + 1.630 \times 10^{-2}\ D + 1.675 \times 10^{-7}\ D^2 - 1.025 \times 10^{-2}\ T(S-35) - 7.139 \times 10^{-13}\ TD^3$$ [32]

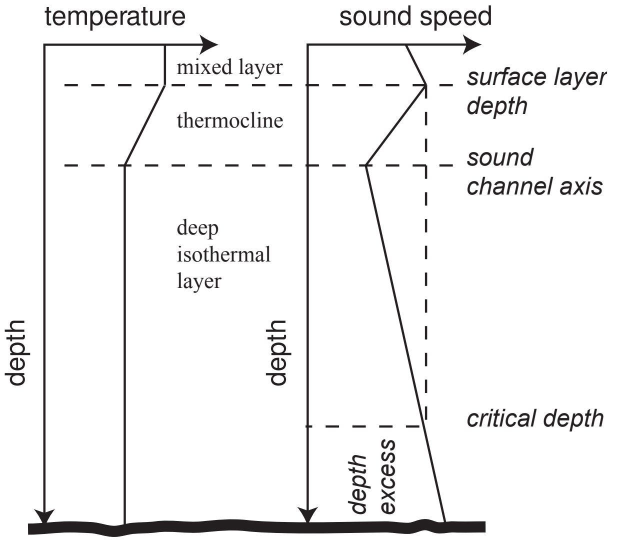


Figure 14: Relationship between temperature and sound speed for a typical, layered ocean.

- negative sound gradient: sound speed decreases with depth => sound refracts downwards
- positive sound gradient: sound speed increases with depth => sound refracts upwards
- sound speed in the deep isothermal layer increases by 1.7m/s every 100m in depth

SOFAR Channel:
- abbreviation for SOund Fixing And Ranging;
- also called **deep sound channel**;
- horizontal layer of water at the depth where c is minimum;
- this depth is called the channel axis;
- axis is about 1000m deep at low latitude and reaches the sea surface at high latitude, i.e. the polar regions;
- acts as a waveguide for sound, 'trapping' propagation paths.

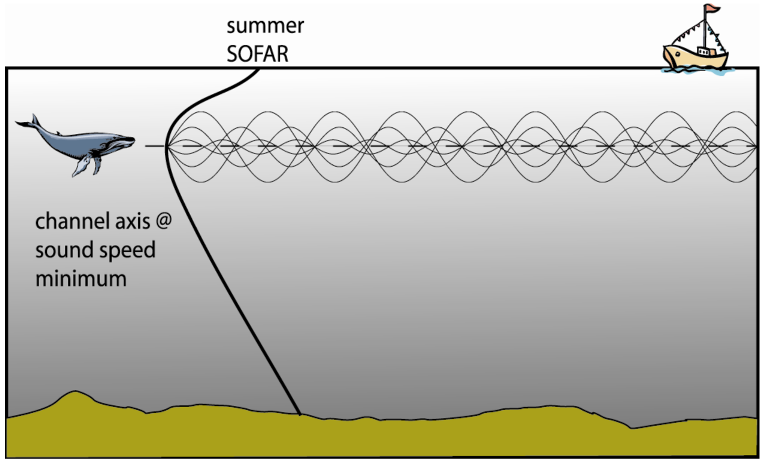


Figure 15: Sound propagation in the SOFAR channel. Thick line indicates the sound speed profile; thin lines indicate acoustic propagation paths. Sound from a source on the channel axis gets trapped in the channel by refraction and travels over long ranges with little loss. Sound from a surface source refracts downwards.

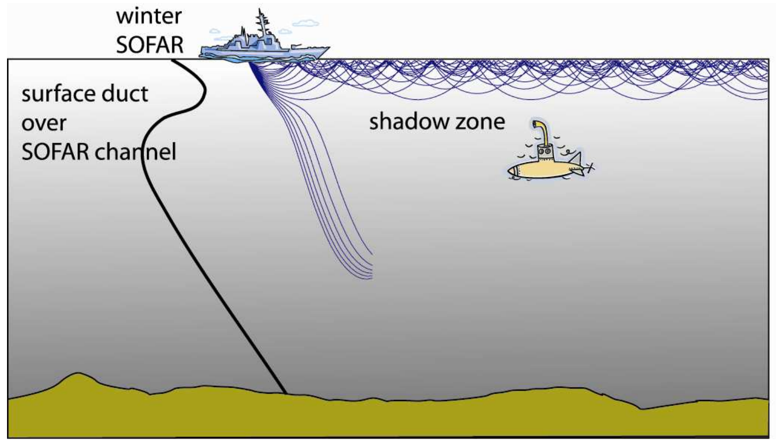
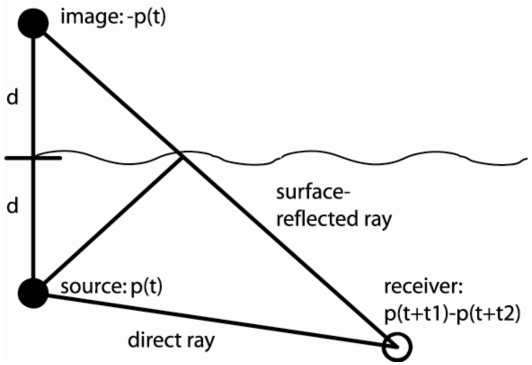


Figure 16: Sound propagation in the winter at mid-latitudes. There is a duct at the surface, resulting in a *shadow zone* underneath this layer. Sound from a surface source refracts upwards and reflects off the sea surface.

Convergence Zone: region where ray paths converge
Shadow Zone: region into which rays cannot enter by refraction alone

Lloyd Mirror Effect:



Consider a source under the water surface (e.g. a ship propeller). A ray emitted upwards reflects off the surface and experiences a 180^{O} phase shift. The surface-reflected path interferes with the direct path at any receiver location. The surface-reflected path can be considered originating from a negative (inverted pressure) image source in air. For horizontal propagation over long ranges, the path lengths of the direct and surface-reflected paths will be similar and the pressures will cancel out. At close ranges, the two rays create a pattern of constructive and destructive interference. The Lloyd Mirror Effect is assumed to play a role in ship strikes of manatees and other marine mammals that spend a significant amount of time near the surface.

4. Sound Receivers

a. Transducers

Hydrophones: convert acoustic (as opposed to hydrostatic) pressure to voltage

Sensitivity: • given as negative number [dB re 1V/μPa]

- depends on frequency, but usually flat over a nominal bandwidth
- e.g. a sensitivity S of -200 dB re 1V/μPa implies a ratio of $1V/10^4Pa$, because:

$$-200 \text{ dB re } 1V/\mu Pa = 20\log_{10}(x/(1V/\mu Pa))$$
$$\Leftrightarrow \quad -10 = \log_{10}(x/(1V/\mu Pa))$$
$$\Leftrightarrow \quad 10^{-10} = x/(1V/\mu Pa)$$
$$\Leftrightarrow \quad x = 10^{-10} V/\mu Pa = 10^{-4} V/Pa = 1V/10^4 Pa$$

- A less negative sensitivity belongs to a more sensitive hydrophone, e.g. a hydrophone with a sensitivity of -180 dB re 1V/μPa is more sensitive than a hydrophone with a sensitivity of -200 dB re 1V/μPa.

Projectors: • convert voltage to a pressure wave underwater
• have a transmit sensitivity that depends on frequency

Near Field (Fresnel Zone): Consider the surface of a transducer a series of separate point sources. At any location in the near field of the transducer, the individual pressure waves will have travelled different distances, arriving with different phases. The near field therefore consists of regions of constructive and destructive interference. All transducers, whether used as hydrophones or projectors, have near and far fields.

The **Fresnel Distance** is the range from the source beyond which the amplitude does not oscillate anymore, but monotonically decreases. Oscillations are only possible as long as the phase difference between two points on the source surface that are maximally apart is greater than half a wavelength.

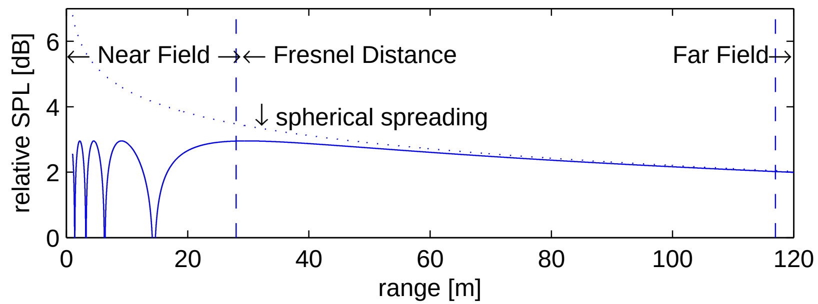


Figure 17: On-axis SPL from a circular piston with radius 6m, f = 1.2 kHz.

Far Field (Fraunhofer Zone): For receivers far from the transducer, travel differences between waves originating at different places on the transducer surface will be minimal, waves will arrive in phase, intensity decreases as $1/R^2$. While the intensity decreases monotonically for ranges greater than the Fresnel Distance, it is only at a range about four times the Fresnel Distance that the intensity approaches the spherical spreading term.

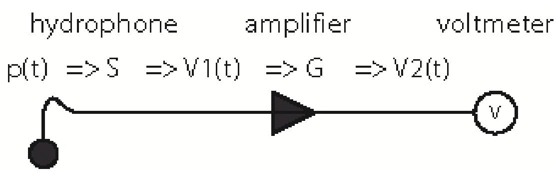
Examples: • line array: $R_{ff} = l^2/\lambda$, where l: array length
• circular piston: $R_{ff} = \pi r^2/\lambda$, where r: radius of the piston
• airgun array: $R_{ff} = l^2/\lambda$, where l: largest active dimension of the source

Directivity Pattern:
- angular distribution of projected energy (in the case of projectors)
- received level as a function of the direction of arrival of the acoustic wave (in the case of hydrophones)
- depends on the shape and size of the transducer, and frequency; e.g. Figure 9
- *omnidirectional*: circular pattern; independent of angle

Beamforming: For an array of transducers (hydrophones or projectors), phase or time shifts between the elements can be chosen such as to steer the direction of the main lobe of the overall directivity pattern of the array.

b. Amplifiers

Gain:



- $G = 20\log_{10}(V2/V1)$, where
  $V1$: input voltage;
  $V2$: output voltage
- E.g. hydrophone connected to amplifier & output voltage measured with voltmeter; then the SPL measured is:
  $SPL = 20\log_{10}(V2) - G - S$
- If $G>0$, then the amplifier increases the amplitude.
- If $G<0$, this element works as an attenuator, not an amplifier.
- E.g., S = -200 dB re 1V/μPa; G = 20 dB:
  $SPL = 20\log_{10}(V2) - G - S$
  $= 20\log_{10}(V2) - 20\text{ dB} - (-200\text{ dB})$
  $= 20\log_{10}(V2) + 180\text{ dB}$

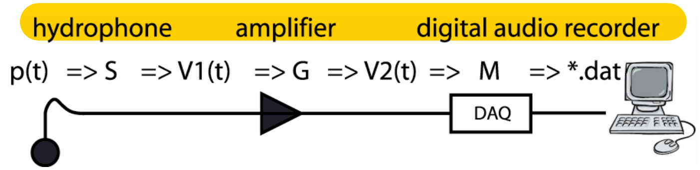
Take $20\log_{10}$ of the measured voltage [in units of Volt] and subtract (!) the gains, that's your SPL in dB re 1 μPa.

c. Data Acquisition (DAQ) Boards

- analog-to-digital A/D converters, e.g. digital audio recorders
- have a digitization gain of M [dB re FS/V], where FS is the digital full scale value that is divided by the input voltage $Vmax$ [V] required to reach digital full scale
- e.g. M = 10 dB re FS/V means that 0.32V input leads to full scale because: $10 = 20\log_{10}(x/(FS/V))$
  ⇔ $\log_{10}(x/(FS/V)) = 0.5$
  ⇔ $x = 10^{1/2}\, FS/V = FS/0.32V$
- The full scale value depends on the number of bits (n) of the A/D converter. In bipolar mode, $FS = 2^n/2 = 2^{n-1}$.
- e.g. 16-bit DAQ: $FS = 2^{16}/2 = 32768$, so the digital values will lie between $-32768 \le dv \le 32767$.

Resolution:
- is the voltage increment from one digital value to the next: $\Delta V = Vmax/FS$
- e.g. for a 16-bit DAQ with $Vmax$ = 10V: ΔV = 0.3mV
- This is the smallest voltage and the smallest voltage difference that can be resolved. In between values will be rounded, producing a *quantization error* of $\pm\Delta V/2$.

Example:



- $SPL = 20\log_{10}(dv/FS) - M - G - S$, where dv = digital values in the .dat file
- If S = -180 dB re 1V/μPa, G = 20 dB, M = 10 dB re FS/V, then $SPL = 20\log_{10}(dv/FS) - 10\text{ dB} - 20\text{ dB} - (-180\text{ dB})$
  $= 20\log_{10}(dv/FS) + 150\text{ dB}$
  Divide the digital values in the .dat or .wav files by FS; take $20\log_{10}$; subtract all gains; that's your SPL in dB re 1 μPa.

Dynamic Range:

- is the range in *SPL* that the recording system can measure
- same example as above, and assuming the DAQ board is 16 bit
- The *smallest* amplitude that the DAQ can record corresponds to a digital value of 1. With FS = 32768:
  $SPLmin = 20\log_{10}(1/FS) + 150$ dB re 1 μPa
  $= -90$ dB + 150 dB re 1 μPa = 60 dB re 1 μPa
- The *largest* amplitude that the DAQ can record corresponds to a digital value of *FS*:
  $SPLmax = 20\log_{10}(FS/FS) + 150$ dB re 1 μPa
  $= 0$ dB + 150 dB re 1 μPa = 150 dB re 1 μPa
- Louder input signals (waves with larger amplitudes) will be clipped.

Part B: The Effects of Noise on Marine Mammals

5. Marine Mammals of the World

The following distribution maps are approximate only and were mainly taken from [43]. For many species, in particular many beaked whale species, the maps were drawn 'generously' from only very few sightings. The right columns refer to the Figure numbers of the distribution maps.

Order CETACEA: Whales & Dolphins
Suborder ODONTOCETI: Toothed Whales

Family DELPHINIDAE

Cephalorhynchus commersonii	Commerson's dolphin	20
Cephalorhynchus eutropia	Chilean (black) dolphin	20
Cephalorhynchus heavisidii	Heaviside's dolphin	20
Cephalorhynchus hectori	Hector's dolphin	20
Delphinus capensis	Long-beaked common dolphin	21
Delphinus delphis	Common dolphin	21
Feresa attenuata	Pygmy killer whale	21
Globicephala macrorhynchus	Short-finned pilot whale	21
Globicephala melas	Long-finned pilot whale	21
Grampus griseus	Risso's dolphin	22
Lagenodelphis hosei	Fraser's dolphin	18
Lagenorhynchus acutus	Atlantic white-sided dolphin	18
Lagenorhynchus albirostris	White-beaked dolphin	18
Lagenorhynchus australis	Peale's dolphin	18
Lagenorhynchus cruciger	Hourglass dolphin	18
Lagenorhynchus obliquidens	Pacific white-sided dolphin	18
Lagenorhynchus obscurus	Dusky dolphin	18
Lissodelphis borealis	Northern right whale dolphin	22
Lissodelphis peronii	Southern right whale dolphin	22
Orcaella brevirostris	Irrawaddy dolphin	22
Orcinus orca	Killer whale	23
Peponocephala electra	Melon-headed whale	23
Pseudorca crassidens	False killer whale	23
Sotalia fluviatilis	Tucuxi	22
Sousa chinensis	Indo-Pacific humpback dolph.	23
Sousa teuszii	Atlantic humpback dolphin	23
Stenella attenuata	Pantropical spotted dolphin	19
Stenella clymene	Clymene dolphin	19
Stenella coeruleoalba	Striped dolphin	19
Stenella frontalis	Atlantic spotted dolphin	19
Stenella longirostris	Spinner dolphin	19
Steno bredanensis	Rough-toothed dolphin	22
Tursiops aduncus	Indo-Pacific bottlenose dolph.	20
Tursiops truncatus	Common bottlenose dolphin	20

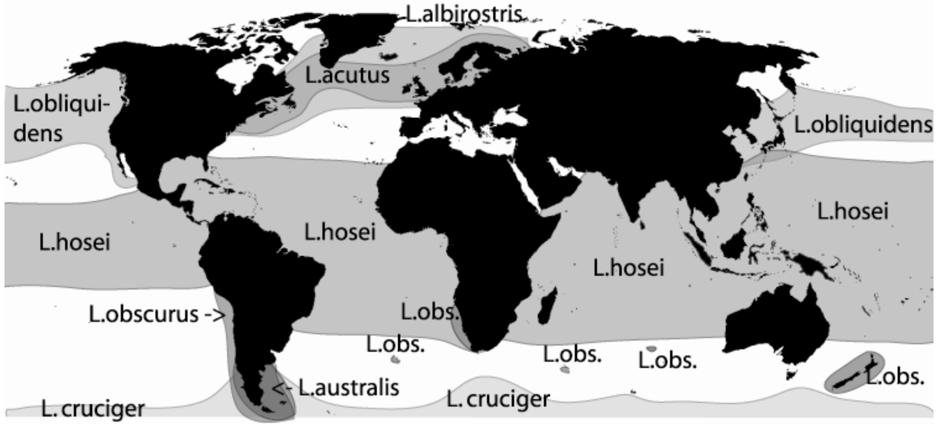


Figure 18: Distribution of *Lagenodelphis hosei* + *Lagenorhynchus* sp.

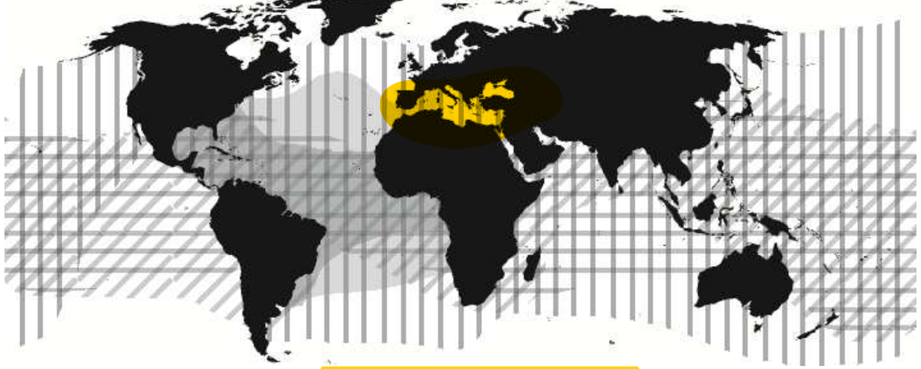


Figure 19: Distribution of *Stenella coeruleoalba* (||), *S. longirostris* (=), *S. attenuata* (//), *S. frontalis* (light + dark grey) and *S. clymene* (dark grey).

Figure 20: Distribution of *Tursiops truncatus* (wide grey band), *T. aduncus* (dark grey; coasts of the Indian ocean and western Pacific), and *Cephalorhynchus* sp. (small localized regions).

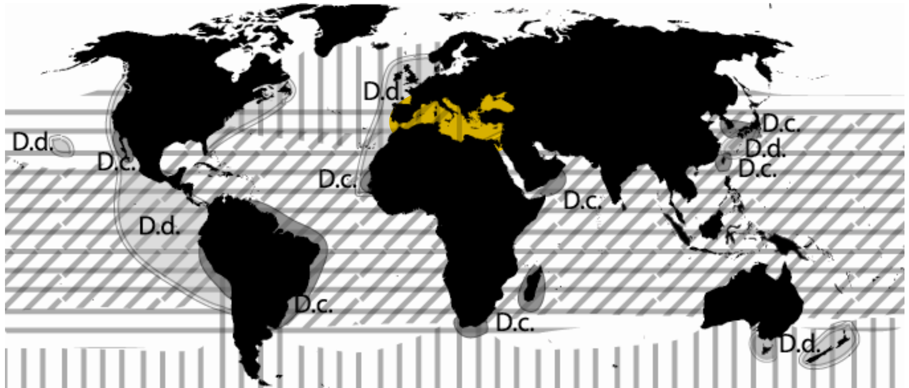


Figure 21: Distribution of *Feresa* (//), *Globicephala macrorhynchus* (=), *G. melas* (||), *Delphinus delphis* (light grey, double-line) and *D. capensis* (dark grey, single line).

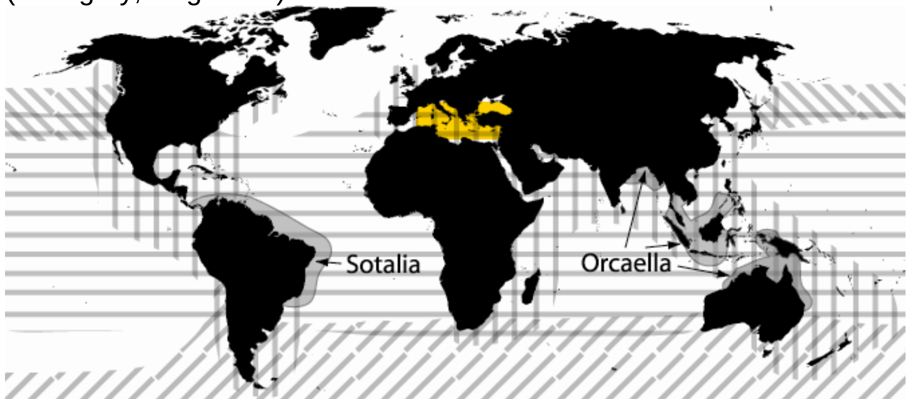


Figure 22: Distribution of *Steno bredanensis* (=), *Grampus griseus* (||), *Lissodelphis peronii* (//), *L. borealis* (\\), *Orcaella* and *Sotalia* (grey).

Figure 23: Distribution of *Peponocephala* (=), *Orcinus* (||), *Pseudorca* (\\), and *Sousa* sp. (grey).

Family PHOCOENIDAE: Porpoises

Neophocaena phocaenoides	Finless porpoise	24
Phocoena dioptrica	Spectacled porpoise	24
Phocoena phocoena	Harbor porpoise	24
Phocoena sinus	Vaquita	24
Phocoena spinipinnis	Burmeister's porpoise	24
Phocoenoides dalli	Dall's porpoise	24

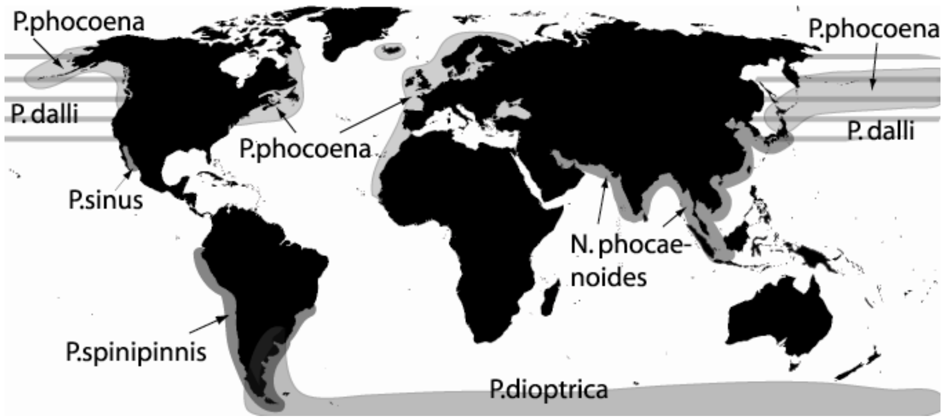


Figure 24: Distribution of porpoises.

Family MONODONTIDAE

Delphinapterus leucas	Beluga whale	25
Monodon monoceros	Narwhal	25

Family PHYSETERIDAE

Physeter macrocephalus	Sperm whale	25

Family KOGIIDAE

Kogia breviceps	Pygmy sperm whale	25
Kogia sima	Dwarf sperm whale	25

Family PLATANISTIDAE

Platanista gangetica gangetica	Ganges river dolphin	25
Platanista gangetica minor	Indus river dolphin	25

Family PONTOPORIIDAE

Pontoporia blainvillei	Franciscana	25

Family LIPOTIDAE

Lipotes vexillifer	Baiji, Chinese river dolphin	25

Family INIIDAE

Inia geoffrensis	Boto, Amazon river dolphin	25

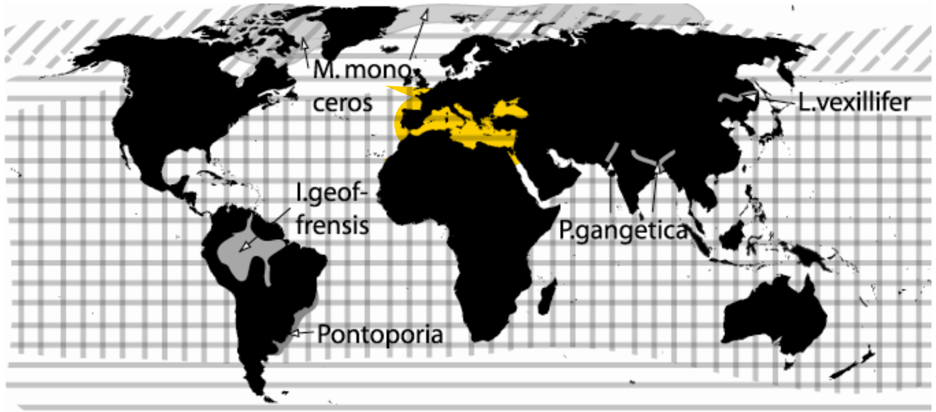


Figure 25: Distribution of *Physeter* (=), *Kogia* sp. (||), *Delphinapterus* (//), *Monodon*, *Pontoporia*, *Lipotes*, *Inia* and *Platanista* (grey).

Family ZIPHIIDAE

Berardius arnuxii	Arnoux's beaked whale	27
Berardius bairdii	Baird's beaked whale	27
Hyperoodon ampullatus	Northern bottlenose whale	28
Hyperoodon planifrons	Southern bottlenose whale	28
Indopacetus pacificus	Longman's beaked whale	27
Mesoplodon bidens	Sowerby's beaked whale	26
Mesoplodon bowdoini	Andrews' beaked whale	26
Mesoplodon carlhubbsi	Hubbs' beaked whale	27
Mesoplodon densirostris	Blainville's beaked whale	26
Mesoplodon europaeus	Gervais' beaked whale	28
Mesoplodon gingkodens	Ginkgo-toothed beaked whale	28
Mesoplodon grayi	Gray's beaked whale	27
Mesoplodon hectori	Hector's beaked whale	26

Mesoplodon layardii	Strap-toothed whale	26
Mesoplodon mirus	True's beaked whale	27
Mesoplodon peruvianus	Pygmy beaked whale	26
Mesoplodon stejnegeri	Stejneger's beaked whale	26
Mesoplodon traversii	Spade-toothed beaked whale	28
Tasmacetus shepherdi	Shepherd's beaked whale	28
Ziphius cavirostris	Cuvier's beaked whale	27

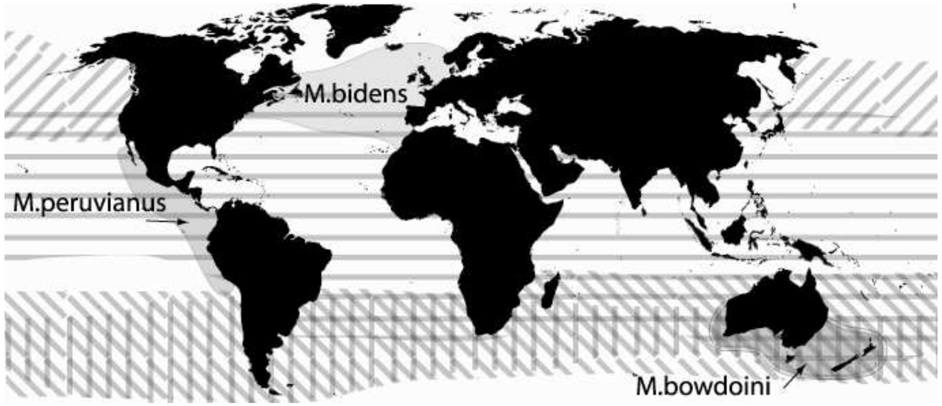


Figure 26: Distribution of *Mesoplodon densirostris* (=), *M. hectori* (\\), *M. stejnegeri* (//), *M.* layardii (||), *M. peruvianus, M. bidens* and *M. bowdoini* (grey).

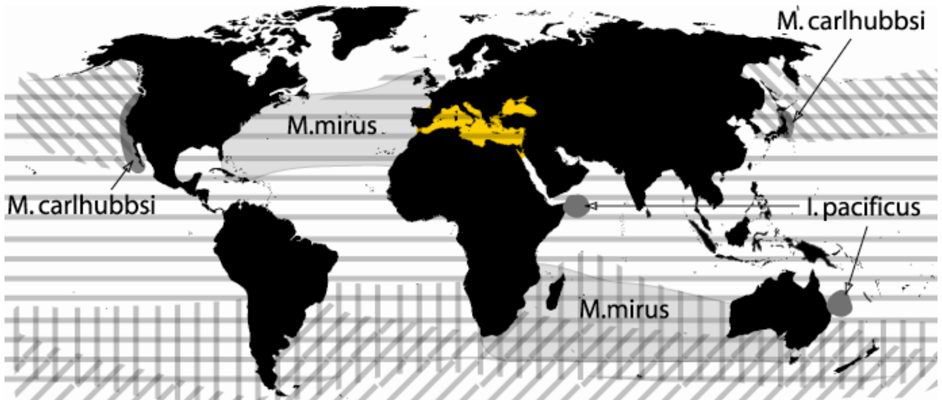


Figure 27: Distribution of *Ziphius* (=), *M. grayi* (||), *B. bairdii* (\\), *B. arnuxii* (//), *M. carlhubbsi, M. mirus* and *I. pacificus* (grey).

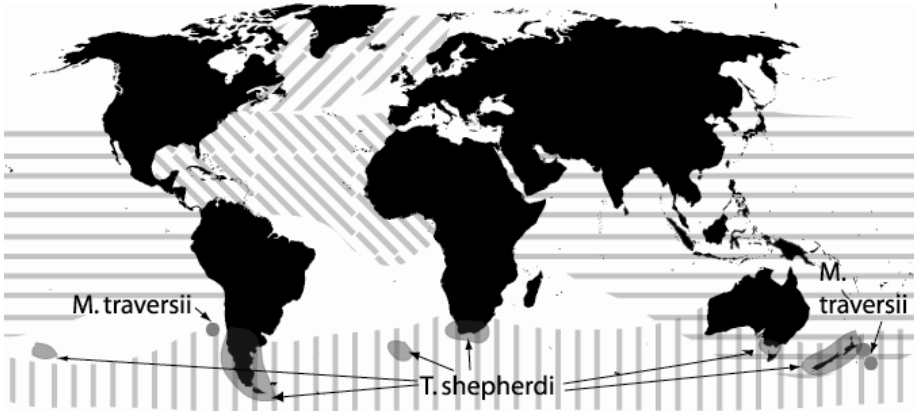


Figure 28: Distribution of *M. ginkgodens* (=), *H. planifrons* (||), *H. ampullatus* (//), *M. europaeus* (\\), *T. shepherdi* and *M. traversii* (grey). *M. traversii* is only known from remains and has never been seen 'in flesh' or alive.

Suborder MYSTICETI: Baleen Whales

Family BALAENIDAE

Balaena mysticetus	Bowhead whale	29
Eubalaena australis	Southern right whale	29
Eubalaena glacialis	North Atlantic right whale	29
Eubalaena japonica	North Pacific right whale	29

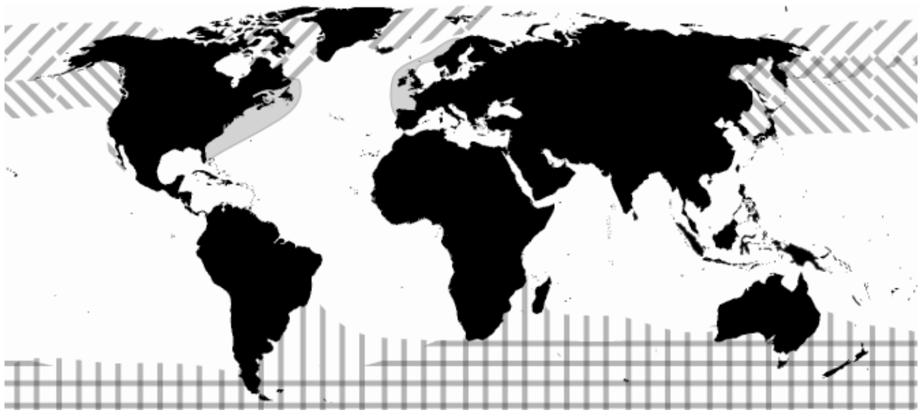


Figure 29: Distribution of *Caperea* (=), *E. australis* (||), *E. japonica* (\\), *B. mysticetus* (//) and *E. glacialis* (grey).

Family NEOBALAENIDAE

Caperea marginata	Pygmy right whale	29

Family BALAENOPTERIDAE

Balaenoptera acutorostrata	Common minke whale	30
Balaenoptera bonaerensis	Antarctic minke whale	30
Balaenoptera borealis	Sei whale	30
Balaenoptera edeni	Bryde's whale	30
Balaenoptera musculus	Blue whale	30
Balaenoptera physalus	Fin whale	30
Megaptera novaeangliae	Humpback whale	30

Family ESCHRICHTIIDAE

Eschrichtius robustus	Gray whale	30

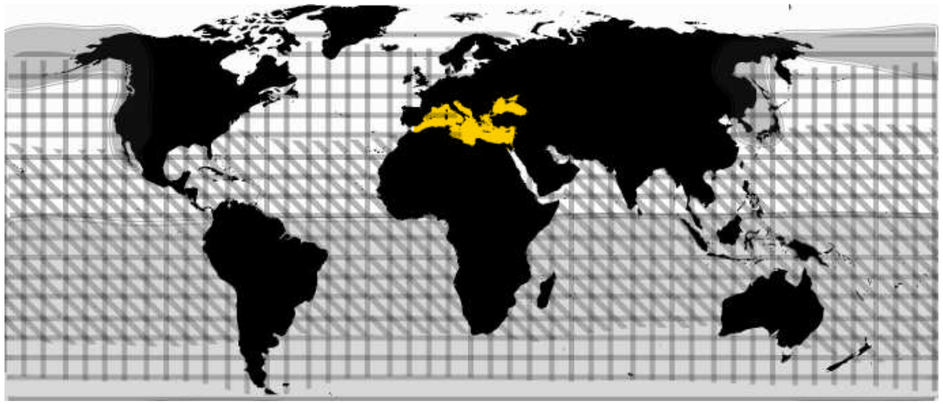


Figure 30: Distribution of *B. musculus*, *B. physalus* and *M. novaeangliae* (=) (note: only *B. physalus* is found throughout the Mediterranean); *B. edeni* (\\), *B. bonarensis* (grey; south of 7^0S), E. robustus (grey; only in the northern hemisphere); *B. borealis* and *B. acutorostrata* (||). *B. acutorostrata* has a northern hemisphere population and a southern (dwarf) population.

Order CARNIVORA: Carnivores (marine)

Suborder PINNIPEDIA: Seals & Sea Lions

Family PHOCIDAE (true, earless, hair seals)

Cystophora cristata	Hooded seal {1}	32
Erignathus barbatus	Bearded seal {2}	31
Halichoerus grypus	Gray seal {3}	32
Histriophoca fasciata	Ribbon seal {4}	32
Hydrurga leptonyx	Leopard seal {5}	32
Leptonychotes weddellii	Weddell seal {6}	32
Lobodon carcinophagus	Crabeater seal {7}	32
Mirounga angustirostris	Northern elephant seal {8}	32
Mirounga leonina	Southern elephant seal {9}	31
Monachus monachus	Mediterranean monk seal {10}	31
Monachus schauinslandi	Hawaiian monk seal {11}	31
Monachus tropicalis†	Caribbean monk seal {12}†	
Ommatophoca rossii	Ross seal {13}	32
Phoca groenlandica	Harp seal {14}	31
Phoca largha	Spotted seal {15}	31
Phoca vitulina	Harbor seal {16}	31
Pusa caspica	Caspian seal {17}	32
Pusa hispida	Ringed seal {18}	32
Pusa sibirica	Baikal seal {19}	32

†The Caribbean monk seal was last sighted in 1952 and is considered extinct.

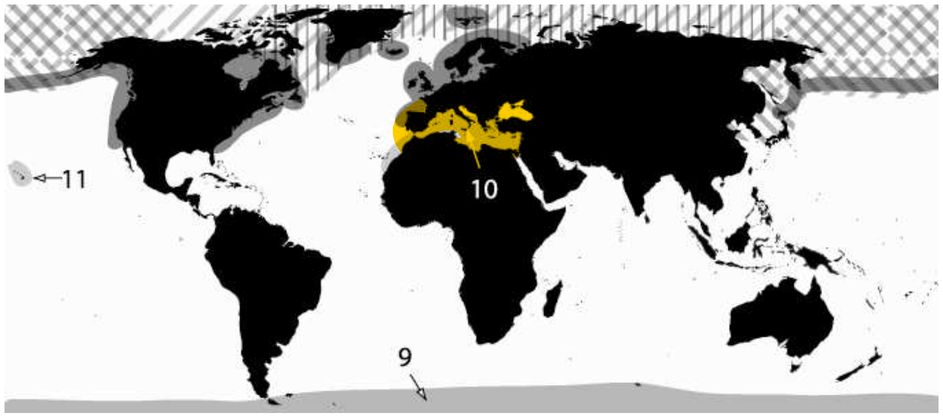


Figure 31: Distribution of true seals: *E. barbatus* (//), *M. leonina* (grey, 9), *M. monachus* (grey, 10), *M. schauinslandi* (grey, 11), *Ph. groenlandica* (||), *Ph. vitulina* (dark grey line), *Ph. largha* (\\).

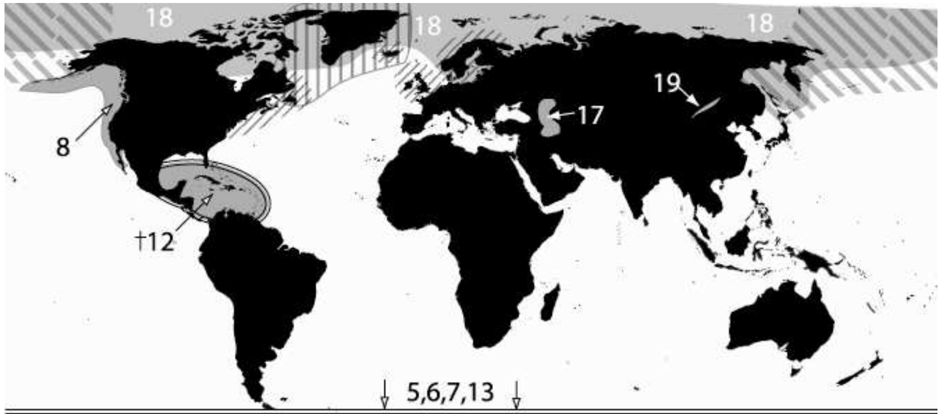


Figure 32: Distribution of true seals: *C. cristata* (||), *H. fasciata* (\\), *H. grypus* (//), *M. angustirostris* (grey, 8), *P. caspica* (grey, 17), *P. hispida* (grey, 18), *P. sibirica* (grey, 19). Around Antarctica (=): *H. leptonyx, L. weddellii, L. carcinophagus, O. rossii*.

Family OTARIIDAE (eared seals)

Arctocephalus australis	South American fur seal {1}	33
Arctocephalus forsteri	New Zealand fur seal {2}	33
Arctocephalus galapagoensis	Galapagos fur seal {3}	33
Arctocephalus gazella	Antarctic fur seal {4}	33
Arctocephalus philippi	Juan Fernandez fur seal {5}	33
Arctocephalus pusillus	South African & Australian fur seals {6}	33
Arctocephalus townsendi	Guadalupe fur seal {7}	33
Arctocephalus tropicalis	Subantarctic fur seal {8}	33
Callorhinus ursinus	Northern fur seal {9}	33
Eumetopias jubatus	Steller sea lion {10}	33
Neophoca cinerea	Australian sea lion {11}	33
Otaria byronia	South American sea lion {12}	33
Phocarctos hookeri	New Zealand sea lion {13}	33
Zalophus californianus	California & Galapagos sea lions {14}	33

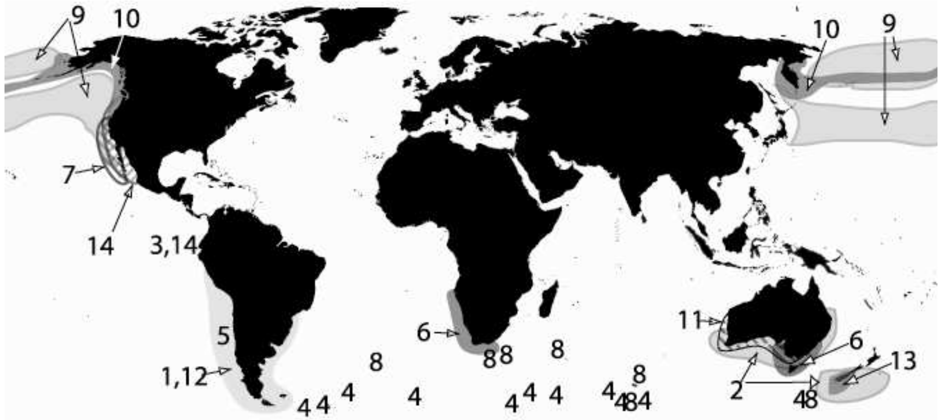


Figure 33: Distribution of eared seals. Numbers with arrows belong to shaded ranges. Numbers without arrows identify breeding sites on islands.

Family ODOBENIDAE

Odobenus rosmarus	Walrus	34

Family MUSTELIDAE (marine)

Lutra felina	Marine otter	34
Enhydra lutris	Sea otter	34

Family URSIDAE (marine)

Ursus maritimus	Polar bear	34

Order SIRENIA: Sea Cows

Family TRICHECHIDAE

Trichechus inunguis	Amazonian manatee	34
Trichechus senegalensis	West African manatee	34
Trichechus manatus	West Indian manatee	34
Trichechus manatus latirostrus	Florida manatee	34

Family DUGONGIDAE

Dugong dugon	Dugong	34
Hydrodamalis gigas †	Steller's sea cow †	34

†Steller's sea cow used to live in the Bering Sea, but has been extinct since the 18th century.

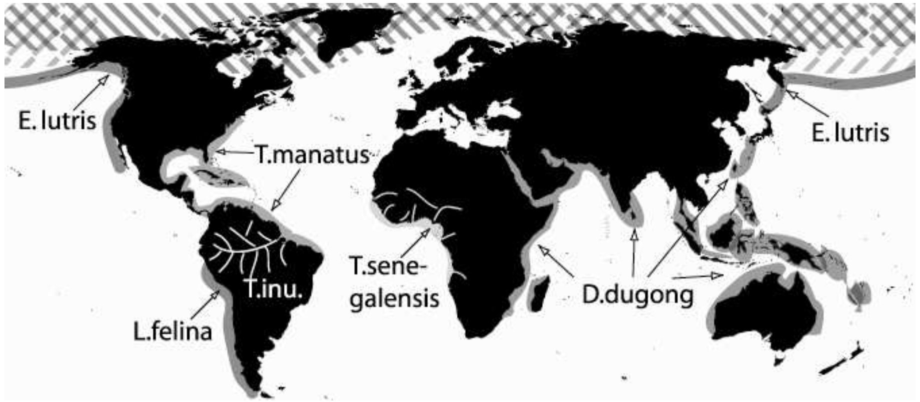


Figure 34: Distribution of *O. rosmarus* (//), *U. maritimus* (\\), *Mustelidae* and *Sirenia*.

6. Marine Mammal Acoustics

Ocean water conducts light very poorly but sound very well. => Marine mammals rely primarily on their acoustic sense for communication, social interaction, navigation and foraging. Odontocetes have an active echolocation system aiding navigation and foraging.

a. Marine Mammal Sounds

All marine mammals emit sound that is produced internally. Other sounds, that may also take a social or communicative role, are generated when an animal strikes an object or the water surface.

Odontocete Sounds:

- generated within the nasal system, not the larynx
- can be classified into 3 categories: tonal whistles, burst-pulse sounds and echolocation clicks
- Within the same species, there exist geographic differences in sound characteristics where populations don't mix.

- *Dialects* refer to sound differences between populations sharing the same geographic region, and have been identified for killer whales [23] and sperm whales [51].
- Whistles and burst-pulse sounds have social function.
- Some odontocetes do not whistle, e.g. *Phocoenidae*, *Cephalorhynchus* sp., *Kogia* sp., *Physeter* macrocephalus.
- *Whistles* have fundamental frequency < 20-30kHz plus higher harmonics.
- Whistles have directional emission pattern, in particular at high *f*.
- Whistles may be categorized acc. to the shape of the fundamental frequency with time: constant frequency, upsweep, downsweep, concave (hill), convex (valley), sinusoidal.
- *Burst-pulse sounds* are series of broadband pulses with substantial ultrasonic energy.
- *Echolocation* clicks are broadband; mostly in the ultrasonic range.
- Burst-pulse sounds have lower source level and lower interclick interval than echolocation click trains.
- Both have highly directional beam-pattern.

Mysticete Sounds:

- sound production mechanism unclear
- 2 categories: calls and songs
- *Calls* have been categorized into simple calls (low *f* < 1kHz, narrow band, frequency and amplitude modulated), complex calls (broadband, 500-5000Hz, *f* and amplitude modulated), grunts & knocks (<0.1s duration, 100-1000Hz), and clicks & pulses (short duration < 2ms, 3-30kHz) [5].
- *Songs* have been recorded from humpback, bowhead, blue and fin whales.
- Humpback song can be broken down into themes, which consist of repetitions of phrases, which are made up of patterns of units (with energy up to 30kHz).

Pinniped Sounds:

- occur in air and under water

- are often described by onomatopoeic words: grunts, snorts, buzzes, barks, yelps, roars, groans, creaks, growls, whinnies, clicks etc. [3; 44]

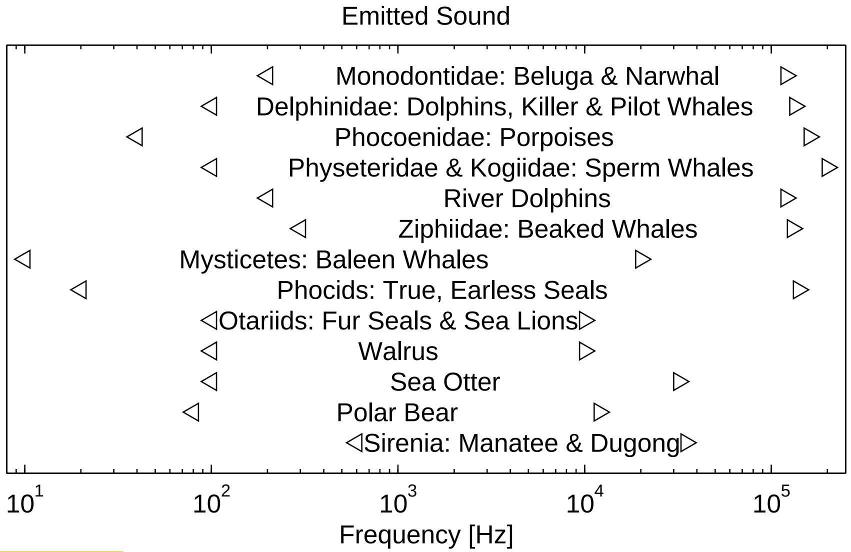


Figure 35: Frequency bands of marine mammal sounds incl. echolocation [13; 40; 44].

b. Marine Mammal Hearing

Audiograms: - graphs showing hearing threshold of pure tones as a function of frequency
- have been measured from only about 20 marine mammal species, and only few individuals
- audiogram variability on an individual (let alone species or genus) level is barely understood
- 'threshold' is a statistical quantity, e.g. (dep. on the method used) the level at which the tone was heard 50% of the time

Marine mammal audiograms, grouped into families, are shown in Figure 36. Published audiograms were assembled [11; 21; 38; 44] and interpolated for the centre frequencies of 1/3 octave bands between 40Hz and 200kHz. Within each family, the lowest threshold of all species and individuals was plotted at each frequency.
There are no underwater audiograms of polar bears, sea otters, sperm whales and baleen whales. It is expected that their frequencies of best

sensitivity overlap to some degree with the frequencies of their calls. Other indicators for what these animals can hear come from controlled exposure experiments looking for responses of animals to sound. Anatomical studies of baleen ears have suggested good hearing sensitivity between 10Hz and 30kHz. At the low-frequency end, sound detection by baleen whales might often be ambient noise limited rather than audiogram limited.

Marine mammal audiograms exhibit a similar U-shape:
- at low *f*, sensitivity improves as ~ 10dB/octave
- best sensitivity is between 30 dB re 1μPa (odontocetes) and 70 dB re 1μPa (pinnipeds), with the exception of the Gervais' beaked whale audiogram, the current estimate of which has a much higher threshold
- at high *f*, sensitivity drops fast: >100dB/octave

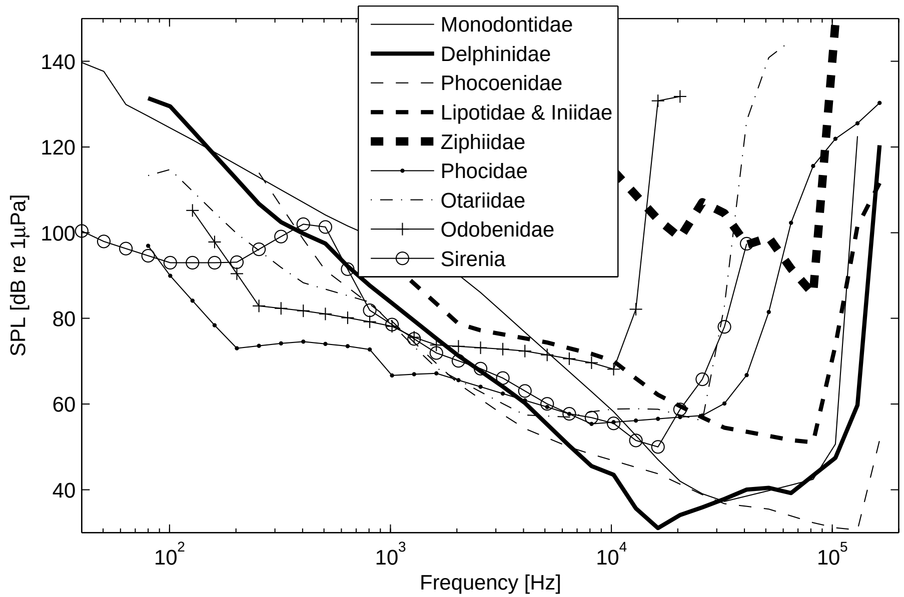


Figure 36: Underwater audiograms of marine mammals, showing the minimum thresholds over all species belonging to the same family.

Temporal auditory summation: Sensitivity decreases, i.e. audiogram thresholds increase, if the signal duration drops below the integration time constant of the auditory system. Depending on species and frequency, the integration time constant is of the order of 0.001 – 0.1s.

7. Effects of Noise on Marine Mammals

The effects of noise and the ranges over which they happen depend on the acoustic characteristics of the noise (level, spectrum, duration, rise time, duty cycle etc.), the sound propagation environment, and the animal under consideration.

Figure 37 sketches the relative extents of some of the possible zones of influence.

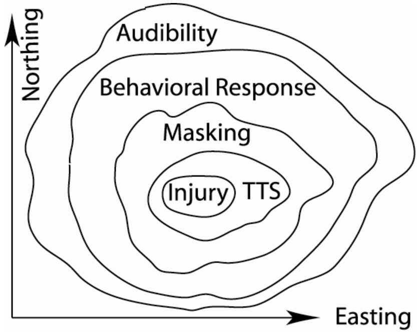


Figure 37: Bird's-eye view of the potential zones of influence around a noise source.

a. Noise Audibility

Noise levels decrease with range due to propagation losses. Audibility is limited by the noise dropping either below the animal audiogram or below ambient noise levels. One way of estimating the zone of audibility is as follows [17]:

1. Model sound propagation of the noise.
2. At a receiver grid in space (e.g. easting, northing, depth) compute critical band levels of the noise by integrating its power density spectrum into a series of bands of the width of the animal's critical bands. In the absence of critical band or critical ratio data, 1/3 octave bands are commonly used.
3. Compute critical band levels of ambient noise.
4. For each band, take the maximum of the audiogram threshold and the ambient noise SPL; this is the audibility-limiting spectrum.
5. Subtract these audibility-limiting band levels from the noise band levels at all ranges and depths.
6. If the difference is > 0 in any band, then this band is deemed audible at this location.

b. Behavioural Responses

The zone of behavioural response is mostly going to be smaller than the zone of audibility, as an animal is not likely to respond to a sound that is just detectable. Yet, ranges over which behavioural responses have been observed, can be quite large (10s of km [18]) in particular for low-frequency sounds in deep water and animals capable of detecting low *f*. Summaries and reviews of observed behavioural responses can be found in [39; 44; 48]. Indicators of 'disturbance' include changes in swim direction and speed, dive duration, surfacing duration and interval, respiration (blow rate), movement towards or away from the noise, and changes in contextual and acoustic behaviour etc. Whether an animal reacts to a sound it hears depends on a number of factors including prior exposure (habituation vs. sensitization), current behavioural state, age, gender and health. The percentage of a population that is likely to respond to a noise is a statistical quantity. E.g., the National Marine Fisheries Service (NMFS) [8] has recently used a dose-response curve (also called risk function) to estimate the probability of response to mid-frequency sonar. Half of a population was expected to respond at 165 dB re 1μPa, with more animals responding to louder sonar signals and fewer animals to quieter sonar signals.

Behavioural analyses should be multivariate, considering the full range of metrics appropriate for the sound source (e.g., *SPLrms*, SPL_{Pk}, *SEL*, *signal-to-noise ratio)* and the full range of behavioural and contextual variables.

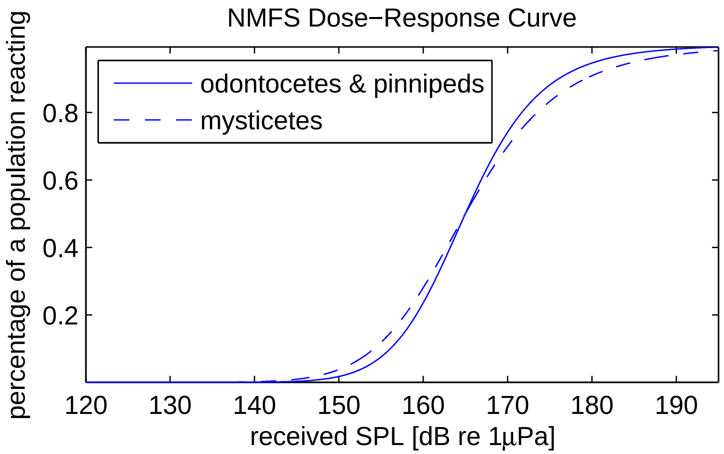


Figure 38: Curve used by NMFS to assess the likelihood of impact from mid-frequency sonar.

c. Masking

Man-made noise can interfere with marine mammal social signals, echolocation, predator sounds, prey sounds and environmental sounds (e.g. the sound of surf) that animals might listen to.

Masking is
- the process by which the threshold of hearing for one sound is raised by the presence of another (masking) sound;
- the amount M by which the threshold of hearing for one sound is raised by the presence of another (masking) sound, expressed in dB: $M = SL_n - SL_0$ [dB] ,
  where SL_0 : signal level @ detection threshold in the absence of noise, SL_n : signal level @ detection threshold in the presence of noise.

Critical Ratio:
Consider broadband white noise masking a pure tone. If PSD_n is the power spectral density [intensity per Hz] of the noise and I_t the tone intensity at threshold in the noise, then

$$CR = 10 \cdot \log_{10} \frac{I_t}{PSD_n}$$ is the critical ratio.

Critical Band:
- consider the auditory system a bank of bandpass filters
- mostly noise energy in the filter surrounding the tone will be effective at masking

Fletcher's Equal-Power-Assumption [22]: At the masked hearing threshold, the tone intensity equals the noise intensity inside the corresponding critical band Δf: $I_t = PSD_n \cdot \Delta f$

The critical band can be computed from critical ratios: $\Delta f = 10^{CR/10}$

Masking [14; 16]
- depends on the spectral and temporal characteristics of signal and noise;
- is reduced if signal and noise are separated in time, frequency, or direction (space);

- can occur if the noise happens shortly before or after the signal (forward and backward masking);
- is reduced if the noise is amplitude modulated over many f-bands (comodulation masking release);
- is reduced if there are gaps in the noise and/or the signal is repetitive or of long duration (multiple looks model);
- might be reduced by anti-masking strategies (e.g. increasing call level, shifting f, repetition [14]).

The zone of masking can maximally be as large as the zone of audibility, as a faint noise might mask a faint signal. Mostly, the zone will be less, because animals can detect signals at levels a few dB below noise, and because of frequency discrimination, temporal discrimination and directional hearing abilities of the marine mammal auditory system. There are different degrees of masking: At a low signal-to-noise ratio (*snr*), a signal might just be audible in the noise; a higher *snr* is needed for the signal to be discriminated or recognized; and an even higher *snr* is associated with comfortable communication. Behavioural experiments to measure the masking of beluga whale calls by ship noise [14; 16] have been used to develop software models for masking, including common signal detection algorithms and neural networks [10; 20].

d. Auditory Threshold Shift

M-weighting [48]:
- emphasizes the frequency band where acoustic exposures to high-amplitude noise can have auditory effects
- curves are wider than the bandwidth of best sensitivity as indicated in audiograms
- To compute M-weighted *SEL* (*SEL*-M), filter the noise spectrum with the appropriate M-weighting curve before integrating energy over all frequencies.

Marine mammals were grouped into 5 functional hearing groups [48]:

- **low-frequency cetaceans**: *Balaena*, *Caperea*, *Eschrichtius*, *Megaptera*, *Balaenoptera*
- **mid-frequency cetaceans**: *Steno*, *Sousa*, *Sotalia*, *Tursiops*, *Stenella*, *Delphinus*, *Lagenodelphis*, *Lagenorhynchus*, *Lissodelphis*, *Grampus*, *Peponocephala*, *Feresa*, *Pseudorca*, *Orcinus*, *Globicephala*, *Orcaella*, *Physeter*, *Delphinapterus*, *Monodon*, *Ziphius*, *Berardius*, *Tasmacetus*, *Hyperoodon*, *Mesoplodon*
- **high-frequency cetaceans**: *Phocoena*, *Neophocaena*, *Phocoenoides*, *Platanista*, *Inia*, *Kogia*, *Lipotes*, *Pontoporia*, *Cephalorhynchus*
- **pinnipeds in water**: all species
- **pinnipeds in air**: all species

$$M(f) = 20\log_{10}\frac{R(f)}{\max(R(f))}$$

where $$R(f) = \frac{f_{high}^2 f^2}{(f_{high}^2 + f^2)(f_{low}^2 + f^2)}$$

	f_{low}	f_{high}
LF Cet.	7 Hz	22 kHz
MF Cet.	150 Hz	160 kHz
HF Cet.	200 Hz	180 kHz
Pin. in water	75 Hz	75 kHz

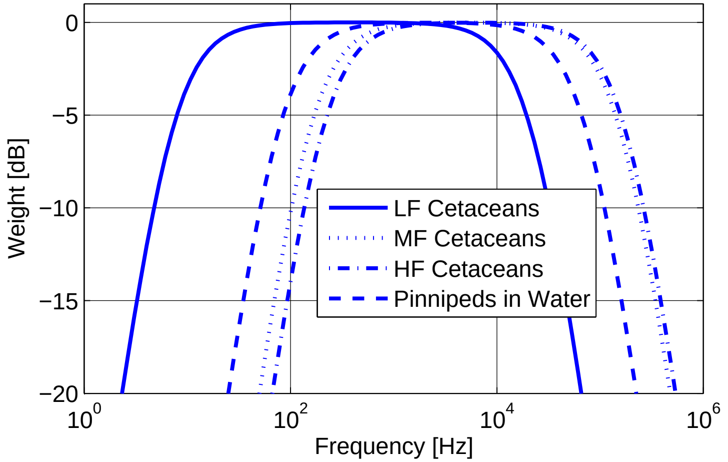


Figure 39: M-weighting curves *M(f)*.

Temporary Threshold Shift (TTS):

At some level and duration, sound can cause hair cells of the inner ear to fatigue, yielding an increase in auditory threshold by an amount called the temporary threshold shift. The amount of TTS depends on the noise level, rise time, duration, duty cycle, spectral characteristics etc. After some quiet time (minutes – days), hearing returns to normal. TTS has been measured in a few individual marine mammals. Reviewing pre-2007 data, Southall *et al*. [48] expected TTS onset in LF, MF and HF cetaceans at 224 dB re 1µPa SPL_{Pk} or 183 dB re 1µPa^{2}s *SEL* M-weighted, whichever level was reached first. For pinnipeds in water, TTS onset was expected at 212 dB re 1µPa SPL_{Pk} or 171 dB re 1µPa^{2}s *SEL*-M. Since then, TTS has been shown in a HF cetacean at 200 dB re 1µPa $SPL_{Pk\text{-}Pk}$ and 164 dB re 1µPa^{2}s *SEL* unweighted [30].

Permanent Threshold Shift (PTS):

If hearing does not fully return to normal after noise exposure, the remaining threshold shift is called a permanent threshold shift. PTS is considered *auditory injury*. Noise-induced PTS has not been measured in marine mammals. To estimate at what level PTS might occur, marine mammal TTS data were used in combination with TTS growth rates (as a function of noise level) from terrestrial mammals [48]. Peak-*SPL* and M-weighted *SEL* values were given; the one that is reached first should be used for impact assessment.

	Single + multiple pulses	**Nonpulses**
LF Cet. + MF Cet. + HF Cet.	230 dB re 1µPa SPL_{Pk} 198 dB re 1µPa^{2}s *SEL*-M	230 dB re 1µPa SPL_{Pk} 215 dB re 1µPa^{2}s *SEL*-M
Pinn. in water	218 dB re 1µPa SPL_{Pk} 186 dB re 1µPa^{2}s *SEL*-M	218 dB re 1µPa SPL_{Pk} 203 dB re 1µPa^{2}s *SEL*-M

Noise Classes:

To predict auditory impact, noise sources have been grouped [48]:

- **single pulses**: one event per 24h; > 3dB difference between measured levels using impulse versus equivalent-continuous time constant (setting on sound level meter); e.g. explosion, single airgun, single pile strike, single sonar ping

- **multiple pulses**: >1 emission within 24h; > 3dB difference between measured levels using impulse versus equivalent-continuous time constant; e.g. seismic surveying, pile driving
- **nonpulses**: 1 or more emissions within 24h; < 3dB difference between measured levels using impulse versus equivalent-continuous time constant; e.g. ship noise, drilling, certain sonar systems, pingers

e. Non-Auditory Physiological Effects

Other systems potentially affected by noise include the vestibular system, reproductive system and nervous system. Noise might cause concussive effects, physical damage to tissues and organs (in particular gas-filled), and cavitation (bubble formation). Data on damage to non-auditory tissues, organs and systems don’t exist, but levels will have to be above those tested in TTS experiments.

Stress is a physiological response that involves the release of the hormone adrenalin, which increases heart rate, gas exchange, acuity and an increase in blood flow to the brain and muscles for a fight-or-flight response. Stress responses are intended to improve survival in the face of immediate threat, however, repetitive or prolonged stress can negatively affect health in the long run. Chronic stress in humans can cause coronary disease, immune problems, anxiety, depression, cognitive and learning difficulties, and infertility. The onset of stress might correspond to fairly low noise levels that induce a behavioural disturbance or masking. Stress might be a direct result of noise, e.g. if an unknown noise is detected, or an indirect result of noise causing, e.g., masking.

The different types of noise effects can be linked, e.g., a temporary shift in hearing threshold will affect the audibility of signals (e.g. of conspecific calls) and thus alter or prevent the ‘normal’ behavioural response to such signals. Or, noise received by a diving animal might induce stress leading to a so-called fight-or-flight response involving rapid surfacing which can cause decompression sickness and injury, and ultimately death.

f. Chronic Noise Effects

While it is quite feasible to model cumulative sound exposure [19], the effects of cumulative sound exposure and the manner in which repeated exposure gets accumulated by the animal are not known yet. Agencies around the world tend to regulate acute noise exposure (e.g. from seismic surveys or naval sonar). Ongoing sound exposure (e.g. from shipping) remains largely unregulated.

g. Biological Significance

Determining whether and how acoustic impact affects the survival of a population is extremely difficult. If a certain percentage of a population receives a certain amount of PTS, could this lead to the population’s decline? Will it matter if a seismic survey deflects migration routes?

The Population Consequences of Acoustic Disturbance (PCAD) model [37] provides a conceptual framework for linking acoustic disturbance to population effects. The bracketed numbers indicate how easily the variables can be measured (3: easy, 0: difficult) and how well the 4 transfer functions F are known (3: well known, 0: unknown). Bioenergetic measurements and models might aid with determining these transfer functions [6].

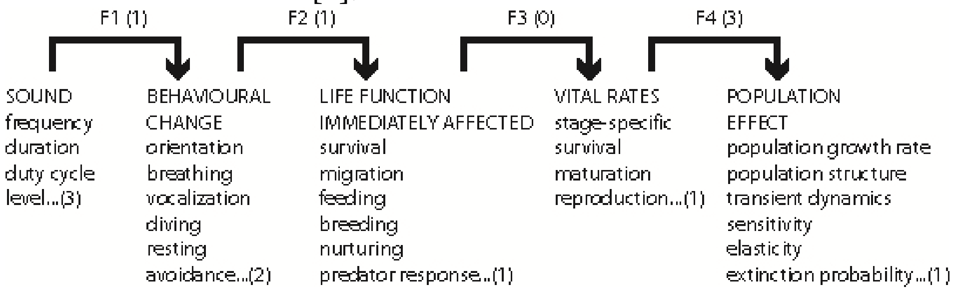


Figure 40: Population Consequences of Acoustic Disturbance (PCAD) model.

h. Mitigation

- Modifying the source
  - choosing alternate equipment and technology
  - reducing source level
  - changing spectral characteristics
- Modifying the timing of activities
  - time of day
  - outside of season of marine mammal presence
- Modifying the geographic location
- Modifying operational parameters
  - ramping up (not proven that animals will actually move away if sound source ramps up)
  - minimizing duty cycle
  - limiting speed of boats
- Installing mitigation equipment, e.g. bubble screens around pile driving
- Implementing mitigation procedures
  - visual or passive acoustic monitoring of marine mammals
  - low-power and shut-down (safety) zones

i. Cumulative Stressors

It is difficult to rank the impact of noise with regards to other stressors on marine animals. Depending on the species, geographic location and time of year, non-acoustic 'stressors' affecting marine mammals result from harvesting (intended catch), culling, fisheries bycatch, entanglement, ocean debris, ship strikes, chemical pollution, ocean acidification, habitat degradation, prey depletion (e.g. by overfishing or environmental factors), and climate change. Isolating and ranking these stressors for management purposes is mostly impossible. Ideally, noise would be regulated together with other stressors. It seems reasonable to assume that an animal that is already stressed by chemical pollution and food depletion would find it harder to cope with additional noise pollution, or vice versa, an animal that is frequently exposed to raised background noise might already be 'too stressed' to effectively cope with additional non-acoustic stressors.

Part C: Noise Effects on Animals other than Mammals

Recent results of studies of noise effects on marine animals including non-mammalian species can be found in [27].

8. Fish

There are > 30,000 species of fish, only a small proportion of which have been addressed in bioacoustic investigations. In 2008, a compendium was published on fish bioacoustics [50]. Threats to the survival of species of fish include over-fishing, habitat degradation, chemical pollution and noise.

a. *Hearing in Fish*

All fish studied to-date can hear. The inner ear of fish resembles an accelerometer. When a sound wave impinges on a fish, a dense mass, the otolith, moves relative to the rest of the fish, and this motion is measured by sensory hair cells. The ear is sensitive to particle motion. Fish with swim bladders close to the ear are also sensitive to acoustic pressure, as the sound pressure excites the gas bladder, which reradiates an acoustic wave, the particle motion of which is detected by the ear. In general, hearing sensitivity is best between 30 – 1000 Hz. However, some species can detect infrasound, some can detect ultrasound [41].

b. Behavioural Responses

Documented behavioural responses include avoidance of vessels and seismic airguns [reviewed in [47]]. Sonars did not produce a response, yet predator sounds (killer whales) did [9]. Startle responses did not correlate with audiograms [29], and it was concluded that behavioural responses depend not only on the noise characteristics, but also on context (e.g. location, temperature, physiological state, age, body size, school size).

c. Masking

Over 800 species of fish are known to emit sound, primarily on spawning grounds. Fish also produce sound during territorial fights, when competing for food or when attacked by a predator [47]. Noise can potentially mask communication, predator and prey sounds, however, this has not been studied in detail.

d. Hearing Loss

Damage to hair cells has been observed after exposure to seismic airguns [33]. Temporary threshold shift has been measured after exposure to vairous types of noise [reviewed in [42]].

e. Physiological Effects

There is anecdotal evidence of fish mortality around pile driving, however data on what noise characteristics cause what type of damage at what level is unavailable. Stress as measured by an increase in the hormone cortisol and an increase in heart rate has been documented [reviewed in [47]].

f. Chronic Effects & Biological Significance

Long-term effects might include growth-retardation and a reduction in reproductive success, although this has not yet been documented [7; 53].

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