Anthropogenic Noise and Marine Mammals

Blue Whale
Fin Whale
Gray Whale
Humpback Whale

John K. Horne
Relevant Web Sites/Reports

Oceans of Noise: www.wdcs.org.au
Ocean noise and Marine mammals: www.nap.edu


Southall *et al.* 2009. Addressing the Effects of Human-Generated Sound on Marine Life

Sources of Noise

Natural
1. Geophysical sources: wind-generated waves, earthquakes, precipitation, ice
2. Biological sources: marine mammal vocalizations, fish & invertebrate sounds

Anthropogenic
Intentional: high intensity, acute; Unintentional: lower level, chronic
1. Ships: propeller, propulsion machinery, hydraulic flow over hull
2. Airguns & seismic exploration
3. Sonars: military, civilian, research
4. Offshore drilling, pile driving
Ocean ‘Background’ Noise

- 50 dB re 1 $\mu$Pa$^2$/Hz (no vessels), 80 to 90 dB (vessels)
- 1950 to 1975 sound levels increased by $\geq$10 dB (vessel traffic)
- doubling # of ships +3 to +5 dB, increased vessel speed +6 dB
- vessel increase (1972 to 1999): 57,000 to 87,000

Overall 16 dB from 1950 to 2000 (Mazzuca 2001)

i.e. doubling every 5 decades, 7% annual increase
Marine Mammal Hearing

Odontocetes:
- 200 Hz to 100 kHz, some to 200 kHz
- peak sensitivity 20 kHz to 80 kHz
- moderate sensitivity 1 kHz to 20 kHz

Mysticetes:
- 20 Hz to 20-30 kHz
- larger species (blue, fin) 10 Hz (?)

Pinnipeds
- 1 kHz to 20 kHz
- northern elephant seal < 1 kHz
Marine Mammal Hearing

Kastelein et al. 2005
Pinniped Hearing

Kastelein et al. 2005
# Mammal Hearing Groups

<table>
<thead>
<tr>
<th>Hearing Group</th>
<th>Generalized Hearing Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency (LF) cetaceans (baleen whales)</td>
<td>7 Hz to 35 kHz</td>
</tr>
<tr>
<td>Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)</td>
<td>150 Hz to 160 kHz</td>
</tr>
<tr>
<td>High-frequency (HF) cetaceans (true porpoises, <em>Kogia</em>, river dolphins, cephalorhynchid, <em>Lagenorhynchus cruciger</em> &amp; <em>L. australis</em>)</td>
<td>275 Hz to 160 kHz</td>
</tr>
<tr>
<td>Phocid pinnipeds (PW) (underwater) (true seals)</td>
<td>50 Hz to 86 kHz</td>
</tr>
<tr>
<td>Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)</td>
<td>60 Hz to 39 kHz</td>
</tr>
</tbody>
</table>

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

<table>
<thead>
<tr>
<th>Hearing Group</th>
<th>a</th>
<th>b</th>
<th>$f_1$ (kHz)</th>
<th>$f_2$ (kHz)</th>
<th>$C$ (dB)</th>
<th>$K$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency (LF) cetaceans</td>
<td>1.0</td>
<td>2</td>
<td>0.2</td>
<td>19</td>
<td>0.13</td>
<td>179</td>
</tr>
<tr>
<td>Mid-frequency (MF) cetaceans</td>
<td>1.6</td>
<td>2</td>
<td>8.8</td>
<td>110</td>
<td>1.20</td>
<td>177</td>
</tr>
<tr>
<td>High-frequency (HF) cetaceans</td>
<td>1.8</td>
<td>2</td>
<td>12</td>
<td>140</td>
<td>1.36</td>
<td>152</td>
</tr>
<tr>
<td>Phocid pinnipeds (PW) (underwater) (true seals)</td>
<td>1.0</td>
<td>2</td>
<td>1.9</td>
<td>30</td>
<td>0.75</td>
<td>180</td>
</tr>
<tr>
<td>Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)</td>
<td>2.0</td>
<td>2</td>
<td>0.94</td>
<td>25</td>
<td>0.64</td>
<td>198</td>
</tr>
</tbody>
</table>

* Equations associated with Technical Guidance’s auditory weighting ($W_{aud}(f)$) and exposure functions ($E_{aud}(f)$):

\[
W_{aud}(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^3]^{a}}\right\} \quad \text{dB}
\]

\[
E_{aud}(f) = K - 10\log_{10}\left\{\frac{(f/f_2)^{2a}}{[1+(f/f_2)^3]^{a}}\right\} \quad \text{dB}
\]
Relative Anthropogenic Sources

<table>
<thead>
<tr>
<th>Sound Source</th>
<th>SPL $\text{dB re} \ 1\mu Pa/1\text{m}$</th>
<th>Ping Energy $\text{dB re} \ 1\mu Pa^2\text{s}$</th>
<th>Ping Duration</th>
<th>Duty Cycle (%)</th>
<th>Peak Frequency (Hz)</th>
<th>Band Width (Hz)</th>
<th>Directionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwater Nuclear Device (30 kilo-ton)</td>
<td>328</td>
<td>?</td>
<td>1000 s</td>
<td>Intermittent</td>
<td>Low</td>
<td>Broad</td>
<td>Omni</td>
</tr>
<tr>
<td>Ship Shock Trial (10,000 lb TNT)</td>
<td>299</td>
<td>?</td>
<td>100 s</td>
<td>Intermittent</td>
<td>Low</td>
<td>Broad</td>
<td>Omni</td>
</tr>
<tr>
<td>Military Sonar (SURTASS/LFA)</td>
<td>235</td>
<td>243</td>
<td>6 – 100 s</td>
<td>10</td>
<td>250</td>
<td>30</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Airgun Array 2000 psi and 8000 in$^3$</td>
<td>256</td>
<td>241</td>
<td>30 ms</td>
<td>0.3</td>
<td>50</td>
<td>150</td>
<td>Vertical</td>
</tr>
<tr>
<td>Military Sonar (53C)</td>
<td>235</td>
<td>232</td>
<td>0.5 – 2 s</td>
<td>6</td>
<td>2,600-3,300</td>
<td>Narrow</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Super Tanker 270 m long</td>
<td>198</td>
<td>CW</td>
<td>20 minutes</td>
<td>100</td>
<td>23</td>
<td>5-100</td>
<td>Omni</td>
</tr>
<tr>
<td>Research Sonar (ATOC Source)</td>
<td>195</td>
<td>CW</td>
<td>8</td>
<td>75</td>
<td>37.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic Harrassment Device</td>
<td>185</td>
<td>185</td>
<td>0.5 - 2 s</td>
<td>50</td>
<td>10,000</td>
<td>600</td>
<td>Omni</td>
</tr>
<tr>
<td>Multibeam (Echosounder Hull-mounted)</td>
<td>235</td>
<td>218</td>
<td>20 ms</td>
<td>0.4</td>
<td>12,000</td>
<td>Narrow</td>
<td>Vertical</td>
</tr>
<tr>
<td>Research Sonar (RAFOS float)</td>
<td>195</td>
<td>120 s</td>
<td>small</td>
<td>250</td>
<td>100</td>
<td></td>
<td>Omni</td>
</tr>
<tr>
<td>Fishing Vessel 12 m long (7 knots)</td>
<td>150</td>
<td>CW</td>
<td>100</td>
<td>300</td>
<td>250-1000</td>
<td></td>
<td>Omni</td>
</tr>
<tr>
<td>Acoustic Deterrent Device (AquaMark300)</td>
<td>132</td>
<td>127</td>
<td>300 ms</td>
<td>8</td>
<td>10,000</td>
<td>2000</td>
<td>Omni</td>
</tr>
</tbody>
</table>
Affect of Noise on Marine Mammals

Factors:

1. Acoustic properties: sound pressure level
2. Animal behavior
3. Ambient acoustic features of environment

Richardson et al. 1995

Annoyance factors: loudness by frequency, fluctuation
Zones of Noise Influence & Responses

- Injury
- Hearing Loss
- Avoidance
- Behavioral Disturbance
- Audibility (above threshold)

Adapted from Richardson & Malme 1995
Hearing Loss

- shift to higher threshold caused by exposure to high-intensity sound

- may be temporary (TTS) or permanent (PTS)

- extent of loss dependent on sound power spectrum, hearing sensitivity, duration of exposure

Examples:

bottlenose dolphin: temporary loss at 193 to 196 dB re 1 μPa at 20 kHz for 1 second tone

beluga whale: temporary loss at 217 dB re 1 μPa
Why is Hearing Loss Important?

- poor communication, reduced echolocation and foraging
- behavior modifications: migration, mating, stranding, vulnerability to predators
Noise Masking

- occurs when a frequency critical band (CB) occurs around a desired signal
- amount a pure tone must exceed noise spectral level to be heard is the critical ratio (CR)

Potential Result: signal may not be heard due to noise
SONAR and Mammal Strandings

- Canary Islands (2002) military exercise
- 4 hours later, 14 beaked whales stranded near site
- gas bubbles present in blood vessels and gas-filled cavities
- liver, kidney, fatty tissue

Cause (?):
- rapid ascent (decompression)
- sound pressure on gas nuclei

Mass Strandings

- only odontocetes are known to mass strand
- most involve Cuvier’s beaked whales (*Ziphius cavirostris*)
- 3 to 10 multi-animal strandings per decade (1960 to 2000)
- correlated with use of high-intensity sonar: first tested 1957, deployed 1960’s
- 11 of 32 documented strandings of beaked whales coincided with concurrent naval activities
- mid-frequency sound (1-6 kHz) implicated in strandings
Acoustic Thermometry of Ocean Climate (ATOC)

aka North Pacific Acoustic Laboratory

Source Level: 195 dB re 1\(\mu\)Pa @1m

Signal: centered at 75 Hz with 37.5 Hz bandwidth

Duty Cycle: 5 min. ramp up, 20 minute duration, 4 hour interval

- goal to monitor average ocean temperature over long time to see if ocean warming
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ATOC and Humpbacks

• no change in abundance, some change in pod distribution (but difficult to interpret)

• increases in duration and distance between successive surfacings with increase in ATOC sound level (5-15% variation)

• similar behavioral responses found at similar receive levels. RL is good predictor of response

• aggregate intensity level of song does not change with transmission condition

Conclusion: behavioral response barely detectable
Low Frequency Acoustics (LFA)

Surveillance Towed Array Sensor System (SURTASS)

100-500 Hz

active sonar to enable long range (kms) detection of submarines
Humpback Migration & Breeding

Source in corridor
- whales changed course to avoid sound source

Source moved offshore (1 mile)
- whales did not change course
- low risk at RL
Examining Effects of LFA

Potential impacts on: whale feeding, migrating, breeding

• 19 animal observations
• No overt behavioral responses
• No changes in whale distribution could be related to LFA operations
Marine Mammal Mitigation Sonar

may be used in conjunction with other sonars

HF/M3

SURTASS Receive Array

HF/M3

Rotating Search Beams (4)

Transmit Array

Mitigation Zone

(Rad: 1 km, Height: 70m)
Monitoring Marine Mammals

- stop transmission of SURTASS if animal detected within 180 dB re 1 µPa
- range 0.75 to 1 km, depth 87 to 147 m
Whale Behavior & Sound

**Observed:** Miller et al. (2000) Humpbacks
- length of male song increased during LFA broadcast
- potential masking of communications

**Not Observed:** Croll et al. (2001) Blue and Fin
- foraging activity did not change during LFA broadcast (RL >140 dB re 1 µPa)
- encounter rates and dive behavior correlated with prey density and oceanography

Croll et al. 2001
Behavioral Response Review

• Response to single stimulus variable
• Response dependent on environment, source and receive characteristics
• Magnitude and period of signal/response may indicate biological importance

*But* not a linear response among animals to the same sound
U.S.S. Shoup

16 – 18 June, 2005 Haro Strait, WA

- 7.3 kHz sonar
- Source level 235 dB re 1 µPa @ 1 m
- 3 hour exposure
- Max RL estimated 180 dB rms
- Behavioral response
- Not loud enough to cause TTS
Challenges to Anthropogenic Studies

- Behavioral changes (e.g. song length, migration) are short term (< 2 hrs); Can effects be measured on demographic scale (e.g. fitness - survival, calving rates)?

- How to decouple multiple effects of general increase in ambient noise from local sources? What about places where noise has decreased?

- If LFA effects are behavioral, shouldn’t you be looking at ‘shy’ species? Dahl’s porpoise vs harbor porpoise, Californian sea lions vs Steller sea lions
Research Priorities

Ocean Noise
1. Support long-term ocean noise monitoring programs
2. Collect, organize, and analyze historic marine anthropogenic noise data
3. Develop global models for ocean noise
4. Report signal characteristics for anthropogenic noise sources
5. Quantify the relationship between anthropogenic activity and noise level

Noise Effects
1. Understand causes of mass stranding events
2. Quantify behavioral responses to anthropogenic sound
3. Improve tools for marine mammal behavioral observation (e.g. tags, passive recorders)
4. Develop tools to study marine mammal physiology (stress, hearing)
5. Characterize marine mammal populations within high sound areas