Ocean Noise and Marine Mammals

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2004 Behavioral Significance of Marine Mammal Responses to Ocean Noise
NRC Committee:

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Colleagues:

Angela D'Amico (SPAWAR)
David Fromm (NRL)
John Hildebrand (MPL/SIO)
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**Objective**
- To review the scientific issues and recent developments pertaining to ocean noise and marine mammals.

**Outline**
- **Introduction**
  - motivation for tutorial
  - timeline of recent events
  - outline of tutorial
- **Relevant Legislation**
- **The Biological Component**
  - biological ocean noise
  - marine mammal audition
  - response to noise
    - behavioral responses
    - masking
    - TTS to PTS
- **Sources of Sound in the Ocean**
  - natural biological sources (already covered by Doug)
  - natural physical sources
  - man-made sources
Outline (continued)

- Propagation of Sound in the Ocean
- Metrics of the Sound Field and Noise “Budgets“
- Long-Term Trends in Ocean Noise
- Current Issues
  - i. seismic surveys
  - ii. beaked whale strandings
- Some Recent Events
  - i. Marine Mammal Commission
  - ii. NRC 2004 report
  - iii. NOAA workshops
  - iv. JASONS study
- Gaps in Knowledge and Recommendations from the NRC Reports
- Conclusions and the Future
Timeline of Some Recent Events


- ATOC
- Greek event
- ONR Wkshop
- Bahamas Rep't
- NSF Baja
- NOAA Acoust. Reson. Wkshp
- JASONS Study
- MMC Advise Comm
- HF M3
- NDAA
- NAS Rep't
- NOAA Acoust. Reson. Wkshp
- MMC Beaked Whale Wkshp
- NOAA Noise Budg Wkshp
- NOAA Noise Monitor Wkshp
- NOAA Ship Wkshp
- Ship Shock
- MMPA reauthor.
- Greek Event Rep't
- MMS HESS
- NAS Rep't
- LWAD
- NAS Rep't
- Baja Event
- Canary Isl Event
### Timeline of Some Recent Events

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
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<tbody>
<tr>
<td>1992</td>
<td>(ATOC) Acoustic Thermometry of Ocean Climate</td>
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<tr>
<td>1994</td>
<td>(MMPA Reauthor.) MMPA Reauthorization</td>
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<td>1994</td>
<td>(Ship Shock) Ship shock trials lawsuit</td>
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<tr>
<td>1994</td>
<td>(NAS Rep't) Low-Frequency Sound and Marine Mammals:</td>
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<tr>
<td></td>
<td>Current Knowledge and Research Needs</td>
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<tr>
<td>1996</td>
<td>(Greek Event) Greek mass stranding event</td>
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<tr>
<td>1997</td>
<td>(MMS HESS) MMS High Energy Seismic Survey committee</td>
</tr>
<tr>
<td>1998</td>
<td>(Greek Event Rep't) Report on Greek mass stranding event</td>
</tr>
<tr>
<td>1998</td>
<td>(ONR Wkshop) Workshop on the Effects of Anthropogenic</td>
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<tr>
<td></td>
<td>Noise in the Marine Environment</td>
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<tr>
<td>2000</td>
<td>(Bahamas Event) Bahamas mass stranding event</td>
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<tr>
<td>2000</td>
<td>(NAS Rep't) Marine Mammals and Low-Frequency Sound:</td>
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<tr>
<td></td>
<td>Progress Since 1994</td>
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<tr>
<td>2001</td>
<td>(LWAD) Littoral Warfare Advanced Development program</td>
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<tr>
<td></td>
<td>lawsuit</td>
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<tr>
<td>2001</td>
<td>(Bahamas Rep't) Joint Interim Report, Bahamas Marine</td>
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<tr>
<td></td>
<td>Mammal Stranding Event of 15-16 March 2000</td>
</tr>
<tr>
<td>2002</td>
<td>(NOAA Acoust. Reson. Wkshop) NOAA Workshop, Acoustic Resonance as a Source of</td>
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<tr>
<td></td>
<td>Tissue Trauma in Cetaceans</td>
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<tr>
<td>2002</td>
<td>(Canary Isl. Event) Canary Isl. mass stranding event</td>
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<tr>
<td>2002</td>
<td>(Baja Event) Stranding of two beaked whales in Baja California</td>
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<tr>
<td>2002</td>
<td>(NSF Baja) Baja California lawsuit - NSF, multi-million dollar,</td>
</tr>
<tr>
<td></td>
<td>multi-institution experiment shut down</td>
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<td>2002</td>
<td>(LFA) Low-Frequency Active sonar lawsuit</td>
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<tr>
<td>2004</td>
<td>(NOAA Noise Budg Wkshop) NOAA Workshop on Ocean Ambient Noise Budgets and Long-Term</td>
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<td>Monitoring: Implications for Marine Mammals</td>
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<tr>
<td>2004</td>
<td>(NOAA Ship Wkshp) NOAA Workshop, Shipping</td>
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<td></td>
<td>Noise and Marine Mammals</td>
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<td>2004</td>
<td>(NDAA) Nat'l Defense Authorization Act,</td>
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<td>Reauthorization of MMPA discussion</td>
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<td>2004</td>
<td>(NOAA Noise Monitor Wkshop) NOAA Workshop on Ocean Ambient Noise: Designing a</td>
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<td></td>
<td>Monitoring System</td>
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<td>2004</td>
<td>(NAS Rep't) Behavioral Significance of Marine Mammal Responses to Ocean Noise</td>
</tr>
<tr>
<td>2004</td>
<td>U.S. Commission on Ocean Policy</td>
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</table>
Well Documented Beaked Whale Mass Stranding Events

- **1996 event off the west coast of Greece**
  - 12 or so animals, all beaked whales
  - 2 day period (12 - 13 May) over 35 km of coastline
  - Shallow Water Acoustic Classification (SWAC) experiment, SACLANTCEN (D’Amico et. al., 1998)

- **2000 Bahamas Islands Event**
  - 16 cetaceans, both beaked and minke whales (2)
  - 36 hour period (15 - 16 March) over 240 km of coastline
  - U.S. Navy ASW exercise involving hull-mounted sonar systems on 5 ships (Evans and England, 2001; Fromm and McEachern, 2000)

- **2002 Canary Islands Event**
  - 14 or so animals, all beaked whales
  - Most believed stranded on morning of 24 September, on the SE and NE sides of two islands
  - Neo Tapon exercise involving 11 NATO countries
Relevant Legislation
U.S. Laws

Laws of Primary Importance

- Marine Mammal Protection Act (MMPA)
- Endangered Species Act (ESA)

Laws of Secondary Importance

- National Environmental Policy Act (NEPA)
- Outer Continental Shelf Lands Act (OCSLA)
- Coastal Zone Management Act (CZMA)
Marine Mammal Protection Act

Harassment is any act of pursuit, torment, or annoyance which:

- has the potential to injure a marine mammal or marine mammal stock in the wild [Level A]
- has the potential to disturb a marine mammal or a marine mammal stock in the wild by causing disruption of behavioral patterns including, but not limited to, migration, breeding, nursing, breathing, feeding, or sheltering [Level B]
Marine Mammal Protection Act

Harassment for the U.S. Navy and Federally-funded research is slightly different, as of 2003:

- any act which injures or has the significant potential to injure a marine mammal or marine mammal stock in the wild [Level A]
- Any act which *disturbs or is likely* to disturb a marine mammal or a marine mammal stock in the wild by causing disruption of natural behavioral patterns including, but not limited to, migration, surfacing, nursing, breeding, feeding, or sheltering, to a point where such behavior patterns are abandoned or significantly altered [Level B]
Marine Mammal Protection Act

All research on marine mammals, including research to determine how they receive and react to sound, may be conducted only under an approved scientific research permit.
Other activities that introduce sound into the marine environment such as geophysical research, resource extraction activities, and construction need to obtain a Letter of Authorization or an Incidental Harassment Authorization demonstrating:

- Negligible impact
- Specified geographical region
- Small numbers
Marine Mammal Protection Act

Noise associated with shipping activities has never been regulated under MMPA. Shipping has never received an Incidental Harassment Authorization in spite of introducing the greatest amount of human-generated sound energy at low frequencies into the marine environment.
Endangered Species Act

ESA prohibits “taking” of any endangered species

“Take” means “to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct”

Regulation has extended this protection to threatened as well as endangered species
Endangered Species Act

- In any instance in which MMPA is more restrictive than ESA, MMPA takes precedent
  - MMPA Negligible Impact is more restrictive than ESA Jeopardy
  - Incidental Take Authorization under ESA requires a prior ITA under MMPA
Biological Ocean Noise
Biological Components of Ocean Noise

- **Snapping shrimp**
  - Broad energy peak 2-15 kHz; some energy to 200 kHz
  - Individual snaps peak-to-peak source levels to 189 dB re 1 µPa at 1 m

- **Fish choruses**
  - Raise ambient by more than 20 dB in range of 50 Hz to 5 kHz for several hours
Biological Components of Ocean Noise

- **Marine Mammals**
  - Vocalizations range from $<10$ Hz to $>200$ kHz
  - Source levels of 228 dB re 1 $\mu$Pa at 1 m for echolocation clicks of false killer whale and bottlenose dolphin in the presence of noise
Biological Components of Ocean Noise

- Marine Mammals
  - Highest recorded source level is 232 dB re 1 μPa at 1 m for sperm whale clicks
Biological Components of Ocean Noise

- **Marine Mammals**
  - Blue whales and fin whales produce 190 dB re 1 μPa at 1 m in 10 – 25 Hz range
  - Weddell seals produce underwater trills to 193 dB re 1 μPa at 1 m in 1 – 10 kHz range
Biological Components of Ocean Noise

- **Marine Mammals**
  - Along the U.S. West Coast, blue whale choruses in September and October increase ambient noise by 20 – 25 dB
  - In the underwater canyons off Kaikoura, New Zealand sperm whales are continuously audible and a dominant acoustic feature
  - During humpback breeding season time-averaged peak levels of choruses reached 125 re 1 µPa at 1 m at 2.5 km offshore
Biological Components of Ocean Noise

D.H. Cato, 1995

AMBIENT SEA NOISE PREDICTION CURVES - AUSTRALIAN WATERS

NOISE SPECTRUM LEVEL (dB re 1 µPa²/Hz)

FREQUENCY (Hz)

Tasman
Indian
Coral
Remote
deep
Timor
Arafura Seas
Fish
chorus
Evening
chorus
Sperm
whales
Shrimps
inshore
Rain, heavy
Rain, moderate
Shrimps
30 knots
20 knots
10 knots
5 knots
Usual
lowest
ocean
noise

D.H. Cato, 1995
## Energy Budget per Year

<table>
<thead>
<tr>
<th></th>
<th>SPL dBuPa</th>
<th>T sec</th>
<th>#</th>
<th>OP Day</th>
<th>Ping/min</th>
<th>Energy Joules</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottlenose dolphin</strong></td>
<td>226</td>
<td>1xE-4</td>
<td>1,000,000</td>
<td>365</td>
<td>1.5xE4</td>
<td>6xE14</td>
</tr>
<tr>
<td><strong>ASW Sonar</strong></td>
<td>235</td>
<td>2</td>
<td>100</td>
<td>10</td>
<td>3</td>
<td>4xE13</td>
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<tr>
<td><strong>Wind (sea state 3)</strong></td>
<td>90</td>
<td>CW</td>
<td>N/A</td>
<td>365</td>
<td>CW</td>
<td>2xE13</td>
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<tr>
<td><strong>Heavy rain</strong></td>
<td>123</td>
<td>0.05%</td>
<td>N/A</td>
<td>365</td>
<td>N/A</td>
<td>1xE13</td>
</tr>
<tr>
<td><strong>Airguns</strong></td>
<td>250</td>
<td>.02</td>
<td>50</td>
<td>100</td>
<td>3</td>
<td>1xE13</td>
</tr>
<tr>
<td><strong>Supertanker</strong></td>
<td>185</td>
<td>CW</td>
<td>11,000</td>
<td>300</td>
<td>CW</td>
<td>7xE12</td>
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<tr>
<td><strong>Humpbacks</strong></td>
<td>185</td>
<td>0.025%</td>
<td>200,000</td>
<td>365</td>
<td>N/A</td>
<td>4xE12</td>
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<tr>
<td><strong>LFA Sonar</strong></td>
<td>235</td>
<td>6</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>4xE12</td>
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<tr>
<td><strong>Container Ship</strong></td>
<td>165</td>
<td>CW</td>
<td>40,000</td>
<td>300</td>
<td>CW</td>
<td>3xE11</td>
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<tr>
<td><strong>Research Exper</strong></td>
<td>195</td>
<td>1</td>
<td>10</td>
<td>360</td>
<td>1</td>
<td>2xE9</td>
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</tbody>
</table>

Calculations by Jim Miller, University of Rhode Island
The Biological Component
– Marine Mammal Audition
Marine Mammal Audition

- **Comparison with land mammal ears**
  - External ears typically absent
  - Middle ear extensively modified
    - Migrated outward relative to the skull
    - No substantial bony association with the skull
    - Large and dense ossicles
    - Air-fluid impedance matching function supplanted by direct conduction through fatty channels to inner ear
Marine Mammal Audition

- Inner ear subtly modified
  - More bony buttressing of the basilar membrane
  - Greater thickness-width ratios in the high frequency hearers
  - Enhanced ganglion cell densities (up to 3000 cells/mm cf. mammalian average of 100/mm)
  - Ganglion cell:hair cell ratios of 6:1 in Type I odontocetes (see below) cf. 2.4:1 in humans
Marine Mammal Audiograms

A

B
Marine Mammal Audition

- Pinnipeds (seals, sea lions, walrus) have better underwater hearing at low frequencies than cetaceans, a high-frequency cutoff between 30 and 60 kHz, and maximal sensitivity of about 60 dB re 1 µPa.

- Odontocetes have best frequency of hearing between 80 and 150 kHz and maximum sensitivity between 40-50 dB.

- No audiograms exist for baleen whales, but anatomy and vocalizations suggest low frequency hearing.
Odontocete Audiograms
Beaked Whale Inner Ear: High Frequency Odontocete

- Well-developed semi-circular canals
- Base of cochlea
- Auditory nerve
- Outer laminar groove
- Buttressed Eustachian tube

Courtesy D.R. Ketten
The Biological Component
– Response to Noise
Zones of Noise Influence

- Injury – Acoustic Trauma
- Hearing Loss – Permanent Threshold Shift
- Temporary Threshold Shift
- Avoidance, Masking
- Behavioral disturbance declining to limits of audibility

Adapted from Richardson and Malme 1995
Factors Influencing Marine Mammal Response to Noise

- Individual hearing sensitivity, activity pattern, and motivational and behavioral state
- Past exposure to the noise resulting in
  - Habituation
  - Sensitization
- Individual noise tolerance
- Demographic factors such as
  - Age
  - Sex
  - Presence of dependent offspring
Responses of *Phocoena* to 145 dB pinger

Control

50% avoidance of 100 dB assuming 15 log r

Spreading Loss

Effect reduced by 50% after 3 days of transmit

Transmit

Culik et al 2001 Mar Ecol
Prog Ser 211:255-260
Factors Influencing Marine Mammal Response to Noise

- Resting animals are more likely to be disturbed than animals engaged in social activities.
- Gray whale mother-calf pairs or humpback whale groups with a calf are more likely to be disturbed by whale-watching boats.
Factors Influencing Marine Mammal Response to Noise

- Whether the source is moving or stationary
- Environmental factors which influence sound transmission such as a surface duct
- Habitat characteristics such as being in a confined location
- Location, such as the proximity of the animal to the shoreline
Migration Deflection Relative to LFA Source Location

Inshore: Path deflection at received levels of 140 dB re 1 µPa

Offshore: No path deflection at received levels greater than 140 dB re 1 µPa
Range of Responses – Beluga Whales
Range of Responses – Beluga Whales

- In high arctic
  - Respond to early spring sounds of icebreakers in deep channels at received levels below 105 dB re 1 µPa
  - Respond at ranges up to 50 km
  - Respond by fleeing up to 80 km
  - Respond when high-frequency components are just audible
Range of Responses – Beluga Whales

- Possible explanations:
  - Partial confinement in heavy ice
  - Good sound transmission in arctic deep channels in spring
  - Possible similarity of high frequency components to killer whale sounds
  - Lack of prior exposure in that year
    - Returned in one to two days to area in which received sound levels were 120 dB re 1 μPa
Range of Responses – Beluga Whales

- In St. Lawrence River
  - Appear more tolerant of large vessels moving in consistent directions than small boats
  - But, vocal responses were the opposite; in response to ferries
    - Call rate reduced from 3.4 – 10 per whale per min to 0 – 1 per whale per min
    - Repetition of specific calls increased when vessel within 1 km
    - Frequency of vocalization shifted from 3.6 kHz to 5.2 – 8.8 kHz when vessels close to whales
Range of Responses – Beluga Whales

- In Alaska
  - Beluga feeding on salmon in a river are more responsive to small boats with outboard motors than to larger fishing vessels.
  - Beluga feeding in Bristol Bay continue to feed amongst fishing vessels even when purposely harassed by smaller motorboats.
Long Term Responses

- Killer whales almost completely abandoned Broughton Archipelago in British Columbia when Acoustic Harassment Devices (AHD) were installed at salmon farms to deter harbor seal predation between 1993 and 1999.

- After removal of AHD in 1999 whales returned within six months.
Gray whales abandon Guerrero Negro breeding lagoon during shipping/dredging.
Masking

- Masking is a reduction in the animal’s ability to detect relevant sounds in the presence of other sounds.
- Masking is reduced by directional hearing.
- Directivity Index (DI) measures increase in omnidirectional noise required to mask signal coming from a particular direction.
Bottlenose dolphins have a DI for signals originating directly ahead of 10.4 dB at 30 kHz to 20.6 dB at 120 kHz.
Masking

- Icebreaker masking of beluga calls – measured as noise-to-signal ratio
  - Underway ice breaking: 29 dB
  - Ice ramming (primarily propeller cavitation): 18 dB
  - Bubbler system (high-pressure air blown into water to push floating ice away from ship): 15.4 dB

- Calculations of range of masking (noise above threshold within the critical band centered on the signal) extended to 40 km for ice ramming sounds
Responses to Masking

- Beluga whales increase call repetition and shift to higher frequencies in response to boat traffic.
- Gray whales increase amplitude, change timing, and use more frequency modulation in noisy environment.
- Humpback whales exposed to Low Frequency Active (LFA) sonar increased song duration by 29%.
Responses to Masking

- Masking occurs in the natural environment and marine mammals show remarkable adaptations
  - A beluga whale required to echolocate on an object placed in front of a noise source reflected sonar signals off water surface to ensonify object
  - Strongest echos returned along a path different from that of the noise
Temporary Threshold Shift

- When the mammalian auditory system is exposed to a high level of sounds for a specific duration, the outer hair cells in the cochlea begin to fatigue and do not immediately return to their normal shape. When the hair cells fatigue in that way, the animal’s hearing becomes less sensitive.

- If the exposure is below some critical energy flux density limit, the hair cells will return to their normal shape; the hearing loss will be temporary, and the effect is termed a *temporary threshold shift* in hearing sensitivity, or TTS.
Temporary Threshold Shift

TTS experiments have been conducted in three species of odontocetes (bottlenose dolphin, false killer whale, beluga whale) with both behavioral and electrophysiological techniques and three species of pinnipeds (harbor seal, California sea lion, elephant seal) with behavioral techniques.
False killer whale

Fatiguing stimulus – broadband received level of 179 dB rms re 1 µPa, which was about 95 dB above the animal’s pure-tone threshold at the test-tone frequency of 7.5 kHz

Exposure to 50 min of the fatiguing stimulus

TTS of 10-18 dB

Recovery from the TTS occurred within 20 minutes
Temporary Threshold Shift

- Harbor and elephant seals and California sea lion
  - Fatiguing stimulus – continuous random noise of 1-octave bandwidth 60 - 75 dB above threshold
  - Exposure to 20-22 min of the fatiguing stimulus
  - TTS of 4-5 dB for test signals at frequencies between 100 Hz and 2 kHz
  - Recovery from TTS had occurred at the next test of threshold conducted after 24 hours
Temporary Threshold Shift

- **Bottlenose Dolphins and Beluga Whales**
  - Fatiguing stimulus – single impulsive sound of approximately 1 ms, peak pressure of 160 kPa, a sound pressure of 226 dB peak-to-peak re 1 µPa
  - Produced a TTS of 7 and 6 dB at 0.4 and 30 kHz respectively in beluga whales, but no TTS at 4 kHz. Stimulus to 228 dB peak-to-peak produced no threshold shift in dolphins at these frequencies
  - Recovery in 4 minutes
Summary of TTS for captive odontocetes

Courtesy J. Finneran

The threshold shift was 5 to 10 dB with a recovery time of less than an hour.

The existing data fit an “equal energy” line; i.e., one that shows a 3 dB decrease (halving) in required SEL for each doubling of exposure time.
Permanent Threshold Shift

If the sound exposure exceeds a limit higher than that for onset of TTS or TTS is repeated many times over a long period of time, the outer hair cells in the cochlea become permanently damaged and will eventually die; the hearing loss will be permanent, and the effect is termed a **permanent threshold shift** in sensitivity, or PTS.
Because of ethical reasons, PTS is never directly investigated in marine mammals.

PTS is estimated based on TTS → PTS shifts in typical laboratory animals:
- At least 40 dB of repeated TTS is required for PTS.
- No more than 18 dB of TTS has been experimentally produced in any marine mammal.
- TTS increases in laboratory animals at 1.6 dB per dB of SEL (Sound Exposure Level) or energy flux density ($\mu$Pa$^2$·s).
- Slope of the growth of TTS with sound energy remains to be determined in marine mammals.
Acoustic Trauma

Usually associated with single occurrence, acute trauma such as the blast effects seen in ear bones of two humpback whales recovered from fishing nets in Newfoundland near where there had been blasting using 5000 kg charges.
• Sources of Sound in the Ocean
  i. natural biological sources (already discussed)
  ii. natural physical sources
  iii. man-made sources
• Propagation of Sound in the Ocean
• Metrics of the Sound Field and Noise “Budgets”
• Long-Term Trends in Ocean Noise
Natural Physical Sources of Sound in the Ocean
Natural Physical Sources

- lightning and thunder
- precipitation
- wind
- ocean surface waves
- bubbles
- bolides
- ice cracking, glacier calving
- volcanic activity and venting
- sediment transport
- underwater landslides and turbidity currents
- earthquakes

* biology
Most Natural Physical Sources of Ocean Sound (Noise)

I. Sources At and Near the Ocean/Air Interface
   - Nonlinear wave-wave interactions and microseisms
   - Turbulent pressure fluctuations on the ocean surface
   - Wave breaking
   - Open ocean wave breaking and whitecapping
   - Surf (bottom-limited breaking)
   - Bubbles
   - Precipitation (rain, snow, hail, sleet)
   - Hurricanes and cyclones

II. Sources At and Near the Ocean/Earth Interface
   - Volcanoes
   - Hydrothermal venting activity
   - Pebble/rock grinding and gravel transport
   - Turbidity currents and underwater landslides

III. Sources in the Atmosphere
   - Lightening strikes and thunder
   - Bolides
   - Aurora, sound generated by wind turbulence (mountains, strong storm systems)

IV. Sources in the Earth
   - Earthquakes

V. Sources within the Ocean
   - Thermal agitation and molecular motion
   - Turbulence
   - Neutrinos

VI. Sources At and Near the Ocean/Ice Interface (Marginal Ice Zone)
   - Ice cracking (thermal and stress-induced)
   - Glacier calving
Fairly Quiet Daytime Period (wind speed < 4 m/s)

“microseisms”

Wenz curves

(PLATE 1, NRC, 2003; adapted from Wenz, 1962.)
Sources of Man-Made Noise in the Ocean
Sources of Man-Made Noise in the Ocean

- Military sonars (53C, LFA)
- Seismic survey arrays
- Ships and Boats

\{ Intentional \}

\{ Unintentional \}

- Commercial sonars and sources
  - Depth sounders and navigation sensors
  - Sources focused on marine life
    - Fishfinders
    - Acoustic harassment devices
    - Acoustic deterrent devices

- Others
  - Explosions (nuclear, chemical)
  - Industrial activity (e.g., oil production, offshore construction, dredging)
  - Aircraft
  - Research sources
Temporal Character of Man-Made Sounds

**Periodic Transients in Time**
- active sonars
- seismic air gun arrays
- pingers and AHDs
- pile-driving

**Continuous in Time, Aperiodic (continuous in frequency)**
- broadband ship cavitation
- dredging
- ice-breaking

**Continuous in Time, Periodic (discrete in frequency)**
- ship prop cavitation tonals
- engine rotation tonals
- Prop-driven aircraft

**Single Transient in Time**
- explosions
Source Signature – Acoustic Pressure Time Series

Periodic sequence of transient pulses

- Frequency
- Amplitude
- Rise Time
- Waveform character

Pulse duration

\[ T_s \] (interpulse time)

\[ A \]

* Frequency
* Amplitude
SQS 53 Sonar

- AN/SQS 53C sonar is the most advanced surface ship ASW sonar in the U.S. Navy
- typical range ~30 nm
- 294 U.S. Navy ships and submarines
- 58 % (~170) have sonar
- 45 % underway at any time


Table 2. Surface Ship Sonar Systems of the 11 NATO Countries reportedly participating in Neo Tapon 2002 (Jane’s Underwater Warfare Systems, 2004; Friedman 1989).

<table>
<thead>
<tr>
<th>Country</th>
<th>System</th>
<th>Frequency</th>
<th>Type (1)</th>
<th>Installed on (class)</th>
<th># of Units (2)</th>
</tr>
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<tbody>
<tr>
<td>Belgium</td>
<td>AN/SQS-510</td>
<td>4.3 – 8 kHz</td>
<td>HM</td>
<td>Wielingen</td>
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<td>4.3 – 8 kHz</td>
<td>HM</td>
<td>Halifax</td>
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<td>HM</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>DUBV 23</td>
<td>4.9 - 5.4 kHz</td>
<td>HM</td>
<td>Suffren</td>
<td>1</td>
</tr>
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<td>Cassard</td>
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<td>DUBV 25</td>
<td>4.9 - 5.4 kHz</td>
<td>HM</td>
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<td></td>
<td>DUBV 43B/C</td>
<td>5 kHz</td>
<td>VDS</td>
<td>Suffren</td>
<td>1</td>
</tr>
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<td></td>
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<tr>
<td></td>
<td>DUBV 23</td>
<td>4.9 - 5.4 kHz</td>
<td>HM</td>
<td>Cassard</td>
<td>1</td>
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<tr>
<td></td>
<td>DUBV 43B/C</td>
<td>5 kHz</td>
<td>VDS</td>
<td>Suffren</td>
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</tr>
<tr>
<td>Germany</td>
<td>DSQS 21</td>
<td>In the band 3 - 14 kHz</td>
<td>HM</td>
<td>Bremen</td>
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<tr>
<td>Greece</td>
<td>1 BV</td>
<td>Greater than 14 kHz</td>
<td>HM</td>
<td>Thetis</td>
<td>(*) 5</td>
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<td></td>
<td>AN/SQS-56</td>
<td>6.7 – 8.4 kHz</td>
<td>HM</td>
<td>HYDRA</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>(#) (DE 1160)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(DE(1164))</td>
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<tr>
<td></td>
<td>AN/SQS-505</td>
<td>7 kHz</td>
<td>HM</td>
<td>Kortenaer</td>
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<td></td>
<td>DE 1191</td>
<td>5 - 7 kHz</td>
<td>HM</td>
<td>Charles F Adams</td>
<td>2</td>
</tr>
</tbody>
</table>

The table lists the surface ship sonars obtained from published sources (Jane's Underwater Warfare Systems, 2004; Friedman, 1989) employed by the 11 NATO countries that were reported to have participated in the Canary Islands naval exercise.

Sonar system types other than those deployed from surface ships are not included in the list. Information on which, if any, of the classes of surface ships and the types of sonars that were in operation in Neo Tapon is not readily available.

<table>
<thead>
<tr>
<th>Country</th>
<th>System</th>
<th>Frequency</th>
<th>Type (1)</th>
<th>Installed on (class)</th>
<th># of Units (2)</th>
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<tbody>
<tr>
<td>Norway</td>
<td>TSM 2633</td>
<td>6 - 8 kHz</td>
<td>HM</td>
<td>Oslo</td>
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<tr>
<td>Portugal</td>
<td>DUBA 3A</td>
<td>22.6 - 28.6 kHz</td>
<td>HM</td>
<td>Cdt Joao Belo</td>
<td>3</td>
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<td></td>
<td>AN/SQS-510</td>
<td>4.3 – 8 kHz</td>
<td>HM</td>
<td>Cdt Joao Belo</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HM</td>
<td>Vasco da Gama</td>
<td>3</td>
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<tr>
<td>Spain</td>
<td>AN/SQS-35</td>
<td>13 kHz</td>
<td>VDS</td>
<td>Baleares</td>
<td>5</td>
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<td></td>
<td>AN/SQS-56</td>
<td>6.7 - 8.4 kHz</td>
<td>HM</td>
<td>Baleares</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(#) (DE 1160)</td>
<td>4.3 – 8 kHz</td>
<td>HM</td>
<td>Descubierta</td>
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<td>(DE(1164))</td>
<td></td>
<td></td>
<td>FFG 7</td>
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<td>Turkey</td>
<td>AN/SQS-26</td>
<td>3 kHz</td>
<td>HM</td>
<td>Knox</td>
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</tr>
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<td></td>
<td>AN/SQS-56</td>
<td>6.7 - 8.4 kHz</td>
<td>HM</td>
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<td></td>
<td>(#) (DE 1160)</td>
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<td>HM</td>
<td>YAVUZ</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>(DE(1164))</td>
<td></td>
<td></td>
<td>FFG 7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>DUBA 25</td>
<td>8 – 10 kHz</td>
<td>HM</td>
<td>Type A69</td>
<td>6</td>
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<tr>
<td>U.K.</td>
<td>Type 2016</td>
<td>4.5 - 7.5 kHz</td>
<td>HM</td>
<td>Invincible</td>
<td>3</td>
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<td></td>
<td></td>
<td></td>
<td>Type 42</td>
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<td>7</td>
</tr>
<tr>
<td></td>
<td>Type 2050</td>
<td>4.5 - 7.5 kHz</td>
<td>HM</td>
<td>Type 22</td>
<td>5</td>
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<td></td>
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<td></td>
<td>Type 23</td>
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<td>16</td>
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<tr>
<td></td>
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<td></td>
<td>Type 42</td>
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<td>11</td>
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<td>U.S.</td>
<td>AN/SQS-53</td>
<td>3 kHz</td>
<td>HM</td>
<td>Spruance</td>
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<td>Ticonderoga</td>
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<td>27</td>
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<tr>
<td></td>
<td>AN/SQS-56</td>
<td>6.7 - 8.4 kHz</td>
<td>HM</td>
<td>Arleigh Burke I/II/IIia</td>
<td>38</td>
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<tr>
<td></td>
<td>(#) (DE 1160)</td>
<td>4.3 – 8 kHz</td>
<td>HM</td>
<td>FFG 7</td>
<td>33</td>
</tr>
</tbody>
</table>

(1) HM: Hull-mounted; VDS: Variable-depth sonar
(2) number of units is the total number in each country’s navy, NOT the number of those units in the exercise
(*) may actually be an acoustically passive, rather than active, sonar system; not clear from the references
(#) the DE 1160 and DE 1164 systems are very similar to the SQS-56 sonar
Towed Vertically Directive Source (TVDS)

Mid Frequency

3-kHz APERTURE

SOURCE LEVEL = 226 dB re 1μPa @
TRANSMIT BANDWIDTH * = 800
VERTICAL BEAMWIDTH =

Low Frequency

600-Hz APERTURE

SOURCE LEVEL = 228 dB ** re 1μPa @
TRANSMIT BANDWIDTH = 200
VERTICAL BEAMWIDTH = 23°

* -3 dB Down beamwidth
** During Phase II, one of the five LF elements was inoperable so that the SL was down 2 dB from the five element maximum of 230dB.

D'Amico et al, SACLANTCEN Rep't, 1998
Common Features of Sonars Operating during Some Well Documented Beaked Whale Mass Stranding Events

- High amplitude (rms SL > 223 dB re 1 µPa @ 1 m)
  (approaching cavitation limit near the surface)
- Periodic sequence (15 – 60 sec) of transient pulses (up to ~ 4 sec)
- Radiate significant energy at mid frequencies
- Operation over several hours
- Horizontally directive arrays
- Sources moved at speeds of 5 kt or greater

- Source depths coincide with the center of acoustic waveguides where one boundary is formed by refraction within the water column
Low Frequency Active (LFA) Sonar

- 100-500 Hz
- Up to 18 LF sources
- Individual source level of 215 dB re 1 uPa @ 1m
- Pings of 6-100 sec duration
- Array center ~122 m depth

Figure 1. Schematic of the SURTASS LFA sonar system

(NMFS, “Biological Opinion,” 2002)
Seismic Airgun Operations

An Example Airgun Array of 3397 Total cu. in.

FIGURE 2-4  Schematic diagram of an air-gun array. A total volume of 3,397 cubic inches is shown. This array has 3 subarrays (each line of circles), and uses 24 air-guns. Each circle represents an air-gun, except for the circles at the head of each array, which represent 3-gun clusters. The nearest number represents the volume of air expelled by individual air-guns in cubic inches.

NRC, 2003
Six individual sound sources

Individual sound-source signatures have strong bubble pulses

The sum of the six individual sound source signatures

Tuned six-source array

When a carefully chosen suite of sound sources is triggered simultaneously, a tuned signature is produced.

Reasons to Create an Array of Acoustic Sources

- Focus sound in a desired direction(s)
- Shape the waveform
- Circumvent the limitations caused by cavitation
- Reduce losses due to geometrical spreading
Table 1. Summary of Acoustic Source Array Properties.

<table>
<thead>
<tr>
<th></th>
<th>TVDS Low Freq</th>
<th>TVDS Mid Freq</th>
<th>AN/SQS 53C</th>
<th>AN/SQS 56</th>
<th>Air Gun Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform</td>
<td>HFM/CW (1)</td>
<td>HFM/CW</td>
<td>FM/CW (1)</td>
<td>FM/CW</td>
<td>BB Pulse (2)</td>
</tr>
<tr>
<td>Source Level (3)</td>
<td>228 dB (4)</td>
<td>226 dB (4)</td>
<td>235 dB</td>
<td>223 dB</td>
<td>260 dB (5)</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>4 sec</td>
<td>4 sec</td>
<td>1-2 sec</td>
<td>1-2 sec</td>
<td>0.02 sec</td>
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<tr>
<td>Inter-Pulse Time</td>
<td>1 min</td>
<td>1 min</td>
<td>24 sec</td>
<td>24 sec</td>
<td>10-12 sec</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>600 Hz</td>
<td>3000 Hz</td>
<td>2600 Hz</td>
<td>3300 Hz</td>
<td>6800 Hz</td>
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<td></td>
<td></td>
<td></td>
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<td>8200 Hz</td>
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<tr>
<td>Bandwidth</td>
<td>250 Hz</td>
<td>500 Hz</td>
<td>100 Hz</td>
<td>100 Hz</td>
<td>wideband (7)</td>
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<td>Source depth</td>
<td>70-85 m</td>
<td>70-85 m</td>
<td>8 m</td>
<td>6 m</td>
<td>6-10 m</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>23°</td>
<td>20°</td>
<td>40°</td>
<td>30°</td>
<td>function of freq</td>
</tr>
<tr>
<td>Beam Direction</td>
<td>horizontal</td>
<td>horizontal</td>
<td>3° down from horizontal</td>
<td>horizontal</td>
<td>vertical</td>
</tr>
</tbody>
</table>

1) hyperbolic frequency modulated (HFM), continuous wave (CW), and frequency modulated (FM);
2) broadband (BB);
3) source levels (rms for sonars and 0-pk for the air gun array) are in units of dB re 1 uPa @ 1 m;
4) the simultaneous low frequency and mid frequency transmissions considered as one pulse has a source level of 233 dB re 1 uPa @ 1 m (coherent addition) and 230 dB re 1 uPa @ 1 m (incoherent addition);
5) 0-pk source level for an equivalent point source along the main beam in the far field;
6) peak levels in the 5-300 Hz band;
7) radiated acoustic energy extending up to several kilohertz.

Surface Ship Noise Sources

Flow Noise Sources
- Bow wave
- Wake
- Appendages
- Gap/discontinuity
- Hull

Propeller Noise Sources
- Cavitation Noise
- Blade Rate
- Turbulent Ingestion
- Trailing Edge
  (Singing Prop)

Machinery Noise Sources
- Main propulsion system
- Auxiliary system
- Piping paths
- Structural-borne path
- Sea-connected system

Propeller Cavitation

* accounts for 80-85% of the ship-radiated noise power

FIG. 5. Selected source spectra (colored curves) and the ensemble average spectrum (black curve).

Modeled surface ship source spectral densities for the 5 classes of ships used in the RANDI ambient noise model. The curves in each class also are a function of ship length and ship speed; those shown in the figure pertain to the mean values of ship length and ship speed in each class.

\[
\bar{S}(f) = 230.0 - 10\log(f^{3.594}) + 10\log\left(1 + \frac{f}{340}\right)^{0.917}
\]


A comparison of the mean source spectral density for merchant ships from Wales and Heitmeyer, 2002 (equation on p. 1216), plotted as a solid curve, with the maximum and minimum merchant ship source spectral densities from the RANDI model (calculated using the maximum and minimum ship lengths and ship speeds for this class) plotted as dashed curves. SOURCE: Wagstaff, 1973.
Fundamental Propeller Blade Rate Frequencies and Source Levels for Merchant Ships

Commercial Ship Arrivals in US Ports

West coast total ship calls 14,086
- 2,233 Tankers
- 6,854 Container
- 3,219 Dry Bulk
- 1,780 Others
Alaska tankers not counted

East coast total ship calls 17,915
- 3,148 Tankers
- 7,963 Container
- 2,379 Dry Bulk
- 4,425 Others

South coast total ship calls 19,033
- 9,318 Tankers
- 1,887 Container
- 4,949 Dry Bulk
- 2,879 Others

Wenz curves

(PLATE 1, NRC, 2003; adapted from Wenz, 1962.)
Small Boat Acoustic Signatures

Figure 2. A spectrogram of a typical small boat run past the bottom hydrophone is shown for a rigid hull inflatable boat powered by a 150 horsepower outboard engine. Frequency is displayed on the horizontal axis while time is shown on the vertical axis. The colorbar represents the narrowband spectral levels at the bottom hydrophone.

1995 French Polynesia Nuclear Test Recorded at Pt. Sur

* Distance of 6,670 km
* Signal/Noise Ratio of 20–45 dB

Contour plot of the spectral ratio spectrogram for the 27, October, 1995, French nuclear test on the Mururoa Atoll, as recorded by the Pt. Sur hydrophone. This event had an announced yield of 60 ktons (prototype international data center, 1998). The spectral ratio was calculated by estimating the noise spectral density from 10 s of data prior to the main explosive arrival (providing seven statistically independent estimates for the incoherent average), and using it to normalize the spectral densities estimated during the period shown in the plot. This procedure eliminates the need to account for the data acquisition system response. The contours occur in 6 dB steps from 22 dB to 46 dB.

Bottom Hydrophone 1.5 km offshore, 10 m water

- Small land detonation
- Helicopter flyover
- Prop-driven aircraft
- Biological sound
- Tracked vehicle on beach
- Research source tones
Propagation of Sound in the Ocean
Rays, Wavefronts, and Refraction

* Energy spreads out in 2D rather then 3D (cylindrical vs spherical spreading)

Ray; direction of propagation (normal to wavefronts)

Wavefront (surface of peaks)

SSP

Refraction (Mother Nature likes to go slow)
Geometrical Spreading

Power crossing sphere and power crossing cylinder must be conserved.
Since power equals integral over a surface of the component of intensity normal to the surface:

\[ P = 4\pi r_1^2 \left| \vec{I}_1 \right| = 2\pi r_2 D \left| \vec{I}_2 \right| \]

(assuming that no energy flows thru the top or bottom of the waveguide)

\[ TL = 10\log \left( \frac{P}{4\pi r_1^2} \right) = 10\log \left( \frac{P}{2\pi r_2 D} \right) = 10\log (r_2 D / 2) \]

\[ TL = 10\log r_2 + 10\log D − 10\log 2 \]

\[ TL = 10\log (r_1) + 10\log(D) \]
Types of Acoustic Waveguides (Acoustic Lenses)

Reflection/Reflection (e.g., shallow water)

Reflection/Refraction (e.g., surface ducts)

Refraction/Refraction (e.g., deep sound channel (SOFAR))

* Waveguide boundaries more important than interiors in determining propagation characteristics
Absorption of Sound in the Ocean

* due mostly to salts

Urick, R. J., *Sound Propagation in the Sea*, DARPA, 1979
Figures 1 and 2. Sound speed profiles in the 3 events.

Figure 2. Ray-trace for the sound field from the TVDS source at 85 m depth in the 1996 Greek mass stranding event along with the sound speed profile. Rays are launched from the source at 0 km range in the angular interval about the horizontal direction corresponding to the vertical beam pattern of the TVDS source (re Table 1). Horizontal dashed lines are placed at 20, 85 and 600 m depth in the left-hand panel (Fig. 8.2.1 of D'Amico et al., 1998).
Surface Duct Processes

- Bubbles
- $c(z)$, $\alpha(z)$
- Internal waves
- Rough ocean surface
- $T(z)$ nearly constant with depth
Surface Ducts

- Formed by mixing, creating an isothermal surface layer
  - sound speed gradient in isothermal layer: 0.016 m/s/m

- Seasonally dependent - fairly common during Winter and Spring months

- Low frequency cutoff
  \[ f_{\text{min}}(\text{kHz}) \approx \frac{176}{H(m)^{3/2}} \]
  \[ f_{\text{min}} = 0.5 \text{ kHz} \quad \text{for } H=50 \text{ m} \]

- Warm water ducts have smaller intrinsic absorption at higher mid frequencies
  - At 30 km, the difference in intrinsic absorption is:

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Absorption Difference (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
Calm Weather Conditions with Surface Ducts
(weather conditions mostly are irrelevant to DSC propagation)

- Breakdown in duct conditions unless solar heating is minimized
  (cloud cover, cover of darkness)
- Reduced scattering of sound out of the duct
- Reduced near-surface bubble content
- Reduced surface ship motion, helping to keep main beam of hull-mounted
  sonar directed in the duct
- Reduced wind-generated ambient noise levels
  • increased SNR
- Enclosed basins reduce swell-modulated white-capping
Dispersion: Dependence of Speed of Propagation on Frequency

1450 m/s

200 m

1500 m/s

atten = 10dB/\lambda

Simulation Environments (OASES)
Transmission Loss vs Range with OASES
130-170 Hz in 1 Hz steps  Constant Profile 1450 m/s over 0-200 m

Transmission Loss vs Range with OASES
130-170 Hz in 1 Hz steps  n2 Linear Profile 1450-1500 m/s over 0-200 m

Summary of Waveguide Propagation Characteristics

“Shallow” Water
- Formed by reflection
- Bottom geoacoustic properties and bathymetry important
  - interaction with the bottom causes loss of energy
- Dispersive

Surface Ducts
- More efficient propagation to long range at mid to high frequencies
  - ducted propagation can increase received levels by up to 20 dB
- Bottom properties not important except possibly at close range
- Minimal broadband dispersion
  - pulses tend to remain as pulses
Physics of Sound (Sound Physics)

TWO EQUATIONS:

- Conservation of Momentum \( \vec{F} = ma \) \( \rho_0 \frac{\partial \vec{v}}{\partial t} + \nabla p = 0 \) vector equation

- Conservation of Mass (plus properties of fluid when squeezed or stretched: “equation of state”) \( \frac{\partial p}{\partial t} + K_s \nabla \cdot \vec{v} = 0 \) scalar equation

A. Two properties of the fluid

\[ \rho_0 : \text{ambient density (mass/vol)} \]
\[ \frac{1}{K_s} : \text{compressibility of the fluid} \quad \left( c^2 = K_s / \rho_0 \right) \]

B. Two acoustic field variables – 1st order

\[ p(x,t) : \text{acoustic pressure (scalar)} \]
\[ \vec{v}(x,t) : \text{acoustic particle velocity (vector)} \]

C. Two types of operations

\[ \frac{\partial}{\partial t} : \text{changes with time} \]
\[ \nabla, \nabla \cdot : \text{changes with space} \]
Physics of Sound (continued)

- Combine the two equations to eliminate $\mathbf{v}$

$$\nabla = \frac{\partial}{\partial t} \begin{pmatrix} c^2 \nabla^2 p \\ \rho \end{pmatrix} \quad \left( c^2 = \frac{K_s}{\rho_0} \right) \quad \text{acoustic wave equation for pressure}$$

a) $2^{nd}$ order linear differential equation for an acoustic field variable at $1^{st}$ order.

b) Better numerical solutions to this equation have been an outstanding achievement in underwater acoustics over the past quarter century.

c) Provides no insight into rel’n between various acoustic field variables.

d) Provides no physical interpretation of field variables at $2^{nd}$ order, e.g., $p^2$

- Transform the two equations to $2^{nd}$ order and combine to get equation for $2^{nd}$ order field variables (e.g., $p^2$, $|\mathbf{v}|^2$, $p\mathbf{v}$)

$$\Rightarrow \frac{\partial}{\partial t} \left( \frac{1}{2} \rho_0 \mathbf{v} \cdot \mathbf{v} + \frac{1}{2K_s} p^2 \right) + \nabla \cdot (p\mathbf{v}) = 0$$

CONSERVATION of ACOUSTIC ENERGY
Prediction of Sound Field Properties

**Physics**
- (Elliptic Wave Equation)
  - Ray Theory
  - Normal Mode
  - Wavenumber Integration
  - Parabolic Equation

**Environmental Input**
- Sound Speed Profile
- Water Depth
- Boundary Properties (e.g., roughness)
- Ocean Bottom Properties

**Source Properties**
- Source Location(s) with time
- Source Signature
- Source Level
- Radiation Pattern

* Lack of knowledge of environmental inputs probably is the greatest source of uncertainty in predicting the character of the sound fields
Metrics of the Sound field and Noise “Budgets”
Ocean Noise “Budgets”

An NRC, 2003 Committee Task

- Evaluate human and natural contributions to ocean noise.

An NRC, 2003 Committee Recommendation

- Develop a global ocean noise budget that includes both ambient and identified events and uses “currencies” in addition to average pressure spectral levels to make the budget more relevant to marine mammals.
What metric ("currency") of that property to use?

1. Source properties
2. Received field properties
3. Perceived field properties
1. **Source metrics**
   - no need for propagation modeling
   - maybe no need for ocean acoustic measurements
   - how to include natural sources of sound?

2. **Received field metrics (hydrophone)**
   - takes account of propagation effects, e.g.,
     - geometrical spreading
     - frequency dependence of absorption
     - waveguide effects
   - location (propagation environment) therefore becomes important

3. **Perceived field metrics**
   - What potential impact should be evaluated?
     - PTS
     - TTS
     - behavior
     - masking
     - habituation, sensitization
     - stress
3. Perceived field metrics

- What is relevant to marine mammals?
  - comments
    - use inverse audiogram as weighting (Dave Bradley)
      - analogous to A-weighted spectra in human hearing
      - mammalian ears process acoustic energy in 1/3-octave frequency bands

- List of some received field metrics of possible relevance to marine mammals
  - sound level (mean squared pressure)
  - sound exposure
    - TTS (P. Naughtigal, 2004. Presentation to the Advisory Committee of the MMC)
  - rise time
    - hearing damage (Cranford, 2004. Public comments to the Advisory Committee of the MMC)
  - spatial diffusivity of sources
    - masking (P. Tyack, 2004. Presentation to the Advisory Committee of the MMC)
  - novelty of the sound
    - adverse behavior (P. Tyack, 2004. Presentation to the Advisory Committee of the MMC, bowhead whale reaction to icebreaker noise in the Arctic)
Possible Metrics of the Received Sound Field

- **Sound Level (Mean Squared Pressure)**
  
  Proportional to acoustic potential energy density
  
  \[ < p^2(t) > \equiv \frac{1}{T} \int_{0}^{T} p^2(t) dt \quad \text{and} \quad SL \equiv 10 \log_{10} \left[ < p^2(t) > \right] \]

- **Sound Exposure**
  
  "Unweighted" Sound Exposure (ANSI, 1994)
  
  \[ SoE \equiv \int_{0}^{T} p^2(t) dt \]

- **Rise Time**
  
  Use as measure: \( \frac{\partial p}{\partial t} \)
  
  If \( G_p(\omega) \) is the spectrum of \( p(t) \), then \( \omega^2 G_p(\omega) \) is the spectrum of \( \frac{\partial p(t)}{\partial t} \)

- **Spatial Gradients**
  
  \( \nabla S_p(\omega) \propto \tilde{Q}_{p\tilde{\nu}}(\omega) \) (reactive intensity)

- **Spatial Diffusivity of Sources**
  
  Use as measure:
  
  - active acoustic intensity divided by the energy density, e.g.,
  
  \[ \frac{C_{p\tilde{\nu}}(\omega)}{S_p(\omega)} \]
Formulation of a Noise Budget whose “Currency” is Total Acoustic Energy

- \( < p^2 > = K_s \frac{E_{tot}}{V} \) (mean over space and time)
  - uses \( E_{pot} = E_{kinetic} \) (Landau and Lifshitz, 1987)
- Most classical ocean noise studies focus on \( < p^2 > \) and its frequency dependence (e.g., Wenz, 1962)
- Is this currency relevant to marine mammals?

Sonar Equation
\[
RL(r) = SL - TL(r)
\]

where the transmission loss \((TL)\) is
\[
TL(r) = 20 \log(r) + \alpha \omega r \quad \quad r \leq r_T
\]
\[
TL(r) = 20 \log(r_T) + 10 \log\left(\frac{r}{r_T}\right) + \left(\alpha_w + \alpha_b\right) r \quad \quad r > r_T
\]

Converting from the logarithmic to linear domain:
\[
p(r) = (A/r) \exp[-\beta_w r] \quad \quad r \leq r_T
\]
\[
p(r) = \left(\frac{A}{r_T}\right) \left(\frac{r_T}{r}\right)^{1/2} \exp\left[-\left(\beta_w + \beta_b\right) r\right] \quad \quad r > r_T
\]
\[
= (A / r_T) (r_T / r)^{1/2} \exp[-\beta_t r]
\]
Formulation of Noise Budget (continued)

- Using \( e_{pot}(r) = \frac{1}{2K_s} p^2(r) \) and \( E_{pot} = \int_V e_{pot} \, dV \)

then in pillbox-type ocean (i.e., azimuthally symmetric)

\[
E_{pot}^{point} = A^2 \left\{ \frac{\pi}{K_s} \left[ \left( \frac{1}{\beta_w} \right) \left( 1 - \exp[-2\beta_w r_T] \right) \right] + \frac{H}{2\beta_t r_T} \exp[-2\beta_t r_T] \right\}
\]

If \( \beta_w, \beta_t \) are very small, then \( E_{pot}^{point} \approx A^2 \left\{ \frac{\pi}{K_s} \frac{H}{\beta_t r_T} \right\} \)

where the ocean waveguide has thickness \( H \) and large horizontal extent

- Source properties completely in \( A^2 \)
- Environmental properties completely in \{ … \} (depends on source frequency)
- Independent of source/receiver geometry
- \( E_{pot} = E_{kinetic} \) for a system undergoing small oscillation (Landau and Lifshitz, 1987).
Comparison of Yearly Sound Energy From Oceanographic Research And Supertankers


A. Oceanography experiments
   • 100 hours total broadcast time
   • 10 experiments per year
   • 200 dB re 1µPa @ 1 m average source level
     @ 50 Hz (1 Hz wide band)

B. Supertankers
   • 127 supertankers at sea at all times
   • 187 dB re 1µPa @ 1 m average source level
     @ 50 Hz (1 Hz wide band) at average speed of
     15 – 22 kts
Wind-Generated Acoustic Energy

For a field approximately independent of depth,

\[ E_{\text{wind}} \approx \frac{Sp_{\text{shallow}}^2}{2K_s \beta_w} \left[ \int_0^{\beta_w D} y^2 \left[ \int_y^\infty \frac{\exp(-x)}{x} dx \right] dy + (\beta_w D) \exp(-\beta_w D) \right] \]

[derived from Urick (1984)]
Downslope-Converted Shipping Noise

- Shipping noise in N. Hemisphere has increased at ~3 dB/decade rate.
- If impact of shipping noise on the deep water environment is an issue, then possibly have ships slow down when passing over continental slopes (r_T to r_B).

\[
E_{\text{downslope}} - E_{\text{shallow}} = \frac{A^2 \pi H}{K_s} \frac{1}{r_B} \left[ \frac{1}{\beta_w} \exp\left[-2 \beta_w r_B\right] - \frac{1}{\beta_t} \exp\left[-2 \beta_t r_B\right] \right]
\]

\[
\left( \frac{E_{\text{downslope}} - E_{\text{shallow}}}{E_{\text{shallow}}} \right) = \left( \frac{\beta_t}{\beta_w} \right) \left( \frac{r_T}{r_B} \right)
\]
Concluding Remarks on Noise Budgets

1. **Must specify a “currency” to develop a noise budget**
   - If the currency is total acoustic energy, then shipping is probably the greatest man-made source.
   - If the currency is peak acoustic pressure, then nuclear and chemical explosions probably are the greatest man-made sources.

2. **Choice of currency may depend on type of potential impact under investigation**
   - several budgets probably will be required to evaluate the potential impact of man-made sound on the marine environment.

3. **Greatest needs for developing noise budgets are:**
   - gather together in one accessible place existing data on man-made sources and noise,
   - measure alternative properties of man-made sources,
   - develop quantitative relationships between man-made noise and levels of human activity,
   - measure effects of alternative properties of man-made sources on marine mammals.
Long-Term Trends in Ocean Noise
Long-Term Trends in Ocean Noise

(NRC, 2003)

5-6 dB/decade increase

~3 dB/decade increase

Very little is known
Long-term Trends in Shipping

The World and U.S. Fleets (000 GT)

U.S. Recreational Boating
Total Expenditures and Boats Owned
1970 to 1998

Compiled by the Market Statistics Department NMMA
January, 1999
Underwater Explosions in the North Pacific 1965 - 1966

Fig. 1. Histogram of number of shots observed on the records for the period August 1965 through July 1966. The number of accepted fuses for each month is shown by diagonal pattern.

Fig. 2. Chart of the North Pacific showing contours of number of shots for the year August 1965 through July 1966. Contour lines are for 1, 5, 10, 50, 100, 500, and 1000 shots per 14400 square miles (a square 120 by 120 nautical miles). Notice that the highest density occurs in the Gulf of Alaska.

Two Current Issues

Seismic surveys

Beaked whale strandings
Marine Seismic ‘Spread’ Elements

- Streamer length = 6 kms & 480 channels
- marine streamer = acoustic receivers
- acoustic (sound) source

Philip Fontana, Veritas DGC, Inc.
Airgun Arrays – Near vs Far Field

In the far-field, the output of the array decreases inversely with the distance \((1/r)\).

However, the maximum pressure in the water is around 20 dB (i.e. 1/10) less than predicted by the point source assumption.

Philip Fontana, Veritas DGC, Inc.
Comparison of Normalized Sensitivity Spectra for Toothed Whales Relative to Acoustic Output from a Typical Deep Water 3D Airgun Array

Philip Fontana, Veritas DGC, Inc.
High Frequency Emissions from Airgun Arrays

Observations - Acoustic event from seismic exploration
Gabor transform (time-frequency analysis) of first arrival

Survey type: standard North Sea
Water-depth: 40 m
Observation distance: 500 m

Slide Courtesy of Peter Van der Sman, SIEP
The presentation showed the results of a controlled exposure experiment conducted by Peter Tyack and colleagues. The results, to be published and not reproduced here, showed that the behavior of sperm whales was not affected by the approach of an operating seismic vessel based on three measures.
Sperm Whales and Seismic

- Horizontal Avoidance
- Diving behavior
- Energetics of Foraging
Public Concerns

Whales Downed by Sound?

Navy sonar may have caused a mass stranding of whales this spring in the Bahamas. The National Marine Fisheries Service (NMFS) and the U.S. Navy are jointly investigating that possibility. Beaked whales beached at several different locations in the northern Bahaman islands within several hours. The whales stranded in a south-to-north pattern, as navy ships using tactical sonar passed through an underwater canyon beneath the New Providence channel.

NMFS asked marine biologist Darlene Ketten of the Woods Hole Oceanographic Institute and Harvard Medical School, where she is assistant professor of otology and laryngology, to assist in the investigation. Ketten is an expert on whale auditory systems and underwater acoustic trauma in particular, including impulse and blast effects. What caused other scientists found in studying the six whales that died from the stranding (the rest were successfullyashed back into the sea) was that all had hemorrhages in or around the ears. Says Ketten. The trauma we found were to the auditory system and to some brain and throat regions that are commonly injured by intense pressures.
Beaked Whale Strandings

The association with mid-range naval tactical sonar is strong. Since the early 1960s when such sonars were deployed, 10 of 41 mass strandings [two or more animals—not a mother-calf pair] of Cuvier’s beaked whale (*Ziphius cavirostris*) were associated with naval exercises.

*Z. cavirostris* accounts for 81% of the stranded animals. Other beaked whales stranding in these circumstances include *Mesoplodon europaeus, M. densirostris, and Hyperoodon ampullatus*.

The best studied cases have been Greece (1996), Bahamas (2000), and Canary Islands (2002).

Brownell *et al.* (2004) recently reported 10 mass strandings of a total of 47 *Z. cavirostris* and one mass stranding of four Baird’s beaked whales (*Berardius bairdii*) in Japan in Sagami Bay and in Suruga Bay between 1960 and 2004. Sagami Bay is the command base for the US Pacific Seventh Fleet; Suruga Bay is the adjacent bay. This is a correlation in location. Any correlation with Naval activity is unknown.
Beaked Whale Heads

Ziphius cavirostris

Photo courtesy N. Hauser and H. Peckham
Findings in Bahamian and Madeiran Beaked Whales

Head and ear trauma in all animals

- Intracranial hemorrhages (9/9)
- Intracoeclelar hemorrhages confirmed (3/4)
- Auditory hemorrhages confirmed (3/4)
- Inner ear degeneration (4/6)

Data from D.R. Ketten
Beaked Whale Stranding Hypotheses

- Physically facilitated
  - Resonance
  - Rectified diffusion

- Behaviorally mediated
  - Facilitated panic
  - Diathetic fragility
  - Remaining at the surface → Decompression sickness

Note that in the Bahamas stranding (the only one for which such estimates are available), the best estimate of received signal level of the whales that stranded is in the range of 160 dB. If correct, physically facilitated hypotheses are hard to substantiate.
Beaked Whale Stranding Hypotheses – Facilitated Panic

- The panic behavioral response of one animal leads to other group members responding similarly until positive feedback has all members of the group in flight which may end them all on the beach.

- One problem with this hypothesis is that normal beaked whale group size is less than the size of the overall number which have stranded in the best studied cases, thus whatever is causing the whales to strand, it transcends normal group size.
Beaked Whale Stranding Hypotheses
– Diathetic Fragility

- It is known that humans and other animals lacking blood clotting factors can have spontaneous hemorrhages, particularly in response to stress.
- It is known that some cetaceans are lacking in the normal suite of blood clotting factors.
- The sub-arachnoid bleeding and migration of blood into the ears seen in stranded beaked whales has been observed in humans who are missing blood clotting factors.
This and succeeding two slides courtesy D.R. Ketten
Inner ear red blood cells and eosinophilic precipitate:
Base, apex, cochlear aqueduct, IAC Lateral variation
Diathetic disease
Beaked Whale Stranding Hypotheses

Remaining at the Surface ➔ Decompression Sickness

- Beaked whales have diving patterns that lead to chronic tissue nitrogen saturation—possibly as high as 300%.
- If a panic response was to stay at the surface or if the sound was less intense at the surface, the whale would remain there too long and nitrogen gas bubbles would form.
- In the well-investigated cases, a surface duct has been present so when the whale would dive, the sound would become more intense.
- Autopsies from the Canary Islands strandings have shown gas bubbles in acoustic fats and associated with hemorrhages in the brain.
DIVESTYLES

Sperm whales:
Regular dives, 18 hours/day

Beaked whales:
Irregular dives: long and deep then short and shallow

Pilot whales:
Bouts of short deep or shallow dives

Courtesy of P. Tyack
Beaked Whale Stranding Hypotheses

- Horizontally-directed high-power (235+ dB) mid-range tactical sonars (3.5 to 8 kHz) with a high duty cycle (often multiple sonars operating one after the other) and relatively long pulse length (500 msec) ensonify a surface duct.

- Beaked whales that normally return quickly to depths to recompress remain at the surface for extended periods.

- Supersaturated nitrogen (calculated to be 300%) in their tissues forms gas bubbles which account for the internal hemorrhaging and observed bubbles.

- *Seemingly most likely hypothesis, until Tyack recently found a beaked whale in a normal diving sequence that stayed at the surface for 50 min following a long, deep foraging dive.*
Seismic and Stranding

- Seismic is unlikely to cause beaked whale strandings because energy is directed downward, frequency is lower, duty cycle is less.

- Mammalian nervous systems require 200 msec to process the loudness of a sound; therefore, 30 msec seismic pulses are unlikely to be perceived as being as loud as they are and behavioral responses are less likely.

- Although two *Z. cavirostris* that stranded in the Baja California in 2002 were associated with seismic operations of the *RV Maurice Ewing*, the ship was also operating mid-range sonar.
Seismic and Stranding

- But caution is still warranted because there are high frequency components to seismic and these frequencies are not as well focused vertically as the low frequencies; whales have better sound processing capabilities than other mammals and thus may not need 200 msec to process sound loudness; and seismic often occurs in open water areas where strandings would likely not be observed.

- Overall detection probability for beaked whales monitored from seismic survey ships under normal operation is less than 2%.

- There was a reported increase in stranding of adult humpback whales in the Abrolhos Bank region of Brazil in 2002 coincident with seismic exploration.

- Even if baleen whales do not strand, they certainly are displaced from feeding grounds by seismic; e.g., Western Pacific gray whales from the region around Sakhalin Island, Russia.
Some Recent Events
Marine Mammal Commission Sound Program

The Omnibus Appropriations Act of 2003 (Public Law 108-7) directed the Marine Mammal Commission to “fund an international conference or series of conferences to share findings, survey acoustic 'threats' to marine mammals, and develop means of reducing those threats while maintaining the oceans as a global highway of international commerce.”
After an extensive assessment process, the Commission appointed 28 members to the Committee, representing a broad and balanced group of stakeholder interests.

The Sound Program has held three plenary sessions of the Committee, one International Policy Workshop, and the Beaked Whale Stranding Workshop. Two more plenary sessions are planned before submission of a final report to Congress.
“On the one hand, sound may represent only a second-order effect on the conservation of marine mammal populations; on the other hand, what we have observed so far may be only the first early warnings or ‘tip of the iceberg’ with respect to sound and marine mammals.”
Is Noise Significant?

- No evidence that anthropogenic noise has had a significant impact on any marine mammal population.
- Significant declines not attributed to noise:
  - Steller sea lions
  - Southwest Alaskan and California sea otters
  - Alaskan harbor seals
Is Noise Significant for Beaked Whales?

- Beaked whale population sizes are unknown
- Effects on whales that do not strand are unknown
Conflict is Inevitable and Should be Minimized

- Humans and marine mammals use sound for the same reason: communication and environmental monitoring are more effective over longer ranges with sound than with other modalities.

- Human technology-driven and marine mammal evolutionary-driven use of sound in the marine environment will inevitably lead to conflict.
Changes in behavior that lead to alterations in foraging efficiency, habitat abandonment, declines in reproduction, increases in infant mortality, and so on, are difficult to demonstrate in terrestrial animals, including humans, and are much more difficult for animals that may only rarely be observed in their natural environment.
Three Stage Approach

- **Within a year:** Development of web-based intelligent system to determine a *de minimis* threshold below which impacts of activities are clearly not significant.

- **Several years:** Extension of the Potential Biological Removal Model to include sub-lethal “takes” from noise.

- **Decade(s):** Transform a Conceptual Model into a Predictive Model for significance of effects of noise on marine mammals.
Population Consequences of Acoustic Disturbance Model

1. **Sound**
   - Frequency
   - Duration
   - Level
   - Source
   - Duty Cycle

2. **Behaviour Change**
   - Orientation
   - Breathing
   - Vocalization
   - Diving
   - Resting
   - Mother-Infant
   - Spatial Relationships
   - Avoidance

3. **Life Function Immediately Impacted**
   - Survival
   - Migration
   - Feeding
   - Breeding
   - Nurturing
   - Response to Predator

4. **Vital Rates**
   - Stage Specific Survival
   - Maturation
   - Reproduction

5. **Population Effect**
   - Population growth rate
   - Population structure
   - Transient dynamics
   - Sensitivity
   - Elasticity
   - Extinction probability
Potential Biological Removal is a successful model for regulating cumulative impacts

- Used now to regulate fisheries
- Initial regulatory regime simply requires fisheries to register, accept observers, and report serious injury and mortality
- Tallies all serious injury and mortality from fisheries
- If these exceed an acceptable level defined by PBR, a take reduction team is established
PBR Management Goals

Meet with a 95% probability the following management goals based upon the Marine Mammal Protection Act

- Healthy populations will remain above the Optimal Sustainable Population (OSP) numbers over the next 20 years.
- Recovering populations will reach OSP numbers after 100 years.
- The recovery of populations at high risk will not be delayed in reaching OSP numbers by more than 10% beyond the time predicted with no human-induced mortality.
Potential Biological Removal

\[ PBR = N_{\text{min}} \times 0.5 \times R_{\text{max}} \times F_r \]

- \( N_{\text{min}} \) is the minimum population estimate
- \( R_{\text{max}} \) is the maximum population growth rate
- \( F_r \) is a recovery factor ranging from 0.1 to 1.0
If PBR is to address cumulative impacts, it cannot be limited to fisheries nor to mortality and serious injury.

Include mortalities outside of fisheries; there has already been a slight extension to include ship strike mortalities in Northern right whales.

Equate sublethal effects on multiple animals to one "take" under PBR using a Severity Index which is the fractional take experienced by one animal.

Potential sublethal effects with respect to noise can be derived from zones of influence.
Behavioral Take Equivalents

- Significant behavioral ecology modes, e.g., feeding, breeding, migrating, etc. often occur on a cycle approximating 100 days.
- If normal activity were disturbed for 2.4 hours (1/10 of a day), the Severity Index would be 0.1/100 or 0.001.
- If the disturbance lasted only minutes, then the Severity Index might be 0.0003.
Web-based Intelligent System

Event Characteristics
- Location
- Time
- Source

Stocks
- Extent of acoustic exposure

Exposure
- Exposure greater than predetermined acoustic criteria or lack of enough knowledge about stocks

IF YES
Permit Required

IF NO
Proceed to next slide
Exposure

Exposure less than predetermined acoustic criteria, requires testing for behavioral effects

Animal Behaviors

Behavioral ecological state
Baseline behavior
Predicted deviation from baseline

Behavioral Deviation

Deviation within quartile of baseline

IF YES

Allow Activity

IF NO

Permit Required
Exposure – Acoustic Criteria

- Use NOAA Fisheries matrix
- Five functional groups: low-, mid-, and high-frequency cetaceans; pinnipeds in water and in air
- Four sound types: single and multiple pulses; single and multiple non-pulses
- Sound Pressure Level (rms or peak) or energy flux density exceeds Permanent Threshold Shift level
- Forty cells in matrix
Exposure – Behavioral Criteria

- Migration - neither the path length nor the duration of migration could be increased into the upper quartile of the normal time or distance of migration.
- Breeding - disruption of male behavior should not reduce the pool of potential mates from which a female can choose by more than 25%.
- Lactation - disturbance should not reduce the nutrition from lactation to less than the lower quartile of normal.
OBJECTIVES:
- Develop requirements for an ocean noise monitoring system and approaches to creating ocean noise budget(s).

CONCLUSIONS and RECOMMENDATIONS:
- Begin development of specific tasks to:
  - Gather existing information on ocean noise together in one accessible location;
  - Analyze existing data for properties of ocean noise;
  - Establish global ocean noise monitoring system:
    - measure long-term trends and spatial dependence of ocean noise,
    - potential impacts of man-made noise on marine life
    - sounds by marine life
    - use for other scientific studies;
  a) leverage with existing systems and programs (e.g., IMS, IOOS, ORION, U.S. Navy installations);
  b) combination of fixed cabled systems, autonomous fixed and mobile systems, and shipborne systems;
  c) use set of testable hypotheses to determine system requirements
  d) importance of high quality ancillary data/information collection
Long Term Monitoring

- Does manmade sound have an adverse long-term impact on the ocean environment? (i.e. population-level consequences?)
- Marine noise/marine ecosystem monitoring program
  - Biologically sensitive areas
  - *Critical Issue*: Ancillary information to collect
    * Acoustics should be only one component
    1. Make associations between changes in marine ecosystems and ocean noise
    2. Develop predictive capability for noise field
    3. Monitor for other sources of potential adverse impacts
Workshop on Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology

sponsored by
NOAA Fisheries Acoustics Program

18-19 May, 2004
Arlington, VA

OBJECTIVES:
- To bring together biologists and bioacousticians, ship owners and designers, oceanographers, regulators, and developers of ship quieting technology to explore the issue of marine mammals and ship noise.

From www.shippingnoiseandmarinemammals.com
Beaked Whale Workshop

sponsored by

Marine Mammal Commission

13-16 April, 2004
Baltimore, MD

OBJECTIVES:
- To bring together 31 experts from the diverse fields of marine mammal ecology, behavior, physiology, pathobiology and anatomy, human diving physiology, and acoustics to try to understand the impacts of anthropogenic noise on beaked whales.

CONCLUSIONS and RECOMMENDATIONS:
- Findings
  1) Gas bubble disease, induced through a behavioral response to acoustic exposure, may be the pathologic mechanism and merits further investigation
  2) Current monitoring and mitigation methods for beaked whales exposed to sound are ineffective in the detection and protection of these animals
- Research Priorities
  1) Controlled exposure experiments to assess whale responses to known sound stimuli
  2) Physiology, anatomy, pathobiology and behavior of live and dead beaked whales
  3) Baseline diving behavior and physiology of beaked whales
  4) Retrospective review of beaked whale strandings
OBJECTIVES:
- Use the current level of understanding of the recent mass beaked whale strandings to recommend modifications to the sonar waveform for mitigation.

CONCLUSIONS:
- Too little is known to recommend changes in sonar waveform
- Impact probably a result of behavior response rather than direct physiological damage

RECOMMENDATIONS:
- Research on :
  - Population biology (surveys, including use of new genetic techniques)
  - Beaked whale physiology (tags, measurements of tissue super saturation, and clotting properties)
  - Beaked whale behavior
    - Investigate possibility of having one whale in captivity
    - Stranded Whale Action Team
- Mitigation, including:
  - Sonar ramp-up
  - Conduct exercises while transiting away from coastlines
  - Use sonars themselves to check for presence of whales
  - Pre-experiment risk assessments and possible use of low-level sonars to “herd” whales from area
  - Investigate use of Doppler-sensitive complex waveforms
    (peak pressure possibly more important than sound exposure)
Recommendations form the NRC Reports
Recommendations (NRC 2004)

- **Within a year:** Development of web-based intelligent system to determine a *de minimis* threshold below which impacts of activities are clearly not significant.

- **Several years:** Extension of the Potential Biological Removal Model to include sub-lethal “takes” from noise.

- **Decade(s):** Transform a Conceptual Model into a Predictive Model for significance of effects of noise on marine mammals.
Recommendations (NRC 2004)
Recommendations (NRC 2000)

*Groupings of Species Estimated to Have Similar Sensitivity to Sound*

- Research and observations should be conducted on at least one species in each of the following seven groups:
  - Sperm whales (*Physeter macrocephalus*, not to include other physterids)
  - Baleen whales
  - Beaked whales
  - Pygmy (*Kogia breviceps*) and dwarf sperm whales (*Kogia sima*) and porpoises [high-frequency (greater than 100 kHz) narrowband sonar signals]
  - Delphinids (dolphins, white whales [*Delphinapterus leucas*], narwhals [*Monodon monoceros*], killer whales)
  - Phocids (true seals) and walruses
  - Otarids (eared seals and sea lions)
**Recommendations (NRC 2000)**

*Signal Type*

- Standardized analytic signals should be developed for testing with individuals of the preceding seven species groups. These signals should emulate the signals used for human activities in the ocean, including impulse and continuous sources.
  - Impulse – airguns, explosions, sparkers, some types of sonar
  - Transient – frequency-modulated (low-frequency [LFA], other sonars, animal sounds), amplitude-modulated (animal sounds, ship passage), broadband (sonar)
  - Continuous – frequency-modulated, amplitude-modulated (drilling rigs), broadband (ship noise)
**Recommendations (NRC 2000)**

*Biological Parameters to Measure*

- When testing representative species, several different biological parameters should be measured as a basis for future regulations and individual permitting decisions. These parameters include the following:
  - Mortality
  - TTS at signal frequency and other frequencies
  - Injury—permanent threshold shifts
  - Level B harassment
  - Avoidance
  - Masking (temporal and spectral)
  - Absolute sensitivity
  - Temporal integration function
  - Non-auditory biological effects
  - Biologically significant behaviors with the potential to change demographic parameters such as mortality and reproduction.
Basic Question

▪ What is the overall impact of man-made sound on the marine environment?

Committee Conclusion

▪ The overall impact is unknown, although there is cause for concern.

Committee Recommendations (18)

▪ The series of recommendations are designed to increase understanding of:
  ▪ the characteristics of ocean noise, particularly from manmade sources and
  ▪ their potential impacts on marine life, especially those that may have population level consequences
Box 1 Overview of the Committee Research Recommendations.

To Evaluate Human and Natural Contributions to Ocean Noise

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Develop quantitative relationships between man-made noise and levels of human activity;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Develop a global ocean noise budget that includes both ambient and transient events and uses "currencies" different from average pressure spectral levels to make the budget more relevant to marine mammals.

To Describe Long-Term Trends in Ocean Noise Levels, Especially from Human Activities

- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Develop quantitative relationships between man-made noise and levels of human activity.

Research Needed to Evaluate the Impacts of Ocean Noise from Various Sources on Marine Mammal Species

- Measure effects of alternative properties of man-made sources in addition to average acoustic pressure spectral level on marine mammals;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Try to structure all research on marine mammals to allow predictions of population-level consequences;
- Identify marine mammal distributions globally;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Develop short-term, high-resolution, and long-term tracking tagging technologies;
- Search for subtle changes in behavior resulting from masking;
- Search for noise-induced stress indicators;
- Examine the impact of ocean noise on nonmammalian species in the marine ecosystem;
- Continue integrated modeling efforts of noise effects on hearing and behavior;
- Develop a marine-mammal-relevant global ocean noise budget;
- Investigate the causal mechanisms for mass strandings and observed traumas of beaked whales.
Box 1 Overview of the Committee Research Recommendations (continued).

Current Gaps in Existing Ocean Noise Databases

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz and which includes transients;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Conduct research on the distribution and characteristics of marine mammal sounds.

To Develop a Model of Ocean Noise that Incorporates Temporal, Spatial, and Frequency-dependent Variables

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz (data are critical for model validation);
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Develop quantitative relationships between man-made noise and levels of human activity;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Incorporate distributed sources into noise-effects models;
- Develop a marine-mammal-relevant global ocean noise budget.

Administrative Recommendations

- Provide a mandate to a single federal agency to coordinate ocean noise monitoring and research, and research on effects of noise on the marine ecosystem;
- Educate the public.
Concluding Remarks

Human production of sound (both intentional and unintentional) in the ocean involves activities that are beneficial.

- Over 90 percent of the global trade is transported by sea
- Geophysical exploration is important for locating new oil and gas deposits
- Commercial sonar systems allow for safer boating and shipping, navigation, and more productive fishing
- Military sonar systems are important for national defense
- Sound is the primary method by which properties of the ocean water column and ocean bottom can be studied

A major source of controversy on this topic is due to our lack of knowledge.

We need to increase our understanding of relative risks of various human activities to effectively manage ocean resources and provide proper stewardship of the ocean environment.