# A Review of the Impacts of Seismic Airgun Surveys on Marine Life

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Noise from a single seismic airgun survey, used to discover oil and gas deposits hundreds of kilometers under the sea floor, can blanket an area of over 300,000 $km^2$, raising background noise levels 100-fold (20 dB), continuously for weeks or months (IWC 2005, IWC 2007). Seismic airgun surveys are loud enough to penetrate hundreds of kilometers into the ocean floor, even after going through thousands of meters of ocean. Since this exposes large portions of a cetacean population to chronic noise, the International Whaling Commission's Scientific Committee noted "…repeated and persistent acoustic insults [over] a large area…should be considered enough to cause population level impacts." (IWC 2005). A recent report by the Convention on Biological Diversity noted that "...there are increasing concerns about the long-term and cumulative effects of noise on marine biodiversity..." and "...there is a need to...take measures [to] minimise our noise impacts on marine biodiversity..." and "...effective management of anthropogenic noise in the marine environment should be regarded as a high priority for action at the national and regional level..." (CBD 2012).

Nieukirk et al. (2012) analyzed 10 years of recordings from the Mid-Atlantic Ridge, finding that seismic airguns were heard at distances of 4,000 km from survey vessels and present 80-95% of the days/month for more than 12 consecutive months in some locations. When several surveys were recorded simultaneously, whale sounds were masked (drowned out), and the airgun noise became the dominant part of background noise levels.

To compare the total energy output per year (in joules) of the various human-made underwater noise sources, the highest is $2.1 \times 10^{15}$ J, representing the contribution from nuclear explosions and ship-shock trials (explosions used by the Navy to test the structural integrity of their ships). Immediately following in contribution are seismic airgun arrays at $3.9 \times 10^{13}$ J. Next, are military sonars ($2.6 \times 10^{13}$ J) and supertankers, merchant vessels, and fishing vessels at $3.8 \times 10^{12}$ J (Hildebrand 2005).

**Marine mammals**

Gordon et al. (2004) found that marine mammals can be impacted by the intense, broadband pulses produced by seismic airguns through hearing impairment (temporary or permanent threshold shift, TTS or PTS), physiological changes such as stress responses, indirectly by impacting their prey, behavioral alterations such as avoidance responses, displacement, or a change in vocalizations, or through masking (obliterating sounds of interest). Humpback and fin whales appear to communicate over distances of at least tens of kilometers (e.g. Watkins and Schevill 1979), so reducing this distance would compromise their ability to communicate.

Around 250 male fin whales appeared to stop singing for several weeks to months during a seismic survey, resuming singing within hours or days after the survey ended (IWC 2007). Assuming male fin whale songs have a reproductive function, such as attracting and finding mates (Croll et al. 2002), it would be difficult to believe that such an effect would not be biologically significant. McDonald et al. (1995) noted that a blue whale stopped calling in the presence of a seismic survey 10 km away.

A different blue whale population showed the opposite reaction. Even a seismic survey using a low-to-medium power sparker caused blue whales in the St. Lawrence Estuary to modify their vocalizations (Di Iorio and Clark 2010). Blue whales called consistently more on days when the seismic survey was operating than when not, and more during periods within those days in which the sparker was on vs. off. The number of blue whale calls increased within the 1-hr block after sparker onset. The authors postulated that the blue whales were attempting to compensate for the additional introduction of noise, and noted that whales probably received a fairly low level of noise (131 dB re 1 mPa (peak to peak) over 30–500 Hz, with a mean sound exposure level of 114 dB re 1 $\mu Pa^2$ s). Thus, they suggested that even low source level seismic survey noise could interfere with important signals used in social interactions and feeding (Di Iorio and Clark 2010).

Marine mammals also avoid seismic noise by vacating the area. Castellote et al. (2012) showed extended displacement of fin whales by a seismic survey which lasted well beyond the survey length. Weir (2008) found that Atlantic spotted dolphins showed stronger responses to seismic airgun exposure than humpback or sperm whales. These dolphins were found significantly farther away from the airguns when they were on vs. off and only approached the seismic vessel when the airguns were silent. An analysis of cetacean responses to 201 seismic surveys in UK waters exhibited evidence of disturbance (Stone and Tasker 2006). During active seismic surveying, all small odontocetes, killer whales, and all mysticetes were found at greater distances from the seismic vessel than when it was not shooting. Small odontocetes showed the greatest horizontal avoidance, which reached to the limit of visual observation. Sighting rates for mysticetes, sperm whales, pilot whales, and killer whales did not decrease when airguns were off vs. on, but mysticetes and killer whales showed localized avoidance. During seismic shooting, fewer animals appeared to be feeding, smaller odontocetes seemed to swim faster, and mysticetes appeared to remain longer at the surface where sound levels are lower. Reactions were stronger to larger volume seismic arrays. Stone and Tasker (2006) theorized that smaller odontocetes may vacate the area entirely during exposure to seismic, whereas slower-moving mysticetes may remain in the area, simply increase their distance from the noise.

Responses can differ according to context, sex, age class, or species. Bowhead whales avoided seismic air-gun noise at received levels of 120–130 dB (rms over pulse duration) during their fall migration, though they were much more tolerant of noise when feeding in the summer, staying away from levels of 158–170 dB, which are roughly 10 000 times more intense (Richardson et al. 1995, 1999). Humpback cows and calves in key habitat evaded seismic air guns at 140–143 dB re 1 µPa mean squared pressure, which was lower than the reaction of migrating humpbacks at 157–164 dB re 1 µPa mean squared pressure (McCauley et al. 2000). Species with similar hearing capabilities and audiograms showed markedly different responses to airgun noise off British Columbia, with harbor porpoises appearing to be the most sensitive, responding to seismic noise at distances of >70 km, at received levels of <145 dB re 1 µPa rms (Bain and Williams 2006; IWC 2007).

Reactions to seismic airguns can also be quite subtle and hard to detect. Sperm whales in the Gulf of Mexico did not appear to avoid a seismic airgun survey, though they significantly reduced their swimming effort during noise exposure along with a tendency toward reduced foraging (Miller et al 2009). Miller et al. (2009) tagged 8 sperm whales with tags recording sounds and movement while exposing them to operating airgun arrays. The longest resting bout ever observed in any sperm whale (265 min.) happened to the whale most closely approached by the actively firing seismic survey vessel, with the whale finally diving 4 min. after the final airgun pulse. Whales significantly reduced their fluke stroke effort by 6% during exposure to seismic noise compared with after, and all seven sperm whales studied reduced their fluke strokes on foraging dives in the presence of seismic noise. Moreover, there were indications that prey capture attempts were 19% lower during airgun noise exposure (Miller et al. 2009). The authors note that even small reductions in foraging rate could result in lower reproductive rates and have negative consequences for the population.

Though summering bowheads showed no detectable avoidance of seismic surveys, no change in general activities or call types, and no obvious alteration of calling rate, they dove for shorter periods and their respiration rate was lower than non-exposed bowheads (Richardson et al. 1986). Such changes were observed up to 54–73 km from seismic surveys at received levels that could be as low as <125 dB re 1 µPa (Richardson et al. 1995).

Seismic noise has been thought to at least contribute to some species' declines or lack of recovery (Weller et al. 2006a, 2006b; IWC 2007). Critically endangered western gray whales off Sakhalin Island, Russia, were displaced by seismic surveys from their primary feeding area, returning only days after seismic activity stopped (IWC 2005). This change in distribution closely followed the timing of the seismic surveys (IWC 2005, 2007; Weller et al. 2006a). Whales exposed to seismic noise levels of about 153 dB re 1 µPa zero-to-peak and 159 dB peak-to-peak on their feeding grounds also swam faster and straighter over a larger area with faster respiration rates during seismic operations (Weller et al. 2006b; IWC 2007).

Parente et al. (2007) discovered a reduction in cetacean species diversity with increasing numbers of seismic surveys during 2000 and 2001 off Brazil, despite no significant oceanographic changes in this period. Between 1999 and 2004, there was a negative relationship between cetacean diversity and the intensity of seismic surveys.

When exposed to a single airgun or small airgun array, gray seals showed avoidance and switched from foraging to transiting behavior. They also began hauling out, possibly to escape the noise. Harbor seals exhibited a slowing of their heart rate together with dramatic avoidance behavior and stopped feeding (Thompson et al. 1998).

Seismic air guns are a probable cause of whale strandings and deaths as well, especially in beaked whales (Hildebrand 2005). A stranding of two individuals was tied very closely in space and time to a seismic survey in the Gulf of California. Even if impacts are fatal, only 2% of all cetacean carcasses are detected, on average (Williams et al. 2011). The authors state that for cryptic mortality events such as acoustic trauma, analytical methods are necessary to take into consideration the small percentage of carcasses that will be recovered.

A pantropical spotted dolphin suffered rigidity and postural instability progressing to a catatonic-like state and probable drowning within 600 m of a 3D seismic survey firing at full power (Gray and Van Waerebeek 2011). The authors explained the initial aberrant behavior by a possible attempt by the dolphin to shield its sensitive rostrum and hearing structures from the intense acoustic energy of the airguns, by lifting its head above the water's surface. They believed the seismic survey could have caused this observed behavior, presumably resulting from severe acoustic distress and even injury. Other explanations were examined and considered less likely (Gray and Van Waerebeek 2011). It may be of significance that Weir (2008) found the closely related Atlantic spotted dolphin to be the species “with the most marked overt response” to airgun noise of the three cetacean species examined.

Stress effects or physiological changes, if chronic, can inhibit the immune system or otherwise compromise the health of animals. These can be very difficult to detect in cetaceans. Indications of increased stress and a weakened immune system following seismic noise broadcasts were shown for a whale and dolphin (Romano et al. 2004). Loud, impulsive noise produced from a seismic water gun caused significantly increased mean norepinephrine, epinephrine, and dopamine levels immediately after a high, but not low-level exposure in a captive beluga whale (Romano et al. 2004). All three of these stress hormones increased significantly with increasing noise levels. These hormone levels remained high even 1 hour after noise exposure, which is surprising given their short half-life, according to the authors. In a captive bottlenose dolphin, the seismic water gun produced significant neuro-immune values, namely increases in aldosterone and a decrease in monocytes. Aldosterone is one of the principal stress hormones in cetaceans and may surpass cortisol as a more sensitive indicator of stress (Romano et al. 2004).

Mitigation measures to safeguard whales against high noise exposures are very inadequate. Generally, only the area within 500 m of the seismic vessel is observed, yet high noise levels can occur at much greater distances. Madsen et al. (2006) discovered that in the Gulf of Mexico received levels can be as high at a distance of 12 km from a seismic survey as they are at 2 km (in both cases >160 dB peak-to-peak). Received levels, as determined from acoustic tags on sperm whales, generally fell at distances of 1.4 to 6–8 km from the seismic survey, only to increase again at greater distances (Madsen et al. 2006).

Moreover, determining an exposure level that is "safe" for marine mammals is fraught with difficulty. For instance, a harbor porpoise exposed to airgun pulses was found to have lower (more sensitive) masked TTS levels than any other cetacean that has been tested, namely 164.3 dB re 1 μPa2·s SEL or 199.7 dB pk-pk re 1 μPa (Lucke et al. 2009). The noise level required to cause hearing loss (temporary threshold shift or TTS) in whales is still very uncertain, especially for seismic airguns, as there are so few empirical measurements. Between-individual variability, the population's average sensitivity (how representative of the population was the tested animal), and the validity of extrapolating between species, particularly between captive small dolphins or porpoises (on which the few tests have been done) to free-ranging large baleen whales are all unknown. Gedamke et al. (2011) model how various factors and assumptions can change the percentage of whales exposed to damaging levels. When factoring in uncertainty and sources of variability, 29% (10-62%) of whales within 1-1.2 km of a seismic survey would experience levels sufficient to produce TTS onset. Without considering these factors, no whales beyond 0.6 km would be at risk for TTS, showing how even fairly small degrees of uncertainty can have a large effect on risk assessment (Gedamke et al. 2011). If management decisions are to be based on so little data, uncertainty must be taken into consideration. At close ranges, avoidance by whales of the seismic survey actually increased their exposure slightly as their speed was slower than the seismic vessel. Overall, Gedamke et al. (2011) concluded that TTS in baleen whales is plausible at ranges up to several kilometers.

Many (36-57%) of the stranded or entangled dolphins or toothed whales have been shown to have profound hearing loss, implying that impaired hearing could have led to their stranding/entanglement (Mann et al. 2010).

**Marine Turtles**

Marine turtles show a strong initial avoidance response to air-gun arrays at a strength of 175 dB re 1µPa rms or greater (O'Hara and Wilcox 1990; McCauley et al. 2000; Lenhardt 2002). Enclosed turtles also responded progressively less to successive airgun shots which may indicate reduced hearing sensitivity (TTS). One turtle experienced a TTS of 15dB, recovering two weeks later (Lenhardt 2002). McCauley et al. (2000) estimated that a typical airgun array operating in 100–120 m water depth could impact behavior at a distance of about 2 km and cause avoidance at around 1 km for marine turtles. DeRuiter and Doukara (2010) found that 51% of turtles dived at or before their closest point of approach to an airgun array.

**Fish**

A wide range of acoustic impacts on fish has been observed. Seismic air guns extensively damaged fish ears at distances of 500 m to several kilometres from seismic surveys. No recovery was apparent 58 days after exposure (McCauley et al. 2003). Behavioral reactions of fish to anthropogenic noise include dropping to deeper depths, milling in compact schools, ''freezing'', or becoming more active (Dalen and Knutsen 1987; Pearson et al. 1992; Skalski et al. 1992; Santulli et al. 1999; McCauley et al. 2000; Slotte et al. 2004). Reduced catch rates of 40%–80% and decreased abundance have been reported near seismic surveys in species such as Atlantic cod, haddock, rockfish, herring, sand eel, and blue whiting (Dalen and Knutsen 1987; Løkkeborg 1991; Skalski et al. 1992; Engås et al. 1996; Hassel et al. 2004; Slotte et al. 2004). These effects can last up to 5 days after exposure and at distances of more than 30 km from a seismic survey. The impacts of seismic airgun noise on eggs and larvae of marine fish included decreased egg viability, increased embryonic mortality, or decreased larval growth when exposed to sound levels of 120 dB re 1 µPa (Kostyuchenko 1973; Booman et al. 1996). Turbot larvae showed damage to brain cells and neuromasts (Booman et al. 1996). Neuromasts are thought to play an important role in escape reactions for many fish larvae, and thus their ability to avoid predators. Increases in stress hormones have been observed in fish due to noise (Santulli et al. 1999).

**Invertebrates**

Invertebrates also do not appear to be immune from the effects of anthropogenic noise. Nine giant squid mass stranded, some of them live, together with geophysical surveys using air guns in 2001 and 2003 in Spain (Guerra et al. 2004). The squid all had massive internal injuries, some severe, with internal organs and ears badly damaged. Another species of squid exposed to airgun noise showed an alarm response at 156-161 dB rms and a strong startle response involving ink ejection and rapid swimming at 174 dB re 1µPa rms (McCauley et al. 2000). Caged squid also tried to avoid the noise by moving to the acoustic shadow of the cage. McCauley et al. (2000) suggest that the behavioral threshold for squid is 161-166 dB rms. A bivalve, *Paphia aurea*, showed acoustic stress as evidenced by hydrocortisone, glucose, and lactate levels when subjected to seismic noise (Moriyasu et al. 2004). Catch rates also declined with seismic noise exposure in *Bolinus brandaris*, a gastropod, the purple dye murex (Moriyasu et al. 2004). In snow crab, bruised ovaries and injuries to the equilibrium receptor system or statocysts were also observed (DFO 2004). Seismic noise-exposed crabs showed sediments in their gills and statocysts, and changes consistent with a stress response compared with control animals.

**Conclusions**

It is clear that a human-caused modification that extends across 300,000 $km^2$ or distances of 4,000 km from the noise source 80-95% days of the month, year-round, is an ecosystem-wide impact. That seismic airguns are the second highest contributor of human-caused underwater noise in total energy output per year, following only nuclear and other explosions, should underline this point. At least 37 marine species have been shown to be affected by seismic airgun noise. These impacts range from behavioral changes such as decreased foraging, avoidance of the noise, and changes in vocalizations through displacement from important habitat, stress, decreased egg viability and growth, and decreased catch rates, to hearing impairment, massive injuries, and even death by drowning or strandings. Seismic airgun noise must be considered a serious marine environmental pollutant.

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