Underwater Noise from Large Commercial Ships—International Collaboration for Noise Reduction

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1 NOISE FROM SHIP PROPULSION

Underwater noise introduced by ships into the ocean environment originates from a number of sources, both deliberately produced for navigational purposes and incidentally emitted as a function of mechanical operations. The focus of this article, however, is on propulsion systems, which are the predominant sources of overall radiated noise from individual ships.

1.1 Radiated noise from individual vessels

All vessels generate noise as a consequence of their operation. Modern powered vessels typically produce low-frequency (defined here as <1000 Hz) sound from hydrodynamic flow noise, onboard machinery, and, primarily, from propeller cavitation. Wenz (1962) made some of the first characterizations of natural and anthropogenic ocean ambient noise, including typical low-frequency noise spectra from differing levels of shipping activity (Figure 1). Measurements of radiated noise from different classes of

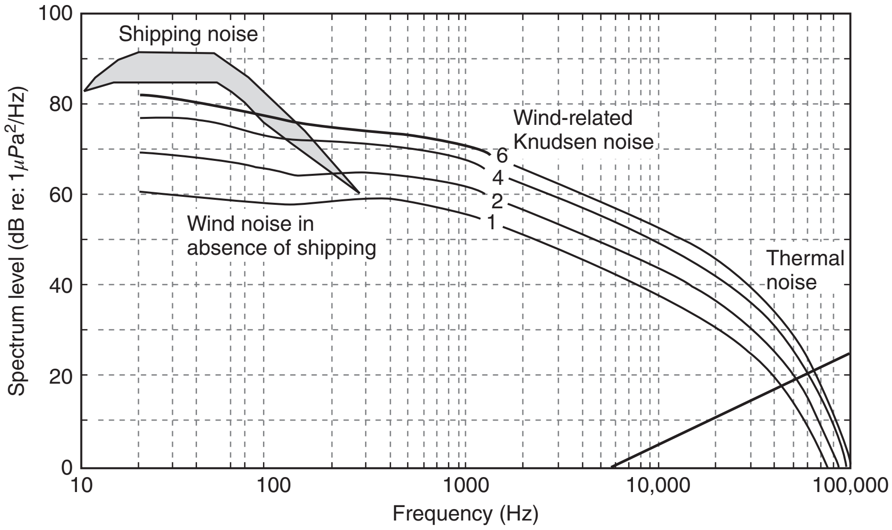

Figure 1. Ocean ambient noise for frequencies between 10 Hz and 100 kHz. This figure shows typical underwater noise profiles developed by Wenz (1962), but has been modified to reflect modern levels of shipping noise (shaded area), which exceed natural wind-noise, even for high sea-states (numbered curves). (Reproduced with permission from Hildebrand, 2009. ©Inter-Research Science Center (2009).)

large commercial vessels (Ross, 1976, 2005; Arveson and Vendittis, 2000; Wales and Heitmeyer, 2002) provide the basis for broader characterizations of vessel noise (Hatch *et al*., 2008; Hildebrand, 2009; McKenna *et al*., 2012).

While vessel-radiated noise is predominately low frequency in nature, higher frequencies (up to tens of kHz) can occur at relatively close (typically <1 km) ranges (Hildebrand, 2009). The overall radiated noise source level and frequency spectrum relate to many factors, including vessel size, speed, load, condition, age, and engine type. Larger vessels (exceeding 100 m) typically generate louder, lower-frequency sounds than smaller boats, with faster vessels being typically louder, although there are notable exceptions (Heitmeyer, Wales, and Pflug, 2004). Reviews by Richardson *et al*. (1995), Hildebrand (2009), and McKenna *et al*. (2012) discuss typical noise spectra and source level characteristics of different classes of modern commercial vessels.

1.2 Contributions of commercial vessels to low-frequency underwater noise

Vessel noise can contribute substantially to a low-frequency ambient noise environment already filled with natural sounds from waves, wind, and animals. Longitudinal increases in low-frequency ambient levels have been documented in several regions with large concomitant increases in the number of commercial ships typically using the area (Curtis *et al*., 1999; Andrew, Howe, and Mercer, 2002; McDonald, Hildebrand, and Wiggins, 2006, 2008).

Low-frequency ambient noise is not steadily increasing at a uniform rate everywhere in the world's oceans. Many factors (largely economic) drive the distribution and magnitude of vessel traffic. Environmental and biological variables influence the natural noise environment into which ship noise is added. However, well-documented increases in the total number and concentration of commercial vessels along with levels of low-frequency ambient noise in the same area (Figure 2) demonstrate that maritime commercial traffic can broadly affect average levels of low-frequency ambient noise on decadal time scales. Furthermore, there are few places remaining in the industrialized northern hemisphere, other than certain areas in the Arctic, where commercial shipping is not among the predominant noise sources below 1000 Hz, particularly at frequencies below 300 Hz (Worley and Walker, 1982; Bachman *et al*., 1996; Zakarauskas, Chapman, and Staal, 1990; Cato and McCauley, 2002; Hatch *et al*., 2008). Furthermore, global trends in commercial shipping suggest an increase in the extent to which this sector may contribute to underwater ambient noise (NRC, 2003). While economic factors drive short-term changes in the numbers and distribution of commercial vessels, there has been an approximate tripling of overall numbers of large commercial vessels between 1955 and 2011. This broad trend of increasing commercial traffic of goods by vessel is expected to continue as industry analysts predict that the total amount of cargo transported by large commercial ships may double or triple over the period from 2005 to 2030 (Lloyd's Register, 2013).

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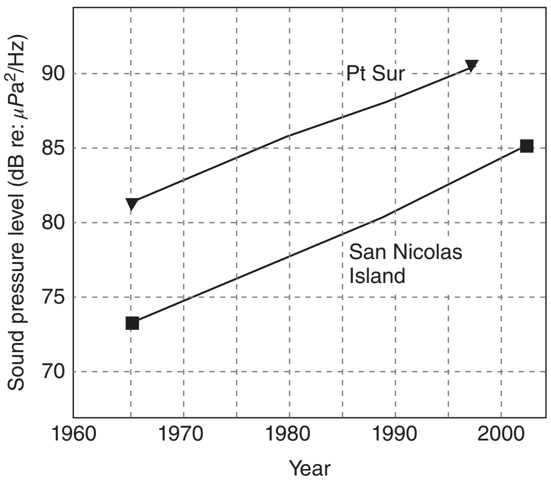

Figure 2. Low-frequency ocean ambient noise increased by about 3 dB/decade at two sites off California by comparing US Navy data from the 1960s with more recent measurements below 100 Hz. (Created by author using data from Wenz (1969), Andrews *et al*. (2002), and McDonald, Hildebrand, and Wiggins (2006).)

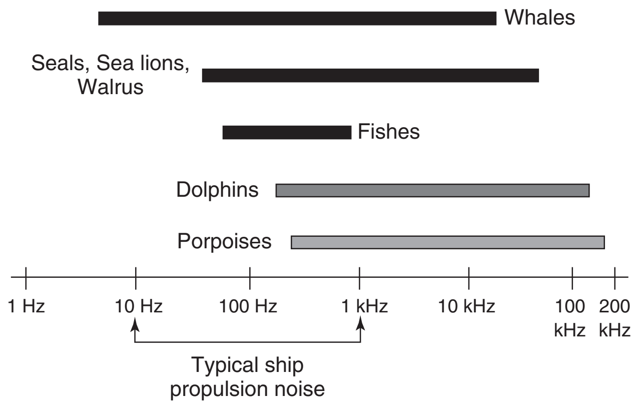

Figure 3. Typical hearing ranges for various groups of marine animals shown relative to the typical predominant frequencies of commercial shipping. (Created by author based on data from Southall *et al*., 2007.)

2 CONSEQUENCES OF SHIP NOISE ON MARINE LIFE

Sound is critically important for most marine animals, including marine mammals, which are the focus here. Sound production and detection serve key biological functions, including communication, foraging, reproduction, navigation, and predator avoidance. Some species (dolphins and porpoises) have sophisticated biosonar capabilities for near-range feeding and orientation (Au, 1993). Others, including the large baleen whales, have communication systems adapted to longer-range use of sounds in reproductive and social interactions (Clark, 1990). Where there is an overlap between the frequencies of the noise sources and those of the sound used by marine life, there can be interference with such important biological functions. The predominately low-frequency sounds associated with large commercial vessels directly overlap typical low-frequency communication sounds and hearing of many marine mammals, particularly large whales and some seals and sea lions (Figure 3).

2.1 Acoustic communication and hearing

More is known about marine mammal sound production than hearing (Wartzok and Ketten, 1998; Southall *et al*., 2007), because of the relative ease of recording animal sounds compared with the challenges of directly measuring hearing. Hearing capabilities have been directly measured in less than one-third of the ~125 species of living marine mammals, and many of these involve data from very few captive individuals (often one). Furthermore, there are no direct measurements of hearing for an entire marine mammal taxa, the large baleen whales, for which concerns about the effects of ship noise may be greatest given the importance of low-frequency sound in their life history.

We actually know the most about hearing in those marine mammals that may be least likely to be affected by ship noise. Dolphins, porpoises, and other toothed whales (odontocete cetaceans) have developed specialized echolocation with high-frequency impulsive clicks to aid in feeding and navigation (Au, 1993). They also use a variety of whistles and other calls to communicate and socialize. These species produce sounds across the widest frequency ranges of any animal group. Communicative sounds generally range from a few hundred hertz to several tens of kilohertz, but echolocation clicks can extend above 100 kHz. Potential acoustic interference from ship noise is limited to short-range (hundreds of meters) effects for these animals or is restricted to those animal signals with the lowest frequencies in this range.

Hearing in the baleen whales (mysticete cetaceans) is estimated from a combination of sound production, anatomical characteristics, and behavioral responses to sound, as well as how hearing would be expected to evolve given the range of historical (preindustrial) ambient noise conditions at low frequencies (Wartzok and Ketten, 1999; Houser *et al*., 2001; Clark and Ellison, 2004; Ketten *et al*., 2007; Cranford and Krysl, 2015). Baleen whales lack the specialized high-frequency biosonar systems found in toothed whales, but use sounds for many important social and spatial orienting functions. Some species may hear into the tens of kilohertz range, but the large majority of sounds they produce occur in the very low, low, and mid-frequency

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ranges (~10 Hz to 10 kHz). It is at these low frequencies, where shipping noise and typical communication signals for baleen whales directly overlap, that these species are most susceptible to potential negative effects from noise interference.

Other marine mammals including the pinnipeds (seals and sea lions) make and listen to sounds for a variety of important communicative and orientation functions, but like the large whales they appear to lack specialized high-frequency echolocation (biosonar) systems (Schusterman, 1981; Wartzok and Ketten, 1999; Schusterman *et al*., 2000). Sounds produced by these species are largely in social contexts and extend to higher frequencies than those used by baleen whales, but occur over a narrower frequency band than those used by toothed whales, generally from ~100 Hz to several tens of kilohertz. Many of these signals directly overlap the predominant low-frequency energy of vessel propulsion noise.

2.2 Effects of noise on marine life

The introduction of noise can adversely affect marine life by altering the behavior; reducing communication ranges for social interactions, foraging, and predator avoidance; and temporarily or permanently reducing hearing sensitivity (Southall *et al*., 2007). Noise also can affect the physiological functions or cause generalized stress responses (Wright *et al*., 2007) and may function as an additive or synergistic stressor (Evans and English, 2002), exacerbating other environmental and anthropogenic pressures experienced by marine life.

Numerous studies have shown that marine mammals may alter their behavior in response to noise from vessels (Janik and Thompson, 1996; Nowacek, Wells, and Solow, 2001; Williams, Trites, and Bain, 2002; Hastie *et al*., 2003; Aguilar Soto *et al*., 2006; Pirotta *et al*., 2012; Merchant *et al*., 2013). Certain species may modify or cease producing sounds that they use to communicate, forage, avoid predators, or assess their environment (Au and Green, 2000; Van Parijs and Corkeron, 2001). For example, North Atlantic right whales (*Eubalaena glacialis*) and North Pacific blue whales (*Balaenoptera musculus*) adjust vocalizations in the presence of vessel noise (Parks and Clark, 2005; McDonald, Hildebrand, and Wiggins, 2006). However, such alterations may have biological costs and can be strongly affected by physical and environmental factors (Halfwerk *et al*., 2011; Holt, Noren, and Emmons, 2011; Holt *et al*., 2015).

An important consideration for shipping noise, as a chronic and widely distributed low-frequency sound source, is masking of biologically significant sounds (i.e., interference with the clear reception of important signals). Masking is strongly dependent on frequency overlap and spatio-temporal relationships between signals and noise. This can result in interference with sounds used in breeding, foraging, and navigation that are critical to species survival (Payne and Webb, 1971; Morisaka *et al*., 2005; Nowacek *et al*., 2007; Clark *et al*., 2009). For example, in the case of one well-studied species, the North Atlantic right whale, localized shipping noise combined with present-day ambient noise to which shipping is a major contributor has been found to severely mask communication more than 70% of the time, within the species' northern feeding grounds (Hatch *et al*., 2012).

3 INTERNATIONAL COLLABORATIONS TO REDUCE VESSEL-RADIATED NOISE

3.1 International recognition of vessel noise as a marine conservation issue

How noise may negatively affect marine life is an issue of increasing interest. Scientists, environmental managers, and conservationists are increasingly realizing that there are many types of human noise that may impact marine animals. Much of the focus has been on loud acute point sources, including military sonars and seismic air guns used in oil exploration. However, there is increasing appreciation of potentially broader issues associated with chronic noise from, for instance, aggregate commercial vessel operations (NRC, 2003, 2005; Southall *et al.*, 2007, 2012; Hatch *et al*., 2008, 2012; Clark *et al*., 2009).

A significant focusing event for this issue, bringing together the shipping industry and the regulatory and scientific communities, was a collaborative 2004 symposium hosted by the US National Oceanic and Atmospheric Administration (NOAA) entitled "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology." This international stakeholder forum was a general introduction to the topic that included presentations by a US Congressman and the Deputy Secretary of Commerce and participation from the shipping industry, researchers, conservationists, lawyers, and managers (Southall, 2005). While uncertainties and complexities regarding the potential effects of vessel sounds were acknowledged, there was recognition that large vessels can represent a substantial contribution to the overall low-frequency ambient noise levels. A key action item identified at the forum was to evaluate whether existing vessel-quieting applications for military vessels and scientific research vessels could be feasibly and economically "scaled-up" for large commercial vessels.

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NOAA followed this recommendation by organizing a more focused follow-on symposium in 2007 entitled "Potential Application of Quieting Technology on Large Commercial Vessels." This meeting also included broad stakeholder representation, but focused specifically on technical aspects and costs and benefits of various noise-reduction options. Additionally, the symposium considered potential factors (regulatory, economic, public perception, and incentive programs) that might motivate the shipping industry to apply vessel-quieting technologies (Southall and Scholik-Schlomer, 2008). A "menu" was developed of various technological design and retrofit options, as well as operational measures, and the relative costs and benefits associated with these proposed quieting options. One recommendation was to advance international awareness and action on vessel quieting by developing an information paper for the International Maritime Organization (IMO).

Shortly thereafter, the US delegation to the IMO submitted such a document to the Marine Environment Protection Committee (MEPC) entitled "Shipping noise and marine mammals" (MEPC 57/INF-4). This document, composed by NOAA scientists involved in the 2004 and 2007 symposia, was a broad introduction to the topic advising MEPC about noise from large commercial ships and its potential adverse impact on marine life. It recognized various levels of international awareness and progress on the issue and "…request[ed] Member Governments to note this information; inform all interested entities, in particular those from the shipping industry, shipyards, and ship builders of this issue, and invite them to participate in the ongoing dialogue regarding identification of potential adverse impacts associated with vessel noise and the potential mitigation of those impacts…". This information paper opened the door for future collaboration on vessel quieting within the IMO, to be advanced by broad new partnerships among environmental groups, scientists, regulators, and the industry.

3.2 Cross-sector partnerships emerge

Recent efforts to address commercial vessel noise have been characterized by far greater cooperation and partnerships among various stakeholders than in other marine-noise issues such as military sonar and oil exploration. These sound sources clearly differ from shipping noise in that they are deliberately produced to sense the environment and they are highly regulated whereas propulsion noise from commercial vessels is not. However, the deliberate effort to find common ground for progress from environmental groups, scientists, and the commercial shipping industry has largely obviated the need for litigation, something common with other ocean noise sources.

Building on the collaborative efforts in the NOAA symposia, a key step in this evolution, was a 2008 workshop convened in Hamburg, Germany, by Okeanos—Stiftung für das Meer [Foundation for the Sea], a private environmental foundation (Wright, 2008). The workshop focused on engaging additional sectors of international maritime transport, particularly ship builders, marine architects, and classification societies, and also included a presentation from the then-Chair of the MEPC. Goals included expanding awareness within the industry, discussing specific design and retrofit options, and calling for specific action on vessel-quieting measures by the IMO. Despite the broad interests represented, all participants agreed on an ambitious objective, calling for "…initial global action that will reduce the contributions of shipping to ambient noise energy in the 10–300 Hz band by 3 decibels in 10 years and by 10 decibels in 30 years relative to current levels. This goal [will] be accomplished by reducing noise contributions from individual ships." Perhaps as important as this bold statement was, it also provided additional momentum to new partnerships pushing for specific action within the IMO.

The formal consideration of this issue within the IMO began at the 58th Session of the MEPC in June 2008, with a US petition to establish a correspondence group to review potential quieting technologies for large commercial vessels (MEPC 58/19). This proposal was accepted, and the United States chaired a correspondence group with broad IMO participation. Subject matter experts worked together with ship owners, naval architects, and design model basins, to begin to formally assess feasibility and develop recommendations as the basis for guidelines for ship design and operational modifications to accomplish vessel quieting (see: MEPC 59/19; MEPC 60/18). The MEPC then sent draft guidelines to the IMO's Ship Design and Equipment (DE) Subcommittee (now the Ship Design and Construction Subcommittee) for further consideration and additional technical expertise (MEPC 61/19), where a second correspondence group and later a drafting group, chaired by the United States, were formed (see MEPC 66/17). The end result focuses primarily on propeller design and modification to reduce cavitation, but also considers hull design, onboard machinery, and operational modifications to reduce the aggregate impacts of ship noise on marine life.

The MEPC formally adopted the Guidelines on 7 April 2014 (see MEPC.1-Circ. 833) and invited member states to bring them to the attention of all concerned parties. Because the Guidelines are voluntary, and underwater noise is not yet the subject of a mandatory code, successful implementation is likely to require commitment from shipping lines, ship classification and green certification societies, and port authorities as well as from the member states. Further work by IMO, including a number of proposals identified in the

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guidelines to quantify underwater noise output and direct management effort (MEPC 66/17), could take place under a new work plan.

In parallel with these formal IMO efforts to address vessel quieting are several significant international developments regarding shipping noise and marine life. These include the development of technical measurement standards for underwater noise from ships (ANSI S12.64) and related measurement protocols being developed by the International Standards Organization. Additionally, the Arctic Marine Shipping Assessment (AMSA, 2009) highlighted potential impacts of novel shipping noise on Arctic ecosystems as shipping becomes more common in these areas. Furthermore, the International Whaling Commission's Environmental Concerns Scientific Working Group convened a special session in 2010 on potential masking impacts of shipping noise and other low-frequency sound. Finally, the European Union (EU) has begun to develop mechanisms to regulate continuous low-frequency noise. The EU Marine Strategy Framework Directive (MSFD) requires member states to set and meet targets for ocean noise in four large marine regions, in order to achieve "Good Environmental Status." In 2010, the European Commission established indicators for ambient noise, including in two low-frequency noise bands (63 and 125 Hz) (EC Decision 2010/477/EU).

A monitoring effort is underway to develop suitable targets to reach Good Environmental Status by 2020 (Van der Graaf *et al*., 2012).

4 CONCLUSIONS AND NEW DIRECTIONS

As with many complex and evolving environmental issues, scientific and technical progress is needed and continues to advance in parallel with action to address impacts. New research is needed to better understand the overall scope and biological significance of disturbance and masking from shipping noise. Furthermore, efforts are needed to sustain recent important progress initiated by NOAA and other US federal agencies in identifying how the distribution and density of marine species correlates with the temporal and spatial distribution of shipping and other anthropogenic noises (see http://cetsound.noaa.gov).

Technical progress is needed in a number of areas, including:

- Better understanding of the relationship between noise and propeller cavitation and standardized individual vessel noise signatures for different ship classes and sizes under various operating and maintenance conditions.
- Coordinated noise measurements for vessels with means of tracking movement and other operational conditions (e.g., Automatic Identification System (AIS)).
- Implementation, efficacy testing, and cost/benefit analyses (e.g., noise reduction vs construction costs and potential associated increases in efficiency) of quieting measures for individual ships, such as those recommended by IMO.
- Quantification of the link between ship noise reduction and regional ambient noise levels, as well as ambient noise levels themselves in many parts of the world.

The scope of potential environmental implications of, and solutions to, shipping noise is vast, requiring concerted and sustained international effort. While regulatory mechanisms such as nation-specific requirements by port and/or flag states may become an important part of how we collectively address these issues, challenges in their implementation and enforcement argue strongly for additional motivation for industry engagement. Building on the NOAA ship noise symposia, Okeanos workshop, and the international progress made through the IMO, proactive involvement of industry can continue to contribute to tangible progress. Moving forward, these approaches should include government incentives (e.g., incentive-based regulations and tax breaks) as well as market incentives (e.g., fuel efficiency and "green" company certifications), in addition to regulation. "Recent progressive approaches to find responsible solutions to environmental challenges within the shipping industry have emerged through evaluation and certification programs (e.g., Green Marine) for a range of issues, including radiated ship noise." This would ideally include this website reference if possible: http://www.green-marine.org/program/ In addition, coordinated efforts with other environmental issues, such as ship-strike mitigation, should be considered. Examples here include areas for speed reduction or vessel traffic avoidance that may simultaneously reduce noise and risk of vessel collisions with animals in those areas.

ACKNOWLEDGMENTS

This article is respectfully dedicated to the memory of Lindy Johnson who was centrally involved in the ship noise-quieting efforts described herein and was a shining light in marine conservation. We acknowledge the many people who were involved with all of the organizations mentioned, and for the collaborative roles they have played in both getting this issue recognized internationally and moving proactive efforts forward within the IMO.

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We acknowledge the visionary insight of Dr. Roger Gentry in conceiving the initial NOAA symposium on shipping noise and marine life.

GLOSSARY

Incidental shipping noise	Radiated noise from vessels incidental to their nominal operation.
Marine mammal	Air-breathing mammals that live in marine environments and feed primarily in water.
Noise impacts	Potentially negative effects of anthropogenic noise on marine life
Vessel quieting	Technologies and/or operational measures designed to reduce incidentally radiated noise from shipping.

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