REGULATION OF UNDERWATER SOUNDS

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Abstract: Government-appointed regulators have an important role in safeguarding the health of the marine environment. In recent years, they have increased their scrutiny of submarine cable operations. A recently-introduced aspect of environmental regulation, that is unfamiliar across much of the submarine cable industry, is the regulators' scrutiny of underwater sounds. This paper reviews underwater sounds made by cable engineering operations; and how these sounds affect marine wildlife. Regulators' requirements in different jurisdictions will be described, based on recent experience of permit applications.

1. INTRODUCTION

Cable route surveys use acoustic instruments for underwater navigation and to map seabed conditions. In many jurisdictions over the past few years, a survey permit application has required documentary evidence of the underwater sounds that will be generated. It seems plausible that cable engineering operations will have to provide comparable documentation in the foreseeable future.

This paper starts by explaining underwater sounds generated by survey and cable engineering operations. How sounds propagate from a source to the auditory systems of marine biota is described. The main concern of regulators is the response of marine animals to the sounds: the literature is reviewed to explain the responses. The paper concludes with a description of regulatory requirements that form part of permit conditionss.

2. NOTE ON UNITS

In the past, different studies have selected a variety of metrics, which makes inter-comparisons difficult or impossible [1], [2]. A suggested standard [3] is in the process of adoption by the International Standards Organisation; this paper follows its recommendations. The units used are listed in Table 1.

Unit	Description
Hz	Hertz, Cycles per second (s^{-1})
kHz	KiloHertz, ≡ 1,000 Hz
Pa	Pascal, S.I. unit of pressure ($N\ m^{-2} \equiv kg\ m^{-1}\ s^{-2}$)
µPa	MicroPascal, ≡ 10^{-6} Pa
dB re 1 µPa	Sound intensity level in decibels relative to a standard of 1 µPa.
dB re 1 µPa-m	Source level; the sound intensity level (dB re 1 µPa) measured 1m from the source.

Table 1: Units Used to Describe Underwater Acoustics

3. SOURCES OF UNDERWATER NOISE IN CABLE OPERATIONS

Ships used in cable industry operations generate underwater sounds, just like any other commercial vessels. These sounds are dominated by three sources with different typical frequency ranges:

- Low frequency: 5Hz-1kHz: Tonal sound from the engine and generator.

- Mid frequency: 1kHz-15kHz: Oscillating vapour bubbles formed by cavitation from the propeller.
- High frequency: 20kHz-50kHz: The vessel's navigation echo sounder.

Source sound intensity of ships varies over a wide range of values, from loud (ice-breakers, tugs, heavy freighters) to very quiet (military and research vessels specifically designed to be quiet). Sounds generated by ships are gradually being considered as part of their environmental impact [4].

In addition to the sounds generated by all ships, cable route surveys use acoustic instruments for underwater positioning and to map the seabed [5]. The combination of instruments' frequency and source levels (as well as other details) are routinely adjusted to suit the survey's objective. Typical values are included in Table 2. For comparison, an oil-industry seismic airgun array and the sound from a large percussive pile-driver have also been included. It is clear that instruments used for cable route surveys are both higher frequency and lower source level than both the airgun arrays and percussive pile driving.

Cable installation & maintenance operations use ultra-short baseline (USBL) instruments for underwater positioning, the same as for survey operations. Common engineering operations that generate sounds underwater include grapnel runs and cable burial by plough or by jetting. Some authorities have simply stated that underwater sounds from these activities are not significant [6]. Measurements of cable trenching operations [7] reported broad-band sources, some transient sounds, tonal machinery noise and high frequency sounds from the USBL. These have also been included in Table 2.

Instrument/ Sound Source	Operating Frequency (kHz)	Source Level (dB re 1 µPa-m)
Side scan sonar	100 - 500	225 - 235
Swath bathymetry	12 - 500	210 - 230
Survey echo sounder	40 - 200	190 - 215
USBL	20 - 30	200 - 210
Pinger	2 - 10	205 - 215
Boomer	0.5 - 2	215
Cable trenching	0.5 - 2	178
Pile-driving	0.04 - 1	242 - 262
Oil-industry airgun array	0.05 - 0.2	255

Table 2: Typical Frequencies & Source Levels of Acoustic Instruments & Engineering Operations

After [7], [8] (updated to 2016 using specifications from instrument manufacturers) and [9].

4. UNDERWATER PROPAGATION OF SOUND

Figure 1 shows that low frequency sounds propagate great distances under water with little attenuation. This gives the potential to cause an environmental impact across large areas. High frequencies are naturally attenuated over short distances.

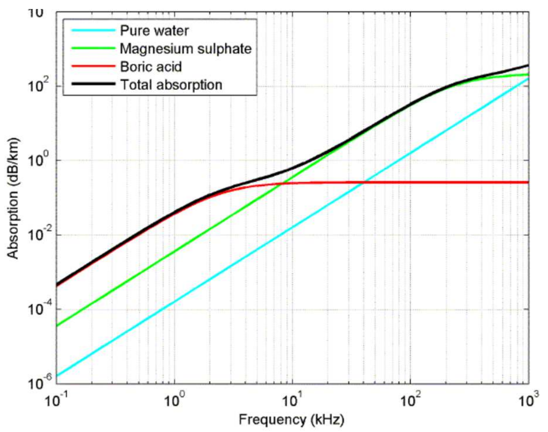

Figure 1: Acoustic Absorption in Seawater [10]

So the high frequency acoustic instruments used in cable industry surveys have small impact areas compared to the low frequency sounds that are generated during engineering and oil industry activities.

For a sound source at depth below the sea surface, the upward-travelling component of the energy will reflect at the sea-air interface. This interface behaves like a mirror, giving the image of a source position above the sea surface. Together, these form a dipolar sound source. Interference between the source and its mirror image gives a more complicated pattern of sound. Constructive interference, vertically below the source, can give more intense sounds than would be expected from the sound source in isolation.

The seabed is a less perfect reflector, a significant proportion of downward-propagating sound will be scattered, absorbed and transmitted into the seabed, leaving a partial reflection at the seabed. This partial reflection gives a weaker mirror image source below the seabed.

Sounds radiated sub-horizontally have a complex interference pattern, depending on the water depth, the depth of the source in the water column and the sound's dominant wavelength. An example is shown in Figure 2. Due to the frequency content, this dipolar effect concerns engineering operations and low-frequency systems more than high-frequency survey instruments.

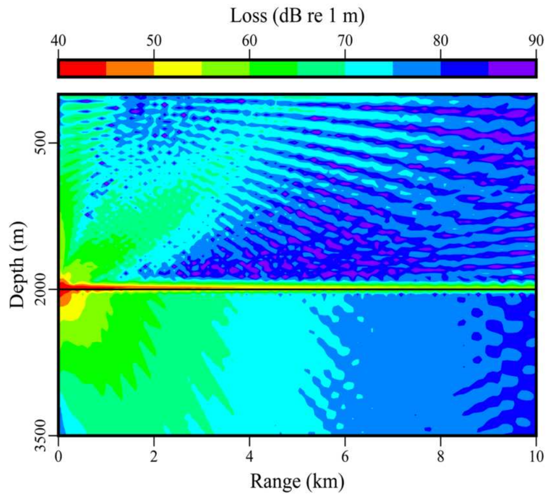

Figure 2: Interference Patterns from Acoustic Reflections [11]

5. SENSITIVITY TO ACOUSTIC DISTURBANCE

Direct observations in the wild show that sounds are important for some marine wildlife [2]. By extrapolation to organisms with comparable anatomies, sound is inferred to be important for many marine species, but simply has not been studied. It is difficult to carry out statistically valid and ethical experiments and measurements on free-ranging marine animals.

Marine mammals have auditory systems comparable to land mammals, though the auditory pathway to the middle and inner ear is often through the mandible rather than an external ear [12]. In addition, *Odontoceti* (toothed whales, including sperm whales, porpoises and dolphins) have highly-developed echolocation capabilities.

Fish have inner ear structures comparable to mammals [13]. Some commercially important species, such as *Cyprinidae* (carp, roach, bream) and the *Gadidae* (haddock, cod, pollock), have "Weberian ossicles" to connect the swim bladder to the inner ear, which increases their sensitivity to sounds [2], Figure 3. The swim bladder of other commercially important species such as *Salmonidae* (salmon, trout, char) have adapted to be separated from the brain, so they are inferred to be less sensitive to underwater sounds. Other species that are commercially important or endangered, such as *Scombrinae* (tuna, mackerels, bonitos) and sharks, do not have swim bladders.

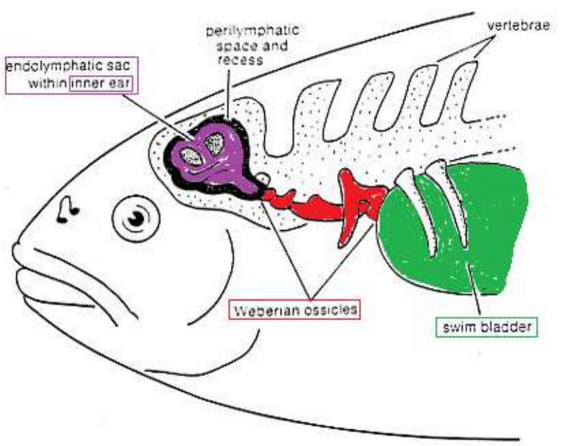

Figure 3: Weberian Ossicles Connect Swim Bladder to Inner Ear

Some *Mollusca*, such as *Cephalopoda* (octopus, squid) and *Bivalvia* (oysters, mussels), as well as some fish, are functionally deaf, but they are exquisitely sensitive to fluid movement [14]. How the physical motions involved in sound propagation contribute to this sensitivity is poorly understood.

6. AFFECTS OF ACOUSTIC DISTURBANCE ON MARINE WILDLIFE

At species population levels, there is little direct knowledge of the consequences of acoustic disturbances on marine biota. Even less is known at the scale of ecosystems [15], [16]. Existing studies have mostly reported individual responses to underwater noise. It has seldom been possible to extrapolate reliably to the larger scales that are of the greatest concern to regulators.

Many studies report that responses vary with the context of the disturbance. Some stages of life are understood to be more critical than others: particularly courtship, mating, birth and young juveniles (e.g. suckling mammals; juvenile turtles need to swim undisturbed far from shore). Further examples are listed below:

- The level of hunger in animals foraging or hunting will affect their reaction to underwater sounds.
- Anthropogenic noise can mask hunting signals, disrupting prey-predator relationships.
- Migratory pressures may force marine wildlife to continue through a disturbance, but they will expend greater energy through altered behaviours, with consequent reduction in fitness.
- Another factor is the timing of the disturbance within the diurnal / nocturnal resting cycle.
- Many reef fish [18], [19] and other commercially important fish [20] use vocalisations during courtship and to synchronise spawning. These include *Gadidae* (haddock, cod, pollock), *Scaridae* (parrot fish) and *Cichlidae* (angel fish). Such sounds could attract predators to both the adults and newly-spawned embryos. It is inferred that at the population level, predation is more than balanced by the greater number of gametes that are fertilised. Masking by anthropogenic sound may disrupt opportunities for sexual reproduction.
- The responses of marine wildlife can vary according to their level of individual fitness: creatures that have an illness might respond differently to healthy individuals of the same population.

The effects of noise on marine mammal populations have probably been studied the most comprehensively. Richardson et al, 1995 [8] and Au, 1993 [12] provide thorough introductions, with detailed references to the literature. The main regulatory concern has been on masking of communication between marine mammals, particularly *Cetacea* (whales, dolphins and porpoises).

Richardson et al, 1995 [8] described a framework of increasing effects of underwater sounds: detection, masking, response, physiological effects (TTS, PTS), injury (e.g. gas embolism) and death. Later studies (e.g., Southall et al, 2007 [21]) have shown the importance of the duration of the disturbance: transient disturbances have lower effect than chronic disturbances. Also there can be overlaps between parts of the framework: for example, the behavioural response to acoustic disturbance can lead to death of whales by mass stranding [22], [23].

Solan et al [24] described laboratory tests where representative benthic invertebrates were exposed to anthropogenic sounds. The species were: a brittlestar (*Amphiura filiformis*); a lobster (*Nephrops norvegicus*); and a clam (*Ruditapes philippinarum*). These species burrow into seabed sediments, a form of bioturbation that contributes to availability of oxygen and nutrients in this benthic environment. Burrowing was reduced when exposed to both continuous and intermittent sources of sound, reducing productivity of this important ecosystem process.

7. AFFECT OF CABLE INDUSTRY SOUNDS ON MARINE ORGANISMS

Worzyk [25] points out that a cable engineering operation is a one-off event. For most organisms, it is unlikely that they will be affected more than once during their lifetime. This contrasts with chronic anthropogenic sounds, such as exploration surveys in hydrocarbon provinces, shipping channels, maintenance dredging or fishing activities.

Nedwell et al [7] reported that cable burial was quiet compared with other engineering activities and with cable route survey instruments. Cable installation by ploughing or jetting could be considered comparable to a small dredging operation: WODA [26] described a sensible risk-based assessment process for dredging operations that could be adapted to cable engineering.

Submarine cable survey and engineering operations often cover great distances at moderate speeds. For this reason, techniques to mitigate very loud sounds that are used in civil engineering, such as bubble curtains and coffer dams, are not likely to be cost-effective for submarine cable operations.

8. TYPES OF REGULATIONS

Scientists advising environmental regulators are well aware of the limitations of existing information. Most existing studies have, necessarily, reported on the responses of individual creatures to anthropogenic sounds (such as [24]); but it is difficult to extrapolate to the population or ecosystem levels that concern regulators [16]. They accept that with the present state of uncertainty, indicator species that are endangered or commercially important may have to be used to represent larger parts of the ecosystem. In coastal European waters, a combination of *Cetacea* (e.g. harbour porpoises) and *Clupidae* (e.g. herring) have been suggested. In deeper waters, *Mysticeti* (baleen whales) and

Ziphiidae (beaked whales such as pilot whales) together with unspecified fish were considered. *Chelonians* (turtles) are often included because they are in authoritative lists of threatened to critically endangered species [27], even though relatively high sound levels are needed to induce a response. Most fish and fish larvae are of comparatively low concern due to their abundance and the high sound levels needed to induce a response. Effects on invertebrates are largely unknown so they are seldom included in regulatory conditions.

Regulations have focussed on the following aspects of underwater sounds:

- Limiting the maximum sound source level.
- Limiting the maximum received sound levels at sensitive receivers.
- Limiting sound exposure levels (integrating the effect over a period of time – the sound "dose").
- Soft starts (applies to airgun arrays used mainly for oil-industry exploration surveys).
- Standoff distances monitored by marine mammal observers.
- Seasonal closure of key areas.
- Some combination of these regulatory tools.

9. EXAMPLES OF NATIONAL REGULATIONS

Many jurisdictions have well established regulations for underwater sounds from high-energy low-frequency sources such as pile-driving, oil exploration surveys and the active sonar used in some military operations. Based on recent experience of obtaining permits for cable route surveys, regulations for low-energy and high-frequency sources are not so well established. The general trend in recent years has been for tighter regulations and greater scrutiny.

The European Union (EU) issued the Marine Strategy Framework Directive in 2008. This directive requires member states to achieve and maintain Good Environmental Status (GES) in their marine environment by 2020. One of the descriptors of EU waters' characteristics when they have achieved GES is that the introduction of energy (including underwater noise) does not adversely affect the ecosystem [15]. The directive and its descriptors specifically include energy introduced by both seismic surveys and submarine cables.

Each country in the EU is obliged to implement the directive in national laws. So far, this has led to regulations that appear similar but are applied differently. For example, Ireland and Denmark nearly always require independent marine mammal observers on board during surveys; the United Kingdom does not.

Canada has regulations comparable to the United Kingdom.

New Zealand and Australia have introduced regulations that appear to be influenced by the EU Marine Strategy Framework Directive. Both countries have well-established regulations for oil exploration surveys. This contrasts with regulations being developed on a case-by-case basis for cable industry operations. Recent experience indicates that the permit conditions are at the most cautious end of the EU regulatory spectrum.

Regulation of underwater sounds in coastal waters of the U.S.A. varies by state. There is a bewildering variety of regulations. California is perhaps the most stringent, due to annual migration of Grey Whales along the coast. Grey Whales' sensitivity / aversion to received anthropogenic sound as low as 120 dB re 1µPa has been reported [28]. Acoustic impact studies are quite often expected: for example, Zykov [29] reported the results of detailed acoustic models for low-energy geophysical instruments to be used in a coastal survey off the Californian coast. U.S. EEZ waters outside the state territorial waters are regulated by federal agencies, notably the Bureau of Offshore Energy Management (BOEM). Regulations are in process of development, with many workshops, seminars and position papers as part of a wide-ranging public consultation process, such as [2]. A consistent robust system may emerge, but recent experience is that permit conditions appear to be imposed on a case-by-case basis.

10. CONCLUSIONS

Environmental regulators have an important role in ensuring that the world's seas and oceans are not damaged by offshore operations. They seldom have detailed knowledge of the operations that they are required to scrutinize.

Planning and scheduling of cable survey and engineering operations should take common-sense precautions to avoid ecologically-sensitive periods and locations, such as during migrations, spawning/calving, or important aggregations for breeding or feeding.

The SubOptic Conference provides an opportunity to advise environmental regulators about the science behind sounds made during cable industry operations. The objective should be to ensure that consistent, appropriate and reliable information can be made available to satisfy the regulators' legitimate concerns.

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