ACOUSTICAL PROPERTIES OF FISHING GEAR; POSSIBLE RELATIONSHIPS TO BALEEN WHALE ENTRAPMENT

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Acoustical Properties of Fishing Gear; Possible Relationships to Baleen Whale Entrapment.

by

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"Do I think a whale talks?
Well, he whistles for help
And he warns friends of danger
With yip and with yelp.
He whines and he chirps and he mews and he smacks
And he barks and he snorts and he clicks and he clacks.

Since his eyes aren't much good
And the water around
May be murky, at that,
He depends upon sound.

So he not only talks (though I'd need a translation)
But he uses his sonar to get his location.
He gives but a squeak
Or a groan or a grunt,
And the echo comes back -
And he knows what's in front.
It may be a ship or a fish. Can you beat it?
He knows where and what
And can dodge it
Or eat it."

excerpt from 'Narwhal' by Richard Amour

Abstract

The incidental entrapment in passive fishing gear of mysticetes, including the humpback whale *Megaptera novaeangliae*, is examined, with specific reference to the role of acoustics as a mechanism in perception. The acoustics of capelin traps and other common net types involved in entrapment are investigated.

Many marine mammals, particularly humpback whales, are incidentally entrapped in fishing gear in Newfoundland and Labrador inshore waters. Explanations of these collisions are complex, and the fundamental question of how a whale perceives a net has yet to be answered. It is clear that the whale fails to detect the net in time to avoid it. It has been argued that the mechanism of sound remains as the most probable primary system of orientation to targets such as nets.

The present state of knowledge on the use of sound by baleen whales is discussed, including the possibility that humpback whales might possess a crude form of echolocation. It is also shown that a potential exists for the use of sound as a passive navigation system. Thus while humpbacks might use sound for orientation purposes, their apparent failure to detect nets might result from the target being acoustically cryptic.

The acoustics of a capelin (*Mallotus villosus*) trap are investigated. It was found that capelin trap mesh produces a wide band signal, which is significantly reduced in level once the trap is filled with capelin. Acoustic damping by schools of bait are discussed.

Capelin trap mesh produces the strongest acoustic signal, while larger mesh sized cod (*Gadus morhua*) trap mesh produces the least detectable signature. It is shown that net noise production can be correlated to the drag that a net imposes in a current. Differences in net acoustic signature are discussed in terms of anecdotal entrapment evidence; there is a negative correlation between probability of entrapment and the strength of acoustic signature of that net type.

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1.Introduction

1.1. The problem of incidental entrapment in fishing gear

Every year, between the months of May and September, the inshore waters of Newfoundland and Labrador host a large number of baleen whales of various species, including minke (*Balaenoptera acutorostrata*), fin (*B. physalus*), sei (*B. borealis*), blue (*B. musculus*) and the northern right whale (*Eubalaena glacialis*) (Lien, 1985). Of the odontocetes, sperm (*Physeter catadon*), killer (*Orcinus orca*), bottlenose (*Hyperoodon ampullatus*), and pilot whales (*Globicephala melas*) are also seen, as well the smaller toothed cetaceans such as harbour porpoise (*Phocoena phocoena*), common (*Delphinus delphis*), white-sided (*Lagenorhynchus acutus*) and white-beaked (*L. albirostris*) dolphin, beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*) (Lien, 1985).

By far the most common of the cetaceans present during this time is the humpback whale, *Megaptera novaeangliae* (Perkins, & Whitehead, 1977). The presence of this species in inshore waters has grave consequences on the fisheries of Newfoundland and Labrador. A conflict arises essentially as the result of competition between humpbacks and humans (Lien, & Merdsoy, 1980). The inshore movement of humpbacks to the eastern coast of Canada is linked to the annual spawning of a small baitfish, capelin (*Mallotus villosus*), which is a primary constituent of the humpback's diet (Bredin, 1986). During the capelin spawning season there is also a substantial land-based fishery for cod, which occurs in the same general locations.

The whales commonly collide with fishing nets during this period (Lien, & Merdsoy, 1980; Northridge, 1984). Introduction worldwide of synthetic fibres in the manufacture of net materials increased the strength of nets and, consequently, the difficulties for an animal in breaking through the net (Lien, 1980). This factor has increased incidental entrapment of cetaceans (Lien, 1980). Collisions and entrapments damage fishing gear and creates high financial burdens on the fishermen both in terms of repair costs and operational 'down-time' (Lien, & Merdsoy, 1980). Whale entrapment in Newfoundland and Labrador is often regarded as both a socio-economic and a whale population impact problem (Lien, Staniforth, & Fawcett, 1985).

1.2. The history of entrapment in Newfoundland and Labrador waters

Entrapments commonly occur in two kinds of gear - the fish trap, and the gillnet. Fish traps basically consist of a box, usually open at the top, where each side is made from a panel of net mesh. A trap leader (a separate panel of net that is attached to the shore) is used to direct fish into the box through one side of the trap that has been modified into doors. The size of mesh that constitutes the box depends upon the type of target species - in Newfoundland, the two primary target species are cod and capelin. Cod trap mesh size ranges between 4" to 8" [10cm to 20cm, approx.], while capelin traps are of a much smaller mesh size - approximately 0.75" [2cm, approx.]. In both cases, the trap leader is usually composed of a larger stretched mesh size than that in the box. Cod traps can be further divided into three types; traditional, modified and Japanese. While the traditional cod trap is very basic in its design, the modified and Japanese types involve attempts to improve the internal structure of the box section around the door area, utilizing more mesh in the construction.

Gillnets consist of single panels of mesh, linked together to form longer 'sets'. The depth and position in the water column where they are set depends upon the target species. Gillnet mesh can be made of nylon monofilament of varying mesh size (depending on target species, between 3" to 8"), although the smaller mesh nets - such as herring or salmon gillnet - are made of nylon multifilament.

Up to 1977, the incidental entrapment of large whales in fishing nets in Newfoundland and Labrador waters was not a significant problem, either in terms of impact on the humpback population, or in cost to the fishermen (Lien, & Merdsoy, 1980). Gear damage due to whales had probably occurred at low levels before this (Lien, 1980; Lien, Dong, Baraff, Harvey, & Chu, 1982). However, as a result of many factors - including a crash in the capelin population (Whitehead, & Carscadden, 1985; Whitehead, & Lien, 1982) and an increase in fishing effort (Lien, & Merdsoy, 1980) - whale entrapment began to reach significant numbers after this date. Lien and Merdsoy (1980) suggest that, in 1978, repair costs to gear damaged by whales were approximately $500,000. This figure does not include an estimate of fishing time lost through down-time. Reported entrapments reached a peak in 1980 of 61 animals (Lien, 1981), with similar costs in damage. It has been shown that for the years 1979 and 1980, damage estimates plus losses due to fishing down-time during repair were approximated at two million dollars (Lien, 1980; Lien, Stenson, & Ni, 1989c). The number of entrapped animals decreased in 1981 to 31 animals (Lien, 1981), with the figure remaining reasonably constant over the next few years (Lien, *et al.*, 1982; Lien, Walter, & Harvey-Clark, 1985).

A second peak in entrapments was observed in 1985 with 52 reported animals, thought primarily to be caused by a further increase of humpbacks inshore (Lien, *et al.*, 1985). Since 1986, the number of animals reported entrapped has steadily increased to record proportions, passing the earlier peaks of the beginning of the decade with a total reported number of 70 animals in 1989 (Lien, Ledwell, & Huntington, 1989b; Lien, Stenson, Todd, & Ni, 1989d), and 75 animals in 1990 (Lien, Huntingdon, Ledwell, & Huntsman, 1990).

Lien, *et al.* (1989b) cite four possible causes for this latest increase. These include a possible under-reporting phenomenon in earlier years, a redistribution of capelin, a possible increase in inshore local fishing effort, and a possible increase in the population of humpbacks. Data remain inconclusive with respect to the first three of these explanations. However, recent studies have suggested an increase in the humpback population since 1980 of approximately 50% (Lien, *et al.*, 1989b, but see Whitehead, 1989), although it is thought that the stock has yet to return to pre-whaling levels (Whitehead, 1987). While it is unlikely that increases in the whale population alone can explain the increasing trend in entrapments (Lien, *et al.*, 1989b), it is undoubtedly a factor that should be considered along with increases in inshore fishing effort (Lien *et al.*, 1990).

Damage costs caused by entrapment have persisted at relatively stable levels, in part because of the introduction of a Whale Release Programme in 1979 developed through the cooperation of Memorial University of Newfoundland, the Department of Fisheries and Oceans, Canada, and the Newfoundland and Labrador Department of Fisheries (Lien, 1980; Lien, *et al.*, 1989c). From 1981 to 1987, total costs to fishermen through gear damage have remained reasonably constant at around $100,000 per year (Lien, Ledwell, & Nauen, 1988). This figure is the result of gear damage only, and does not include down-time losses. Fishermen now have access to a toll-free telephone line through which they can request the aid of a trained team in releasing a whale from the net. Concurrent with this, an education programme has also been developed (Lien, & Atkinson, 1989; Lien, *et al.*, 1985); it is now common for fishermen to release whales from fishing gear without the assistance of the university programme.

While the Newfoundland/Labrador humpback population is apparently robust (Lien, *et al.*, 1989c; Whitehead, 1989), the preventable incidental loss of many animals per year is clearly socially and ethically undesirable. The current increasing trend in Newfoundland and Labrador of collisions of whales with fishing gear, coupled with the costs to the fishing community in times of increasing general economic recession, along with the above moral consideration, has created my incentive to investigate why entrapments occur, and how they can be prevented.

Basic biological and behavioural principles that remain poorly investigated with respect to the humpback must be examined if we are to find solutions to the entrapment problem. It is the purpose of this thesis to examine one of the possible factors that may influence the rate of entrapment - acoustical stimuli associated with fishing gear.

1.3. Research objectives

One cause of collisions might be the inability of the whale to detect a net. As it can be argued that sound provides the most useful information for orientation in an aquatic environment, the acoustics of nets were investigated. It may be postulated that entrapments may occur because either a) there is not enough detectable acoustic information for the animal to deduce the presence of the net, or b) there is enough acoustical information, but it is being masked by levels of ambient noise, or c) the acoustical information is too cryptic to be of any use.

The main purpose of this study, therefore, was to investigate the passive acoustic characteristics of various net types, and to relate the findings to the occurrence of entrapments. A secondary study investigated the acoustics of a school of prey fish, to determine if an 'acoustic signature' might be available for foraging purposes.

2. Perception as a possible cause of entrapment

There is no single cause for the incidental entrapment of whales in fishing gear (Donovan, & Perrin, in press). Lien (1980) failed to find correlations with various oceanographic and gear factors, although low sample sizes in some of the data may have been a problem in the statistical analysis (Lien, pers. comm.). One model of the cause for entrapment would involve an inability to perceive the net. Forbes and Smock (1981) and Watkins and Wartzok (1985) demonstrate that very little is known about the perceptual capabilities of baleen whales

Perceptual cues available to a humpback which could aid in orientation to nets would include visual, chemical and acoustic stimuli (Lien, Todd, & Guigné, 1991; Todd, Lien, Guigné, & Hunt, in prep.). Other sensory systems may exist, but there are little or no supporting data, at least for the purposes of this review. Reliance on a single type of cue by an animal is very uncommon, and orientation is likely the result of a multi-sensory approach with certain stimuli dominant within that framework (Kinne, 1975; Norris, 1966).

2.1. Vision

Eye pigments in the humpback are concentrated for a maximum sensitivity of 492 nm (Forbes, & Smock, 1981), implying a maximal response to the shorter wavelengths in the visible spectrum. Kinne (1975) notes that based on neurological evidence, mysticete vision has greater potential than odontocete vision. But visibility in water is highly variable both in the vertical and horizontal planes; inshore and shallow coastal waters can be particularly turbid because of sediment run-off in the water. In addition, any distinct layers of fresh water present will also impede vision (Watkins, & Goebel, 1984).

It would be unlikely for a complex system of visual perception to be developed through the pressures of natural selection when vision in the primary environment is so limited. Humpbacks have been shown to feed at night when visual perception would be particularly restricted (Goodyear, 1983; Lien, 1980) suggesting that a whale foraging inshore would not rely on the use of visual perception as a means to locate prey - except, perhaps, as a secondary cue (Lien, *et al.*, 1991; Todd, *et al.*, in prep.). Indeed, Kinne (1975) notes that visual cues - and the sense of vision in general - are less important for marine mammals than for their terrestrial equivalents.

2.2. Chemoreception

Two reception systems can be considered for processing chemical cues - olfactory and gustatory. Herman and Tavolga (1980) suggest that the olfactory sense in whales would be severely limited since the nares would be closed for a majority of the time. While Forbes and Smock (1981) note that olfactory systems do exist in mysticete species, it would appear that it is much less developed when compared to terrestrial mammal systems (Watkins, & Wartzok, 1985). Cave (1988) demonstrates that in certain cases - such as the fin whale - the olfactory chamber is unexpectedly "well organized", although he states that morphologically, the system is designed for aerial, not aquatic, olfaction. Cave (1988) also suggests that in surfacing the animal may be able to detect certain chemicals in the air associated with specific prey below the surface. While possible, it seems unlikely that this mechanism would provide an exact positioning of the location of the prey. The olfactory sense, therefore, would be an unreliable method for locating prey or for orientation underwater (Lien, *et al.*, 1991; Todd, *et al.*, in prep.).

There is evidence that some odontocetes might be capable of taste (gustatory) sensitivity, although data for mysticetes are lacking (Herman, & Tavolga, 1980). On the basis of anatomical evidence, Forbes and Smock (1981) re-affirm the general belief that baleen whales "lack a sense of taste". Even if mysticetes possessed a gustatory sense, the turbulent, dynamic nature of the near-shore makes the practicality of gustatory cues for precise object orientation questionable (Lien, *et al.*, 1991; Todd, *et al.*, in prep.). However, fishermen in Newfoundland frequently cite a correlation in increase in whale collisions with fishing gear with cessation of the practice of 'barking' nets, a process which coated nets with a layer of tar (Lien, pers. comm.).

2.3. Audition

Water is an excellent propagator of sound and, therefore, acoustic perception would seem to be a likely target for natural selection in developing aquatic orientational behaviours. Schevill (1964) suggests that marine organisms will adopt sound sensory processes when vision will not serve (see also Norris 1966). Forbes and Smock (1981) note that audition is the most significant sense for marine mammals. Kinne (1975) separates the distinction between active and passive acoustical orientation in stating that,

> "Passive biosonar (orientational hearing) compromises perception and interpretation of ambient sounds for object localization and recognition; the acoustic cues may be sounds generated by the object itself or environmental noises reflected by it. Active biosonar is based on the reflection of specific self-generated acoustic energy by foreign objects; the echo received informs the sound producer about presence, direction, distance, size, shape and other characteristics of an object"

For reasons of practicality, very little work has investigated humpback whale perception within the acoustic sense *per se* , and in the absence of sufficient data among mysticete species regarding perception, one inevitably draws parallels from the odontocete family. While there may be some value in making equivalencies, these models hold obvious disadvantages because of the morphological and physiological differences between the two families. In making such comparisons, of prime importance is the fact that mysticetes have not been shown to echolocate in situations where the use of echolocation would be beneficial (Beamish, 1977; Beamish, 1978). However, this premise is based on limited field data that attempts to examine a behaviour that is extremely difficult to investigate.

2.4. Active acoustics - the controversy of mysticete echolocation

Despite the fact that it has yet to be shown definitively that baleen whales cannot echolocate, the attitude adopted by the scientific community is generally one of scepticism. However, very little can be deduced from available evidence regarding echolocation ability, as little of the research done has focused on a detailed analysis of all factors involved. The argument that mysticetes can not echolocate was summarized by Beamish (1977; 1978), following an *in situ* experiment involving a maze and a tethered humpback. The design of this experiment had serious flaws. The animal was under severe stress, and the experiment involved a sample size of one animal that had been previously caught in a net. Even given the questionable validity of this experiment, it now seems generally accepted that mysticetes do not echolocate. There are, however, other reports that suggest an echolocation ability does exist, as listed below.

2.4.1. "High frequency" echolocation

Beamish (1970), and Beamish and Mitchell (1971; 1973) postulated the existence of certain operational frequencies developed through evolutionary selection pressures by individual whale species according to the size of prey species. Mysticetes do not generally forage on individual prey but on schools and therefore would not require the ability to resolve targets to the same extent as odontocete species. It can be argued that the mechanistic development of the frequency response of biological sonar would be phylogenetically constrained by the size of the prey upon which the whale foraged. When asking the question 'do mysticetes echolocate?', one should not expect the answer to be based upon some form of odontocete echolocation model. Direct comparisons between the two models in this sense should not be made.

Winn and Perkins (1976), Thompson, Winn and Perkins (1979), and Chabot (1985) have reviewed mysticete vocalizations and find evidence for high frequency echolocation inconclusive. For at least six species (gray, blue, fin, sei, minke and humpback whales) a record exists of click-type vocalizations that may be suitable for echolocation, on average within the range of 1 to 10 kHz (the fin, minke and blue whales are reported to have higher frequency emissions above 20 kHz). A seventh species, Bryde's whale (*B. edeni*), has been reported (by Beamish, & Mitchell, 1973) to produce a short-pulse-length click-train, although no recording was made (Thompson, *et al.* , 1979). They correctly conclude, however, that clear, rigorous experimental procedure must be applied before categorically coupling certain mysticete vocalizations and orientation mechanisms.

There are some observations which suggest humpbacks may echolocate, at least under some circumstances. Beamish (1979) recorded a series of clicks with a peak frequencies of 2.0 and 2.1 kHz, along with one occurrence of a click train with a peak frequency of 8.2 kHz. Winn, Beamish, and Perkins (1979) summarize the humpback sound recordings made by Beamish (1977; 1978; 1979). Little reference is made to the click-like vocalizations made by the humpbacks in these cases, although they do admit the possibility of an echolocation function to these vocalizations.

Lien and Storey (1987) report a single case where an ice entrapped humpback issued click-trains similar to 'primitive terrestrial echolocators' when surfacing up through a polyna. During daylight hours, the isolated humpback could presumably orientate to an ice hole using light contrast cues; no click trains were recorded during this time. However, during night-time the absence of such cues appeared to prompt a different orientation system. In each of the three moves between polynas recorded at night, click trains of frequency range between 20-400 Hz were recorded previous to surfacing in a new polyna (Lien, pers. comm.). Analysis of the trains revealed an increase in click rate towards the end of the train, similar to dolphin click-trains where a focussing effect occurs as the animal approaches the target (Goodson, & Klinowska, 1991; Goodson, Klinowska, & Bloom, in prep.).

Norris (pers. comm.) reports a similar recording of such click-trains in the presence of a humpback which became trapped in an estuary in California. Prior to its movement under the bridge, the whale was reported to make low frequency rich pulses. After some time, the whale moved between the pilings, successfully navigating the gap in spite of the turbid condition of the water. To quote Norris, "it was obvious that the whale detected the bridge, and that it was able to find the opening through it". However, Norris also notes that it is difficult to correlate the whale's vocalizations with orientation, although it is obvious that

Humphrey navigated with some precision in the absence of vision (Norris, pers. comm).

2.4.2. "Low frequency" echolocation

In the absence of more substantial evidence, it has been assumed that humpbacks do not echolocate (Watkins, & Wartzok, 1985) - at least not in the same manner as odontocetes - and must therefore rely on other means to perceive the environment. Given the above arguments concerning insufficient, and sometimes inappropriate, experimentation on mysticete echolocation potential, a further possibility remains for baleen whales do utilize sound actively in orientation. As noted by Thompson *et al.* (1979), some mysticetes may possess the ability to use the echoes of their various low frequency sound productions. Norris (1969) notes when referring to echolocation signals that "a very wide variety of sounds may well be useful.... there is no a priori way of saying what sounds are or are not used for echolocation". In the field of human perception at least, it has been shown that blind people possess an ability to use various deliberate vocalizations and non-vocalizations to detect the presence or absence of a target (Rice, 1966; Rice, Feinstein, & Schusterman, 1965). Importantly, Rice (1966) notes that blind people may use forms of echoes produced by ambient noise reflected from surface areas of targets. Yet humans have not developed an echolocation system *per se* ; in this particular case they have enhanced a mechanism already available to them.

The use of such low frequency, 'infrasonic' signals in communication has been demonstrated for terrestrial counterparts of the whale - the low frequency calls of Asian and African elephants serve to communicate over substantial distances, where higher frequency calls would be rapidly attenuated (Payne, Langbauer, & Thomas, 1986). These animals have developed a repertoire of calls, especially noticeable in the infrasonic range, with fundamental frequencies of between 14 - 35 Hz (Poole, Payne, Langbauer, & Moss, 1988); playback of these sounds to subjects have elicited responses that suggest potential orientational significance to the calls (Langbauer, Payne, Charif, & Thomas, 1989). The properties of infrasonic signals underwater would infer great potential for use in orientation, because low frequency sound does not attenuate as rapidly as high frequencies.

Patterson and Hamilton (1964) speculated that the so-called 20 Hz cycle of the fin whale (as recorded by Schevill, Watkins, & Backus, 1964) might have an orientational function. This view has been shared by other authors (Norris, 1966; Payne, & Webb, 1971; Schevill, 1964; but see Evans, 1967). It has been noted that such pulses might be used to discriminate major targets, such as sea floor and sea surface, or even dense schools of prey (with resolution limited to the length of the wavelength used). However, it has also been suggested that the calls might more likely serve a reproductive function (Watkins, Tyack, Moore, & Bird, 1987).

Certain authors have suggested an orientative function to low frequency vocalizations in other species, including the humpback (Airapet'yants, &

Konstantinov, 1973; Kinne, 1975; Herman, & Tavolga, 1980; Moore, 1979; Winn, & Winn, 1978).

Bowhead whales (*Balaena mysticetus*) may utilize the reverberations of their low frequency vocalizations to detect ice cover at the sea surface (Clark, 1990a; Ellison, Clark, & Bishop, 1987; George, Clark, Carroll, & Ellison, 1989). Ellison *et al.* (1987) developed a model in which they predict that relatively thick, rough ice would produce a reverberation (from a 'representative' bowhead vocalization) 20 dB greater than that from a patch of thin ice - a difference certainly detectable to the human ear using a hydrophone system. Field observations (George, *et al.*, 1989) indicate circumstantially that bowheads do avoid areas of thicker ice cover, although they note visual cues are probably also a component in this behaviour. Bowhead vocalizations are typically low frequency; such reverberations would result in a low resolution detection system. In addition, no attempt was made to account for the directionality of the signal, thus limiting the localization of the reverberation. These limitations may not be a factor if rough or thin ice accumulates in large patches.

2.4.3. Echolocation in the context of an odontocete model

It is becoming evident that odontocete entrapment may not be the result of an inability to perceive targets in the ocean environment (for an overall review, see Donovan, & Perrin, in press). Using a sonar equation model, it has been shown that odontocetes are capable of resolving targets of even lower target strength (TS) than net panels (Au, 1990; Au, & Jones, 1989; Au, & Jones, in press), using a high frequency, 120 kHz beam. Au's (in prep.) model shows that for a source level (SL) click of 180 dB, a gillnet remains 90% detectable at distances of 10 - 15 m, even allowing for high levels of ambient noise. Such a model assumes a perpendicular approach to the net. The TS of a net will vary with angle of approach (Goodson, pers. comm.).

In summary, the high resolution of dolphin sonar is directly linked to the high frequency, short wavelength echolocation clicks produced. This resolution seems to surpass the necessary requirements to detect nets. If mysticete echolocation exists, it is probably low frequency in nature, and thus only capable of much poorer resolution; nets may not be detectable by 'mysticete echolocation', if it exists. Kinne (1975) suggests that,

> "The [acoustic] cues [from biologically induced reverberations] may be of restricted or no value for locating discrete objects, but they may be superior to the delphid sonar for long-distance navigation (location of large food-organism aggregations and breeding places, gross assessment of water properties) and long-distance communication among con-specifics"

2.5. Attention and interpretation aspects of perception

If whales are capable of detecting targets, as suggested for the smaller cetaceans by various authors (Au, 1990; Au, in prep.; Au, & Jones, 1989; Au, & Jones, in press), collisions may be due to the lack of attention or correct interpretation of a target cue (Nelson, 1991). Humpback and minke whales are commonly observed swimming in close proximity to gear without becoming entangled. Such observations strongly suggest that at least in some cases, the whale is aware of the net's presence. Although an animal may be capable of perceiving a target such as a net, this is no guarantee that a) the animal will notice the target in time to elicit an escape response, or b) the animal will identify the target as 'a barrier' or as something dangerous.

It has been noted that dolphins do not constantly emit echolocation signals (for example, see Dawson, in prep.; Dawson, in press; Goodson, *et al.*, in prep.; Nelson, 1991). In the absence of constant environmental interrogation, it may therefore only be chance that allows the dolphin to avoid collisions. Also, if the animal is foraging in the vicinity of nets, the 'lock-in' hypothesis (Goodson, & Klinowska, 1991; Goodson, *et al.*, in prep.) suggests a type of acoustic gate deliberately excludes all echoes except those directly related to the target being monitored. Thus, while in pursuit of a prey item, the dolphin may concentrate its sensory processes on the assessment of prey location, excluding all other environmental informational cues (Goodson, & Klinowska, 1991; Goodson, *et al.*, in prep.). Although stray echoes may result from reflections on a net in the vicinity, such information would be filtered out by the interpretation system of the dolphin. That is, while the dolphin receives information concerning the environment, it will only use input that is related to the immediate task that it is performing.

Interpretational processes may also be a factor. The concept of a barrier is probably fairly unfamiliar to oceanic species (Au, & Jones, in press). Goodson (pers. comm.) suggests that because of the nature of a dolphin echolocation beam, a net would appear as a series of "tiny 'sparkling' reflections" - an echo not characteristic of more solid objects. Other acoustically similar barriers of comparable target strength would include beds of seaweed, algal blooms, curtains of fine bubbles, or even just strong volume reverberation such as the Deep Scattering Layer (Au, & Jones, in press; Goodson, pers. comm.), which present no obvious danger to a whale. Norris (1969) further documents that there is likely "a large learned component in all echolocation behaviour... creatures in clear seas may use their systems in quite different ways compared to animals inhabiting tidal flats and muddy bays".

Mortality as a result of entrapment is more common in the smaller cetaceans than in the larger baleen whales. A fatal encounter with a net would, of course, terminate the learning process for that individual. It is not known how many dolphins simply collide and escape entrapment without human aid. With the larger whale species some potential for a learning curve remains, as the whale can often break through the net. Working on these premises, Lien (1980) developed various types of acoustical alarm that were attached to nets so that humpbacks might learn to associate such sounds with the presence of a net in the vicinity. The 'beeper' alarm (Lien, 1980) has been used in Newfoundland waters consistently for the past decade, although the results of this alarm programme are difficult to assess given the low sample sizes in the statistical design of the experiment (Lien, 1980; Lien, *et al.*, 1991; Todd, & Nelson, in prep.). A new design of alarm is now ongoing (inventors: Guigné, Lien, and Guzzwell) utilizing cheap, available materials, and preliminary tests are proceeding (Lien, 1990; Lien, Verhulst, Huntsman, Jones, & Seton, in prep.), using a large database of fishermen to test alarms *in situ* on traps. Many researchers have conducted various other investigations into the effectiveness of both active and passive net alarms. Results from these programmes are generally inconclusive, for a variety of reasons (Todd, & Nelson, in prep.).

2.6. Passive acoustics - "listening"

The nature of sound waves in a fluid environment demands that long-range acoustics be mainly confined to high-intensity low-frequency signals. There are few data on mysticete hearing sensitivity (Dalheim, & Ljungblad, 1990; Ridgeway, & Carder, 1983); in the absence of direct evidence one is forced to use other means of assessing mysticete audition. One method of characterizing mysticete acoustic perception assumes that the frequency range of auditory sensitivity can be correlated to the frequency range of communication signals produced by that animal. Such a pattern has been shown in certain terrestrial species (Payne, & Webb, 1971).

Watkins and Wartzok (1985) summarized that humpbacks produce "widely variable tonal and pulsed sounds with fundamentals from 30 to 3000 Hz". Chabot (1985) reviewed sound production of humpbacks in Newfoundland waters and classified 13 different classes of sound types, the majority of which were thought to be vocalizations. Non-vocal behaviour such as breaching, lobtailing and flipper slapping all carry acoustic components and may aid animals to keep in acoustic contact when visual contact is not possible (Herman, & Tavolga, 1980; Whitehead, 1985; but see Dalheim, Fisher, & Schempp, 1984). There is also evidence that 'bubbling' - the exhalation of air bubbles from the nares when either partially or totally submerged - might also be a significant auditory form of communication (Herman, & Tavolga, 1980). Whether intentionally produced or not, bubbles (as they resonate at their natural frequency) are a source of sound that might be utilized by an animal. There also remains accounts of so-called "wheezy blows", apparently executed deliberately (Watkins, 1967).

Species capable of such complex forms of communication must be proficient in some rudimentary auditory perception. Norris (1966) comments that from available evidence, cetaceans in general are "excellent passive listeners of water-borne sound". The various 'playback' experiments that have been performed on humpback and gray whales (Dalheim, & Ljungblad, 1990; Mobley Jr., Herman, & Frankel, 1988; Tyack, 1983; Tyack, Clark, & Malme, 1983) infer the ability in some baleen whales to discriminate and react to particular sounds. Remarking on the sensitivity of mysticetes to the acoustic environment, Herman and Tavolga (1980) suggest that based on the

> "relatively low upper limits of their vocalization range, the mysticetes probably lack the the very high-frequency hearing capabilities of the odontocetes but, on the same basis, may hear well into the low sonic or infrasonic regions"

There is strong evidence to suggest that sound may play an important role in the orientation mechanisms of a humpback, through the reception and interpretation of acoustic cues from the environment. Such cues can be produced by targets in a variety of ways, either in an active or passive sense. However, for such cues to be of any use at a distance, they would have to be low frequency, to minimize problems of absorption losses to signal energy. In addition, they must be high enough in source level to dominate over local levels of ambient noise. In turn, the utilization of low frequency acoustic cues by a humpback would depend not only upon sensitivity to low frequencies, but also a knowledge of the behaviour of that signal in a given environment. In the account by Norris of the estuary entrapped humpback (pers. comm.), it has been noted that water noise from the bridge might have been used as a cue for orientation. In this case, the acoustic cue would be low frequency in nature; there would also be attenuation, backscatter and reflectivity aspects of the signal that would have to be examined before clearly defining the bridge noise as an acoustic cue.

2.7. Orientation and acoustics

To summarize thus far, one cause of entrapment would be based upon an inability of the whale to detect the net. Very little is known about the orientational abilities of humpbacks, although it seems likely that acoustic cues play a dominant role in orientation underwater. Possible acoustic mechanisms for orientation include echolocation, incidental reverberation, and listening. There is little conclusive evidence that humpbacks can echolocate or use reverberations of their vocalizations. Typically they are silent in the vicinity of fishing nets and yet, in most cases, avoid them, even under minimal light conditions. Use of acoustic cues in a directional hearing context remains as a potential means for orientation, although it is yet to be demonstrated that this is done.

While it has been shown that net materials can be detected with active biosonar, it is not known whether nets can be perceived in a passive sense. No information is as yet available on net 'self-noise', or how such noise might interact within the environment to produce an acoustic cue. It is logical, therefore, to first examine the acoustic nature of nets, and to examine their potential as targets which can be localized through orientative processes.

3. Methods

3.1. The measurement of capelin traps and bait in situ

Field work was done in St. Phillip's, Conception Bay, Newfoundland, Canada. The site was chosen for its close proximity to the University, and because it was a known capelin fishing area. In co-operation with a local fishing crew, a capelin trap was acoustically monitored over the period of the capelin fishing season (17/06/89 to 24/06/89). Results were then analyzed digitally, using specially written computer programmes to compare acoustic spectra.

3.1.1. Apparatus used

Capelin traps consist of a moored square frame of ropes and floats, from which is hung a box of dense mesh (4 cm approximate stretched mesh size), open at the top. The side facing shore is not closed off, but flanked by two doors allowing fish to enter the trap. A length of net of coarser mesh (12.5 cm approximate stretched mesh size), termed the 'leader', links this facing side to the shore, and acts to divert migrating capelin schools which travel along the shoreline into the box of the trap. To haul the trap, the two doors are closed, and the box is gathered in to a point so that the fish can be removed with a dip net.

To help haul the net, a 'spanline' is connected between the middle of the back panel and the door panel. It was to this line that a sensitive hydrophone (Brüel and Kjaer, type 8101) was connected at a distance of 4 m from the back of the net, and 5 m directly downwards from the spanline, so that it was positioned approximately in the centre of the trap (see Figure 1). The location of the hydrophone inside the trap provided convenient access to sounds being produced both by the net and by targets contained within the net. It was assumed that sounds produced by net and contained targets would be omnidirectional.

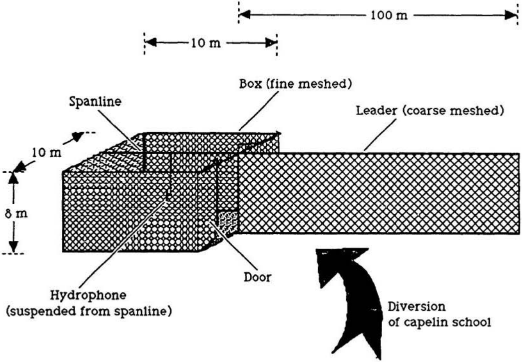
A 100 m length of blocked waterproof cable, fixed along the spanline, connected the hydrophone to the monitoring system. A 16 m length of PVC pipe (5 cm internal diameter) was used to protect the cable in the intertidal zone. A receiver (Brüel and Kjaer 8 channel multiplexer, type 2811), charge amplifier (Brüel and Kjaer, type 2635), and analog tape recorder (Hewlett Packard Instrumentation recorder 3964A) completed the measuring equipment used. Recordings were made on Scotch 3M tape. Appendix A lists technical specifications of the equipment used.

3.1.2. Data collection

It was decided after pilot experimentation that a series of five minute recordings would be sufficient for a representative sound sample. External factors which might influence acoustics were logged, including sea state, wind speed and direction, and general weather conditions. In addition, a photograph was taken daily of a standard view across the bay, to confirm sea conditions - environmental conditions did not vary sufficiently beyon this to warrant a more detailed examination.

Figure 1

Illustration of the positioning of the hydrophone within a typical capelin trap.



depth of net below surface = 0 m
depth of hydrophone below surface = 5 m

For seven days during the capelin season, a series of 5 min. acoustic recordings of the trap were made at approximately 30 min. intervals. In addition, just before fishermen arrived to empty the net, a reading was taken (designated as the 'pre-haul' measurement). Once the net was hauled, a final reading was taken (designated as the "post-haul" measurement). It was possible to collect six separate pairs of pre-haul and post-haul readings for the same trap. The fishing crew provided information on the weight of fish taken, and an approximate measure of the gender ratio within the school.

3.1.3. Data analysis

Data was initially collected in an analog format. Subsequent to the recordings, analysis of data was performed through a digitizer (Datalab DL1200) on a computer. The environmental log was used to select areas of the recording which did not have irregular noise influences - such as boat engines - as part of the record. Digital data was stored on high density floppy disc. Several comparative analyses were then performed to interpret data. Recordings were initially presented in two formats - as a time series graph (amplitude versus time), and as a spectral composition (amplitude versus frequency). The spectral composition graph was further divided into a bandwidth between 0 - 10 kHz, in addition to a bandwidth that specifically detailed the 0 - 1 kHz region (although it should be noted that the equipment used was not capable of recording infrasonics).

For data analysis, two programmes were specifically written (by P. Hunt, C-CORE) to aid in the interpretation of results, using the spectral compositions. The first, a semblance programme, was designed to add spectra together, with the result of enhancing any common frequency, and reducing the strength of any random constituents of the spectra. A second, a subtraction programme, was designed to subtract spectra from each other, thus removing the frequencies of one spectrum from another. Both of these programmes made use of a commonly available spreadsheet programme (Lotus 1-2-3) to manipulate files in graphical format.

To obtain an average spectrum of the sound of an empty net, a semblance programme was used on all the post-haul spectra. Similarly, to obtain an average spectrum of the sound of a full capelin trap, a semblance programme was used on all the pre-haul spectra. It should be noted that both of these semblances contained ambient acoustic noise. Therefore, the semblances obtained were representations of the acoustics of a net in a specific environment.

Finally, to separate out the contribution that the capelin were making to the pre-haul spectra, a subtraction programme was used to subtract the post-haul semblance (that of the empty net and environmental noise) from the pre-haul spectra (that of the net, environmental noise, and the capelin). As the time each day between pre- and post-haul was relatively short, it was assumed that environmental conditions would remain reasonably constant, as would environmental noise. Therefore the resulting spectra from the subtraction would, in theory, represent the effect of the capelin alone.

3.2 The measurement of different net panels *in situ.*

A mooring system was designed and installed approximately 150 m offshore, at 10 m depth in Conception Bay. Samples of different types of net panel were cut to a standard size for the mooring. A hydrophone was used to record the acoustic characteristics of these net panels. Then, as above, results were analyzed digitally using specially designed data analysis programmes.

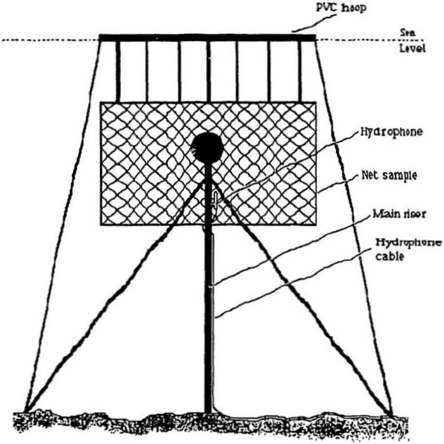
3.2.1. Apparatus used

The mooring system consisted of a main riser of nylon rope, 8 m in length and anchored with a heavy weight (approx 60 kg). This riser was also buoyed with a large float which remained approximately 2 m below the surface at low tide. From this rope, three guide lines were attached to a further three anchors (60 kg each) spaced as a tripod to stabilize the frame (see Figure 2). The absence of metal in construction of the frame was deliberate, to prevent unwanted noise.

A hoop of sealed PVC plastic piping 16 m in circumference was fixed centrally over the mooring. At 1 m intervals around the circumference of the hoop, fifteen lengths of hanging twine were attached, each 2.5 m long. When

Figure 2

The hanging frame system designed to test net self noise of various types of mesh. Experimental samples were hung in a cylinder fashion around the central buoy.


PVC hoop
Sea
Level
Hydrophone
Net sample
Main riser
Hydrophone
cable

hung from these twines, the net samples formed a cylinder of 16 m in circumference, hanging approximately 2 m from the surface.

Finally, a hydrophone (Brüel and Kjaer, type 8101) was clamped onto the main riser of the mooring, 5 m from the sea floor, using an aluminium frame (see Figure 2). Excess slack in the hydrophone cable was taped to the mooring to prevent noise from its movement, and the remainder of the cable was laid along the sea floor to the shore, using a length of PVC piping to protect it across the intertidal zone. The electronic equipment used to record signals from the hydrophone was the same as detailed in Section 3.1.1.

Seven different samples of typical net twines were tested, including four types of cod trap mesh (0.10, 0.16, 0.21, and 0.23 m stretched mesh size, labelled c1, c2, c3, and c4), one type of multifilament herring/salmon gillnet (0.175 m stretched mesh size, labelled h1), one type of monofilament nylon gillnet (0.245 m stretched mesh size, labelled g1) and a one type of capelin trap mesh (0.020 m stretched mesh, ct1). The samples were cut into panels 16 m in length and 3.5 m in depth. So that they would hang correctly in the water column, the panels were specifically cut at a hanging ratio of 50%; that is, two meshes per unit mesh length (see Appendix B for details of calculations). Cut panels were then attached to a buoyant top rope (with 0.2 m oblong floats tied at 5 m intervals), a leaded bottom rope, and two neutrally buoyant side ropes, using fishing twine.

3.2.2. Data collection

Net panels were suspended from the hanging frame system (see Figure 2). The longitudinal join in the cylinder (formed by the two ends of the net panel) was stitched together once the net was in place by a diver. A final inspection by the diver checked that the net sample was hanging correctly and not interfering with any of the mooring frame ropes.

Measurements consisted of two 5 min. readings, 30 min. apart, taken before the addition of the net to the mooring, and two 5 min. readings taken with the net attached to the mooring system, again spaced by an interval of 30 min.. The first pair of readings served as a control, including environmental acoustic conditions at that specific time, and self-noise created by the hanging frame system. The second pair of readings served as the experimental readings of the net. Because measurements would be influenced by environmental conditions on the day, a log was also kept, as described in Section 3.1.2.

Following the final recording, the net was retrieved and dried so that its physical characteristics could be noted. These included stretched mesh size (recorded as an average of ten different readings taken randomly from the net panel), twine diameter (again, an average of ten separate readings), mass per unit area, and exposed area per unit area (effectively a measure of the "solidity" of a net; for details, see Appendix B).

3.2.3. Data analysis

As described in Section 3.1.3, data was collected in analog format as two separate files - a time series, and a spectral composition. It was then digitized and interpreted with the aid of the semblance and subtraction programmes as described previously. Areas of the recording were chosen that had as little irregular noise interference as possible.

For each net sample, the semblance programme was used to combine the control pair of measurements and the experimental set of measurements separately. The subtraction programme was then used to subtract the spectral composition of the control semblance from the experimental semblance. As both control and experimental measurements were taken in a brief time span, during which time environmental conditions remained relatively constant, it was considered that such a subtraction would remove the environmental noise present, along with any system self-noise, effectively isolating the noise of the net panel alone. Thus an acoustic spectrum was constructed for each experimental net panel.

4. Results

4.1. The acoustics of capelin traps and bait

Data are presented in chronological order, on a daily basis for the six days that were sampled. In each case, a series of recordings before net hauling are given as a qualitative description of the acoustic environment that day. The majority of analysis was performed on the penultimate and final recordings for that series - the pre-haul and post-haul recordings. Hauling dates and durations, size of catch and gender ratio of catch are given in Table 1. Only one example of a series of recordings is illustrated here, although all days are described. A full record for all other series in the experiment is presented in Appendix C.

Four important points should be considered when interpreting the data. First, while a capelin trap is unlikely to fill instantaneously with bait, there is no way to readily quantify the rate of filling of the net. Therefore, the only instances when a sound recording can be correlated to a specific amount of fish in the trap are in the pre-haul and post-haul recordings. The hauling process does not guarantee a 100% yield of the fish that were in the net; some inevitably escape through the doors on hauling.

Second, the hydrophone used (although calibrated) was not referenced to a particular source level. The effects of instrument gain have been removed in the digitization process, so that the spectra reported here are referenced to each other. This action permits direct comparison between various recordings, but referenced source levels can not be quoted.

Third, some allowances must be made for unique noise characteristics, because of the location of the experimental site. Specifically, the presence of an underwater power cable in the near vicintiy created a 60 Hz spike in most of the recordings made. The power cycle is also evident in some of the time series presented, as a regular sine wave. While this could be removed to some extent by subtraction programmes, the nature of a power cycle (that is, AC current) meant that its influence could never be totally eliminated from a spectrum. It should also be recognized that the power cycle was powerful enough to create a reasonably distinct set of harmonics, detectable at least up to 300 Hz. It is acknowledged that the use of high-pass filters might have, in part, reduced the overall influence of the power cycle on the spectra taken. However, it was considered important that the low frequency spectrum be recorded, especially as it was expected that an useful acoustic cue, if present at all, would be low frequency in nature.

Finally, at least for the pre-analysis figures (Figures 3, and C1 to C11), an auto-scale facility within the digitization programme meant that while all signatures are plotted on the same relative scale, the range that is actually plotted differs between spectra. The main reason for this is because of the highly variable strength of the power cycle prevalent in the bay. Care should therefore be taken in analyzing the plots given in following figures.

Table 1. Characteristics of haul, including weight and gender ratio of catch.

Day Number	Date	Haul		
		Approx. duration of haul (hrs)	Mass of catch (kg)	Gender ratio, as % females
1	18/06/89	1.5	3765	49
2	19/06/89	1.5	4400	42
3	20/06/89	1.0	4620	68
4	22/06/89	1.0	6175	51
5	23/06/89	1.0	4875	64
6	24/06/89	1.0	4355	35

4.1.1. Pre-analysis recordings

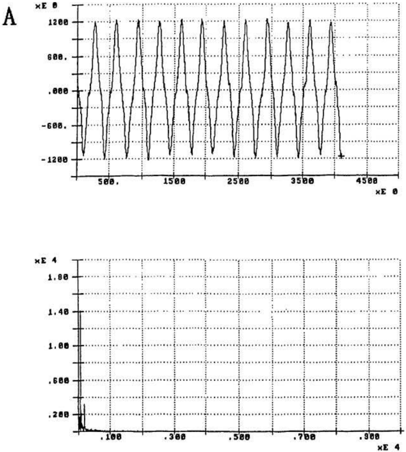
A series of five recordings are presented in Figure 3, representing a total monitored time of five hours. Weather conditions consisted of a light south-westerly wind, some occasional light precipitation (although not during the recordings), and a sea-state of 1 (as defined by the International Sea Scale). As this was the first day that the trap had been set in the water, it is assumed that the very first recording (Figure 3a), taken immediately once the fisherman's boat had returned to the harbour, was of an empty trap. However, there were already capelin in the area, easily visible from the shoreline.

The second sample (Figure 3b) was followed by a diver's inspection of the net. The diver reported that the net appeared 'full' at this time. Subsequent recordings prior to hauling (Figure 3c, d) reveal spectra similar on a gross scale (that is, the signatures of the net did not usually extend beyond 1.5 kHz, with the signal consisting of low frequencies). Figure 3d represents the pre-haul spectrum. The post-haul spectrum is illustrated in Figure 3e. It can be seen that this final recording in the series is substantially noisier, particularly in the range 100 Hz to 300 Hz. Beyond 1.5 kHz, the signal is flat and low in amplitude. It should be noted that sea state did increase slightly over the series (swell period increased from approximately 0.7 m to 1 m).

For Day 2, a set of six recordings, taken over a period of four hours, are presented in Figure C1. Weather conditions for this day consisted of occasional light rain, a light southerly wind, and a sea-state of 1. Wind and

Figure 3

Acoustic recordings from the capelin trap on Day 1. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. Recordings presented were taken at (approx.); a) 1200 hrs, b) 1300 hrs, c) 1335 hrs, d) 1405 hrs (pre-haul) and e) 1700 hrs (post-haul). Note that no low frequency spectrum was available for 1200 hrs.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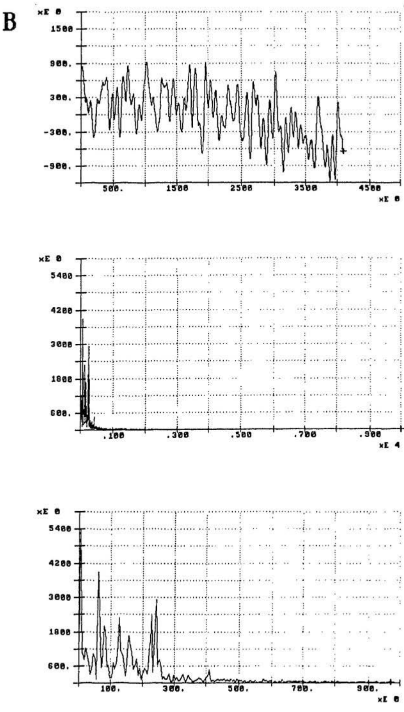
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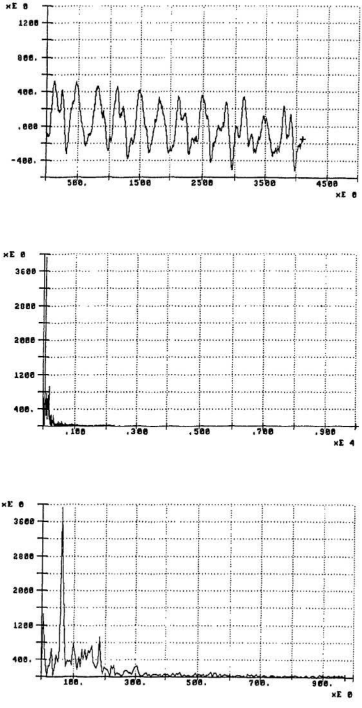
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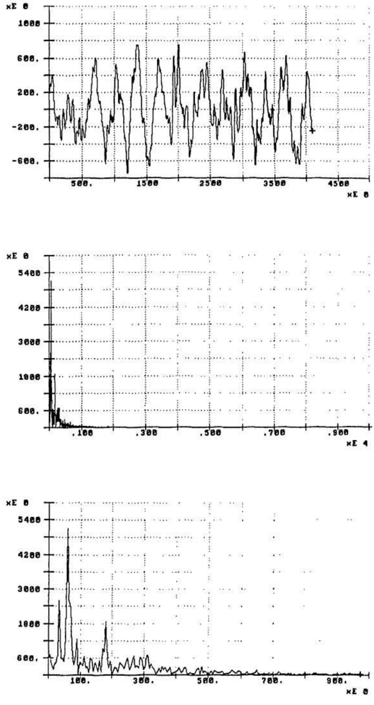
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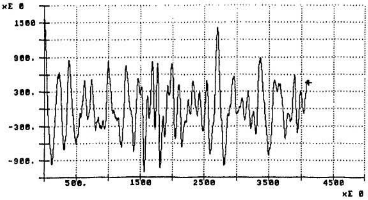
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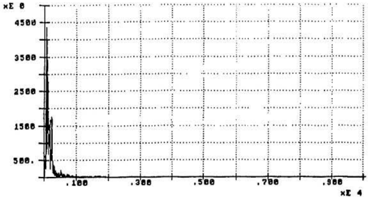
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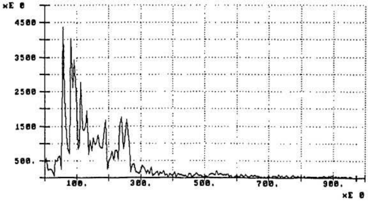
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sea-state conditions decreased slightly over the series. The evidence of precipitation is clearly shown in two recordings of the series (Figure C1a, b). These same two recordings illustrate spectra that exceed 3 kHz, likely a direct result of precipitation causing a noisier spectrum. Recordings made in the absence of precipitation (Figure C1c, d, e) are more typical of recordings made previously. The pre-haul spectrum is presented in Figure C1e, while the post-haul spectrum is shown in Figure C1f. A comparison of these latter two spectra demonstrates that the post-haul recording is noisier (despite decreasing weather conditions), especially in the range between 100 Hz and 500 Hz.

A series of three recordings are available for Day Three (see Figure C2), representing approximately 1.5 hours of monitoring time. Temporary equipment failure prevented further recording. Weather conditions included a light southerly wind, some occasional heavy rain, and a calm sea (with some scaling - sea-state 0). The presence of precipitation in the first and last recordings of the series is evident in the noisier spectra (Figure C2a, c), ranging above 3 kHz. The recording made when there was no precipitation (Figure C2b) is more typical of those taken previously. A pre-haul spectrum is shown in Figure C2c, although no post-haul spectrum is available for this series.

Good recording conditions permitted a detailed series of recordings on Day 4; a set of ten samples are shown in Figure C3, representing a total of six hours monitoring. Weather conditions were calm; the sea-state was 0, wind was light (south-westerly). There was no precipitation. Windspeed increased slightly during the recordings, although there was no obvious change in sea-state.

The majority of recordings prior to hauling (Figure C3a, b, d, g, h, i) show acoustic signatures typical to those previously recorded, with the exception of more low frequency (less than 50 Hz) components. This may have been caused, in part, by increased boat activity on this day. Three noisier spectra taken prior to hauling (Figure C3c, e, f) are more difficult to interpret. In some cases the presence of a boat in the vicinity of the trap might explain the additional noise levels. Some distortion is evident in Figure C3d; this is likely due to the power cycle.

The pre-haul spectrum is shown in Figure C3i, and the post-haul spectrum is presented in Figure C3j. The majority of the spectrum in the post-haul recording, above approximately 200 Hz, is noisier than in the pre-haul recording.

Day Five is represented by a series of four recordings (see Figure C4), sampling two hours of monitoring. Weather conditions were generally calm; the sea-state was zero, winds were light (south-westerly), and there was no precipitation. Prior to hauling (Figure C4a, b), acoustic spectra appear similar to previous days, although there are some high amplitude low frequencies. The pre-haul spectrum (Figure C4c) also demonstrates an unusual pattern of noise, similar to that produced in the presence of precipitation, although there was none in this case. The activity of a speedboat in the bay at the time of recording would explain the different signature. The pre-haul spectrum is unusually broadband when compared to previous pre-haul spectra. Alternatively, the post-haul spectrum (Figure C4d) does not exhibit the extensive broadband (up to 1 kHz in frequency) noise illustrated by previous post-haul spectra. For this series, while lower frequencies (up to 100 Hz) of the post-haul spectrum might have greater amplitude than in the pre-haul spectrum, the majority of the acoustic signal (that is, greater than 100 Hz) is quieter.

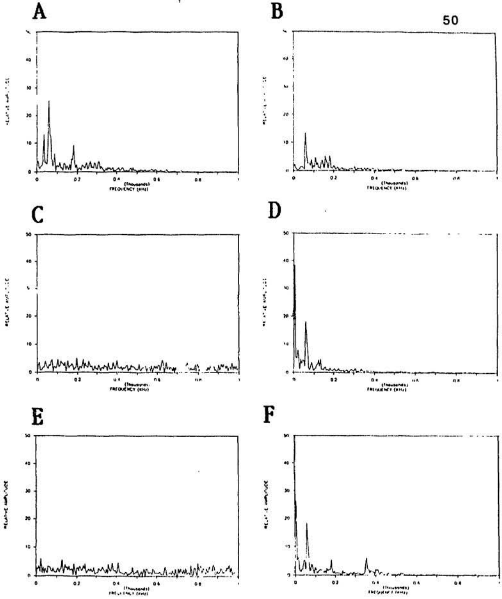
A series of two recordings are available for Day Six. Weather conditions were good, with light south-easterly winds, calm seas and no precipitation. Day Six was the final day of the capelin fishery; only one recording was possible prior to hauling. The prehaul spectrum is shown in Figure C5a, and the post-haul spectrum in Figure C5b. Amplitude levels and signal bandwidth appear to be slighly greater for the pre-haul recording, although a speedboat active in the area at time of recording might explain some of this difference, especially as there is a low frequency component to the spectrum.

4.1.2. Analysis of recordings

To ease analysis, pre-haul and post-haul spectra were re-plotted on a standard scale (Figures 4 and 5). Comparison of the six pre-haul spectra reveals similar acoustic signatures for four of the samples (Figure 4a, b, d, f). In this group of four the signal consists of a number of peaks below 0.6 kHz. Beyond this, the signal is flat, and low in amplitude. Further within this group of four, two of the signatures contain high amplitude low frequency (below 50 Hz) components. The remaining two pre-haul spectra (Figure 4c, e) are characterized by relatively wide-band signals, at least up to 1 kHz, of constant

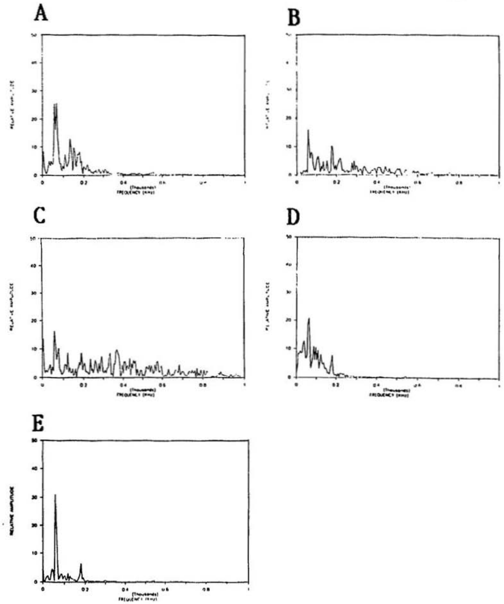
Figure 4

Acoustic recordings from the capelin trap, summarizing pre-haul samples for; a) 18/06/89, b) 19/06/89, c) 20/06/89, d) 22/06/89, e) 23/06/89 and f) 24/06/89.


A
B
C
D
E
F
RELATIVE AMPLITUDE
0
10
20
30
40
50
0
0.2
0.4
0.6
0.8
1
(Thousands)
FREQUENCY (KHz)

<u>Figure 5</u>

Acoustic recordings from the capelin trap, summarizing post-haul samples for; a) 18/06/89, b) 19/06/89, c) 22/06/89, d) 23/06/89 and e) 24/06/89. Note that no recording was available for 20/06/89.


A
B
C
D
E
RELATIVE AMPLITUDE
0
10
20
30
40
50
0
0.2
0.4
0.6
0.8
1
(Thousands)
FREQUENCY (KHz)

amplitude. The causes for the differences between these spectra are likely boat activity or weather conditions, as discussed in Section 4.1.1.

Only five post-haul spectra were available for comparison because of the lack of data for Day Three. Less similarity is exhibited between post-haul spectra than for pre-haul spectra. Generally, the signal for a post-haul spectrum is more substantial than for its corresponding pre-haul spectrum - specifically Days One, Two, and Four (Figure 5a, b, c) - both in terms of amplitude and bandwidth. Day Five is characterized by higher amplitude low frequencies (less than 200 Hz) for the post-haul spectra (Figure 5d), while the pre-haul spectrum is more broadband. Day Six shows a quieter post-haul spectrum (Figure 5e).

A semblance programme combined all pre-haul spectra into one file (Figure 6), and all post-haul spectra into a second file (Figure 7) - excluding Day 3. The semblance of the pre-haul spectra represents the "average"[1] signal of a full net, including environmental signals. The semblance of the post-haul spectra represents the "average" signal of an empty net, including environmental signals. As environmental conditions remained constant between each pre- and post-haul recording, as determined by the environmental log, the only physical diference between these two averages is

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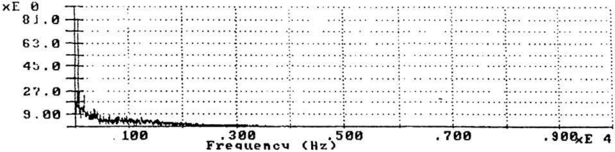
[1] The use of the word 'average' is an unfortunate misnomer. While it is true that the semblance programme by its nature will enhance and emphasize common frequencies through their addition, the final semblance file is in fact a total of all the frequencies added together. A 'true' average would be obtained by dividing each element in this file by the number of component spectra.

Figure 6

An acoustic semblance of all pre-haul recordings (excluding Day 3) from the capelin trap. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz.


xE 0
81.0
63.0
45.0
27.0
9.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)

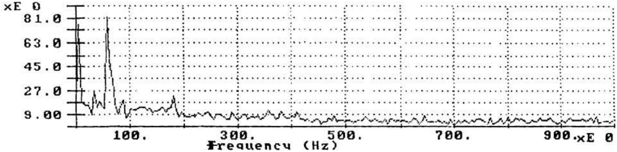
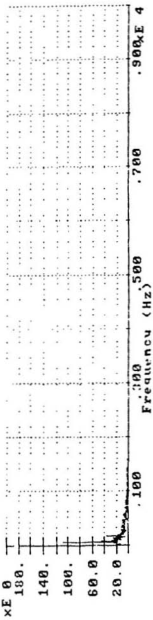
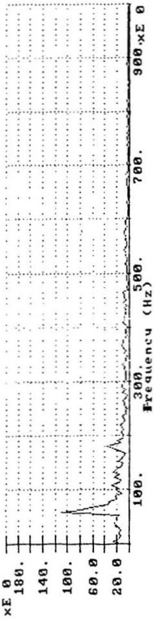

xE 0
81.0
63.0
45.0
27.0
9.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

Figure 7

An acoustic semblance of all post-haul recordings (excluding Day 3) from the capelin trap. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz.


xE 0
180.
140.
100.
60.0
20.0
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)


xE 0
180.
140.
100.
60.0
20.0
100.
300.
500.
700.
900. xE 0
Frequency (Hz)

the presence of capelin in the pre-haul spectrum. A subtraction programme removed the effect of the post-haul spectra from the pre-haul spectra. In this way, a spectrum of the acoustic signature caused by a capelin school could be estimated, as seen in Figure 8.

The acoustic signature that is attributable to a capelin school extends as far as 3 kHz, although the highest amplitudes in the signature are concentrated in a band between 1 kHz and 2 kHz. Figure 8 also shows that below 0.6 kHz, the signature is predominantly negative - meaning that for this range, on average, the post-haul spectra were louder than the pre-haul spectra.

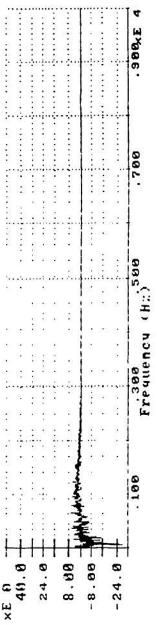
4.2. The acoustics of various net types

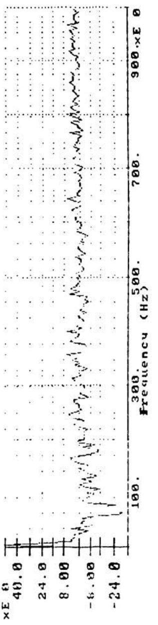
The interpretation of the net sample results should be made in the context of the same considerations as listed in Section 4.1.1., as the same equipment was used for this experiment as for the capelin trap recordings, and as the experimentation was performed at the same site.

For each net sample tested, there are a series of four recordings: the first two represent a control reading to account for environmental conditions and system self-noise that day, while the second two recordings represent experimental readings with the net sample in place. A total of four cod trap types, two gillnet types (one mono- and one multi-filament), and one capelin trap type were sampled. In cases when more than one sample of net type was available, mesh and twine characteristics were varied. Physical

Figure 8

The acoustic spectrum resulting from a subtraction of the post-haul semblance from the pre-haul semblance, estimating the acoustic component of the capelin school contained within the trap. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz.


xE 0
40.0
24.0
8.00
-8.00
-24.0
.100
.300
.500
.700
.900xE 4
Frequency (Hz)


xE 0
40.0
24.0
8.00
-8.00
-24.0
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

characteristics of the net samples used, including calculations of solidity as demonstrated in Appendix B, are shown in Table 2.

4.2.1. Pre-analysis of net samples

Although all four cod trap series are descibed here, only one series - Day 1 (c2) - is presented. The remaining three series can be found in Appendix C.

Day One weather conditions were calm with a slight swell, light south-westerly winds, and no precipitation. Control readings are presented in Figure 9, while experimental readings for the first cod trap sample (c2) are shown in Figure 10. Figure 9 shows relatively similar system self-noise curves, with the signature consisting of frequencies below 1 kHz; beyond this point, the signature is flat and low in amplitude. Figure 10 shows a comparable set of spectra (allowing for differences in scale); the twin peaks at approximately 120 Hz, as shown in Figure 10b, are probably due to harmonics of the power cycle. The second experimental reading indicates larger amplitudes than the first experimental reading.

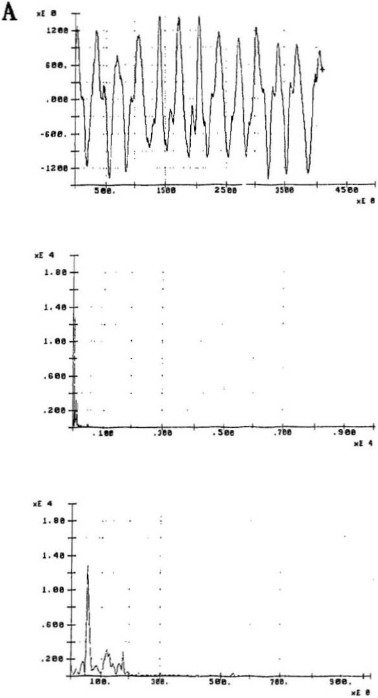
The second cod trap sample (c1) was tested on Day Two. Weather conditions consisted of light to moderate south-westerly winds, no precipitation, and a sea-state of 1. The two control readings (Figure C6) are similar in character. The experimental readings (Figure C7) show a slightly amplitude reduced spectrum in comparison to the control readings.

Table 2. Physical characteristics of net samples used.

Type	Mass/unit area (gm.m^{-2})	Number of twines in thread	Mesh size (m)	Diameter of thread (mm)	Solidity per unit area (cm^2)
Cod trap (c1)	74	3	0.21	1.78	1060
Cod trap (c2)	54	3	0.23	1.26	690
Cod trap (c3)	46	3	0.16	1.38	1080
Cod trap (c4)	64	4	0.10	1.23	1550
Herring net (h1)	7	3	0.175	0.60	430
Gillnet (g1)	1	1	0.245	0.58	290
Capelin trap (ct1)	180	3	0.020	0.97	6070

Figure 9

Control readings for the cod trap sample c2. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1000 hrs and b) 1030 hrs.


A
xE 0
1200
600.
.000
-600.
-1200
500.
1500
2500
3500
4500
xE 0
xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4
xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

B

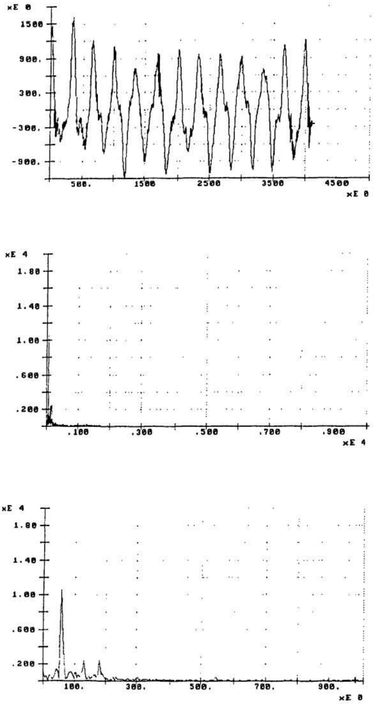
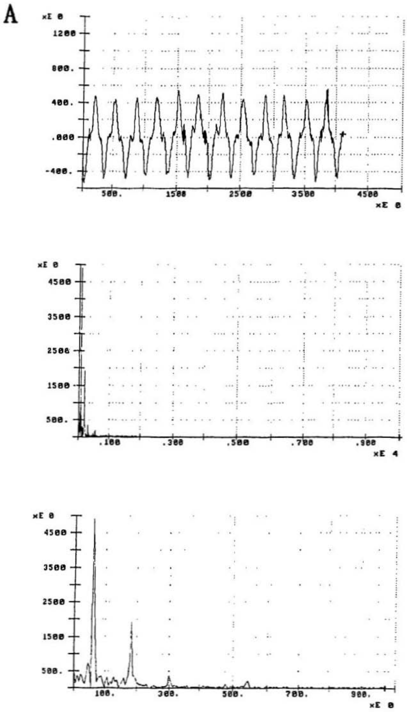
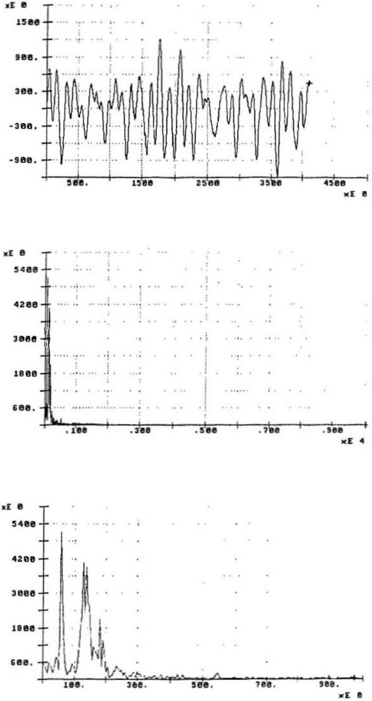

xE 0
1500
900.
300.
-300.
-900.
500.
1500
2500
3500
4500
xE 0
xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4
xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

Figure 10

Experimental readings for the cod trap sample c2. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1730 hrs and b) 1800 hrs.


A
xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

B


xE 0
1500
900.
300.
-300.
-900.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

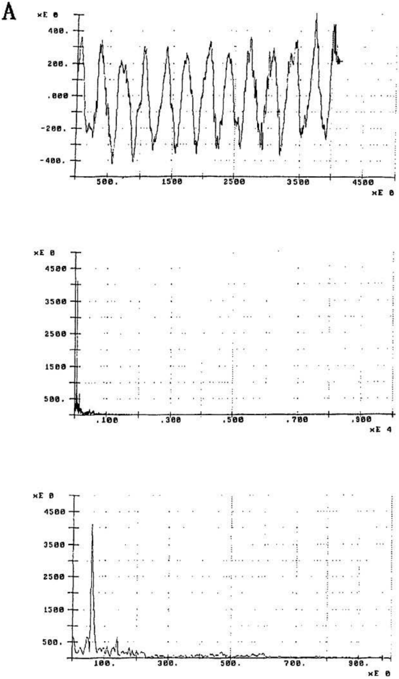
On Day Three the third cod trap sample (c4) was tested. Environmental conditions were basically calm, with light to moderate south-westerly winds, and no precipitation; waves exhibited a light chop, 0.5 m in height. Figure C8 shows the two control readings, while Figure C9 shows the two experimental readings. The first control reading (Figure C8a) shows lower amplitudes than the second control reading (Figure C8b), particularly in the region 100 Hz to 300 Hz. In both cases the majority of the signal is below 500 Hz. Although the two experimental readings are similar in character (Figure C9a, b), they also show a slight reduction in signal amplitude in comparison to the control readings. There was a decrease in sea-state that may have decreased noise levels.

The final cod trap sample (c3) was tested on Day Four. Weather conditions were milder than the previous day, with light south-westerly winds, no precipitation and a calm sea. Control readings are shown in Figure C10, while experimental readings are presented in Figure C11. The two control readings are basically the same acoustic signature. The addition of the net sample slightly increased the low frequency component of the spectrum - otherwise there was little change between the experimental recordings and the control readings.

The multifilament gillnet (h1) was tested on Day Five. Environmental conditions consisted of light to moderate south-westerly winds, no precipitation, and a sea-state of 1. Figure 11 illustrates the control readings, while Figure 12 shows the experimental readings. The first control reading (Figure 11a) shows higher amplitudes, but the basic signature is preserved in the second control

Figure 11

Control readings for the multi-filament sample h1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 0945 hrs and b) 1015 hrs.


A
xE 0
400.
200.
.000
-200.
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

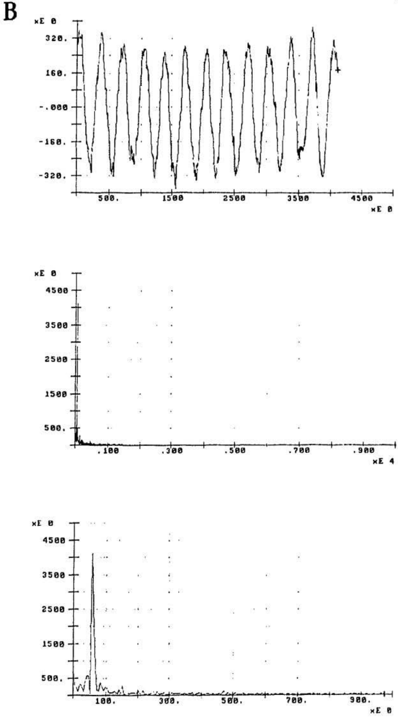
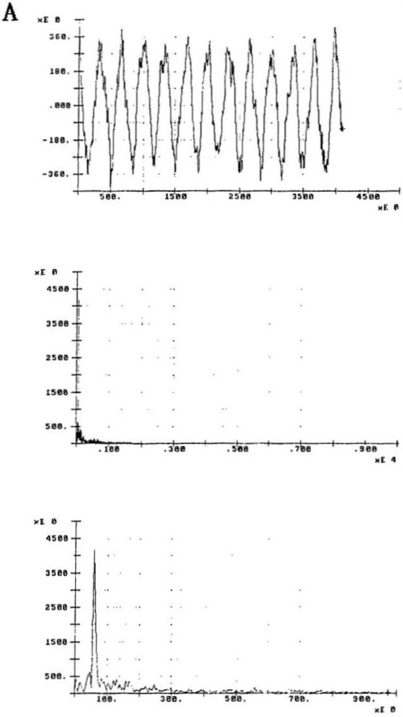
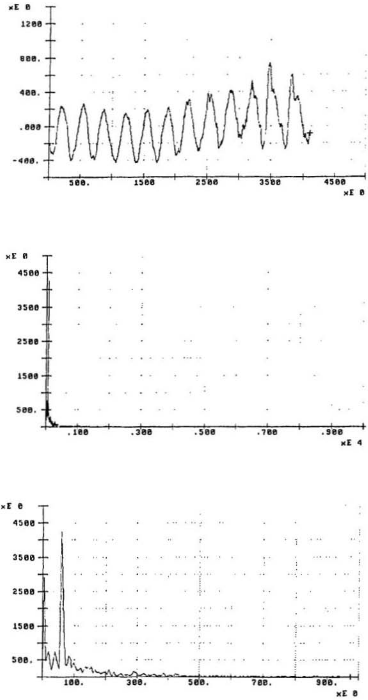

B
xE 0
320.
160.
-.000
-160.
-320.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

Figure 12

Experimental readings for the multi-filament sample h1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1130 hrs and b) 1200 hrs.


A
xE 0
360.
180.
.000
-180.
-360.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

B


xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

reading (Figure 11b). Experimental readings show an increase in signal amplitude, particularly in the second recording in the low frequency area (Figure 12b). It was noted that wind and sea-state conditions were increasing slightly during the period of the experimental recordings. This would account for the absence of a similar low frequency peak in the first experimental recording (Figure 12a)

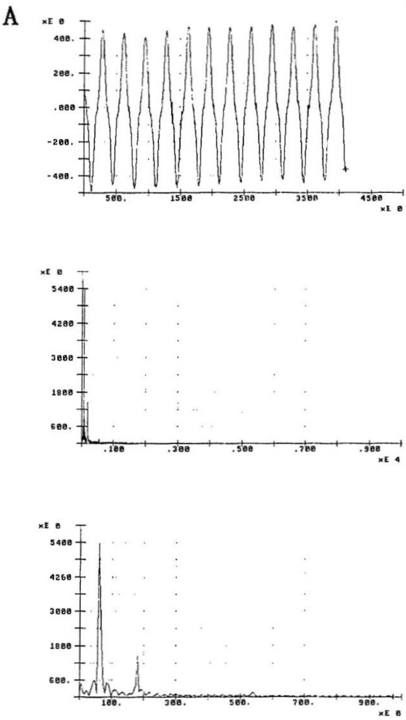
On Day Six, the monofilament gillnet (g1) was tested. Sea-state conditions were calm, with light south-westerly winds, and no precipitation. The control readings are presented in Figure 13; experimental readings are given in Figure 14. The second control reading (Figure 13b) shows higher amplitudes of signal in a broader band, extending up to 3 kHz in frequency, which correlates with the presence of a speedboat in the area at time of recording. The experimental readings show a further increase in signal, particularly between 100 - 200 Hz (Figure 14a, b).

The capelin trap sample (ct1) was tested on Day Seven. Testing conditions were calm, no wind, and no precipitation. Control readings are shown in Figure 15, while experimental readings are given in Figure 16. In the control readings, the first recording (Figure 15a) is louder than the second (Figure 15b).

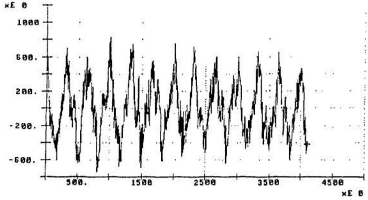
The addition of the net sample produced a very different spectral sample (Figure 16a, b). In both cases, the signature extends above 3 kHz, with a substantially different character compared to control readings.

Figure 13

Control readings for the mono-filament sample g1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1145 hrs and b) 1250 hrs.


A
xE 0
400.
200.
.000
-200.
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4260
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

B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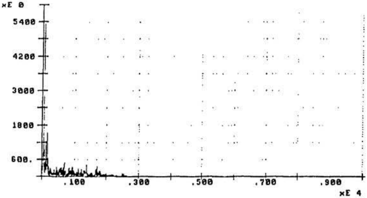
1000
600.
200.
-200.
-600.
500.
1500
2500
3500
4500
xE 0


xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4

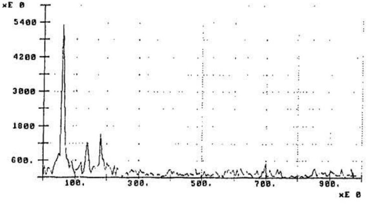
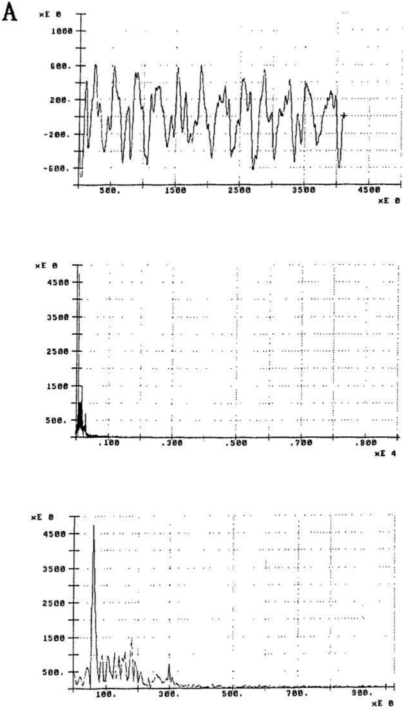

xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

Figure 14

Experimental readings for the mono-filament sample g1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1430 hrs and b) 1500 hrs.


A
xE 0
1000
600.
200.
-200.
-600.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

B

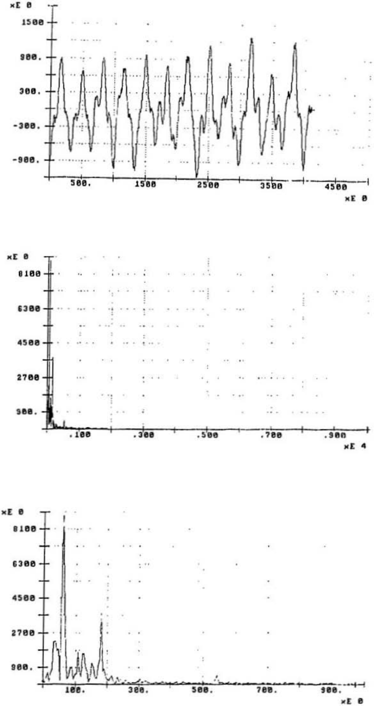
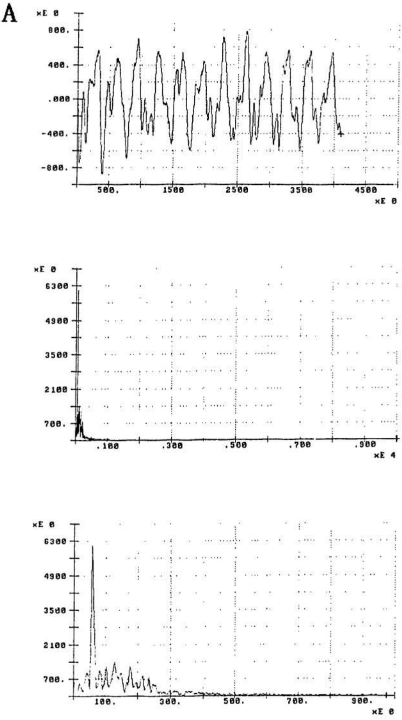

×E 0
1500
900.
300.
-300.
-900.
500.
1500
2500
3500
4500
×E 0
×E 0
8100
6300
4500
2700
900.
.100
.300
.500
.700
.900
×E 4
×E 0
8100
6300
4500
2700
900.
100.
300.
500.
700.
900.
×E 0

Figure 15

Control readings for the capelin trap sample ct1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1130 hrs and b) 1200 hrs.


A
×E 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
×E 0
×E 0
6300
4900
3500
2100
700.
.100
.300
.500
.700
.900
×E 4
×E 0
6300
4900
3500
2100
700.
100.
300.
500.
700.
900.
×E 0

B

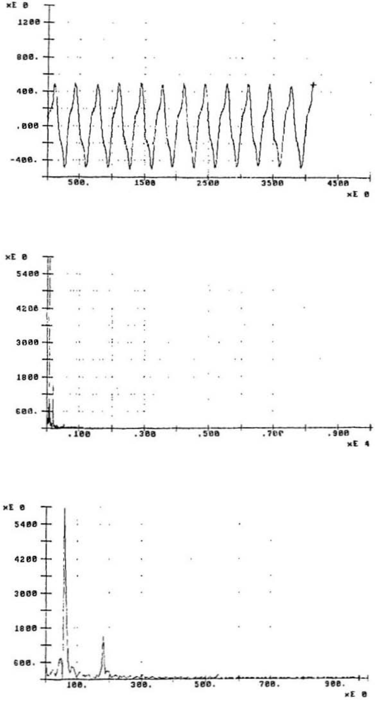
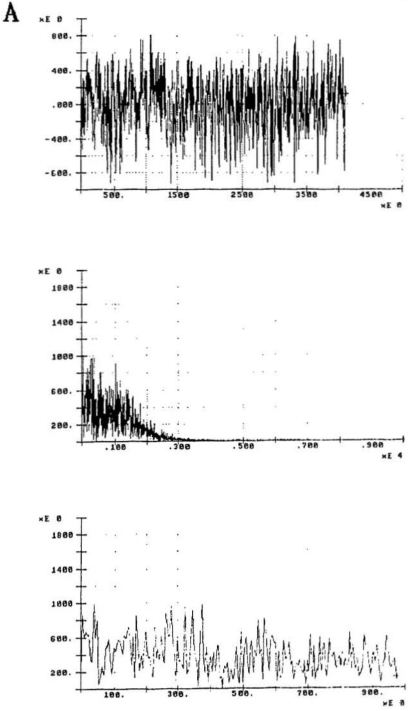
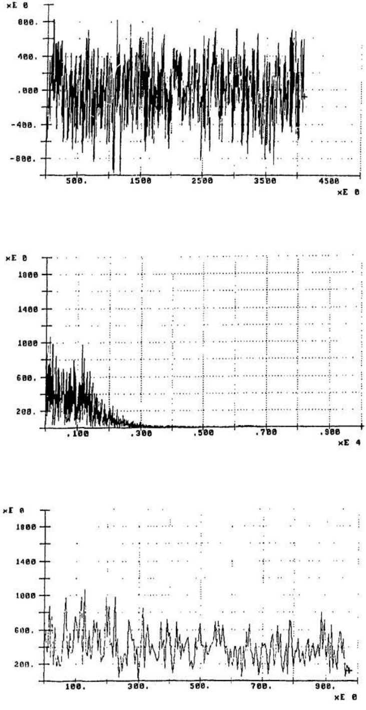

xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

Figure 16

Experimental readings for the capelin trap sample ct1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1330 hrs and b) 1400 hrs.


A
xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4
xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

B


xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4
xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

4.2.2. Analysis of recordings

A semblance programme constructed "average" control and experimental readings for each net sample. For the cod trap samples, the control semblance for c2 is shown in Figure 17a, with the experimental semblance in Figure 17b. The remaining cod trap series - c1, c3 and c4 - are shown in Figures C12a, C13a, and C14a for the control semblances, and Figures C12b, C13b and C14b for the experimental semblances, respectively. A fifth series of semblances for the cod trap samples was created by running a semblance programme on all control readings for cod traps (Figure 18a), and for all the experimental recordings for cod traps (Figure 18b).

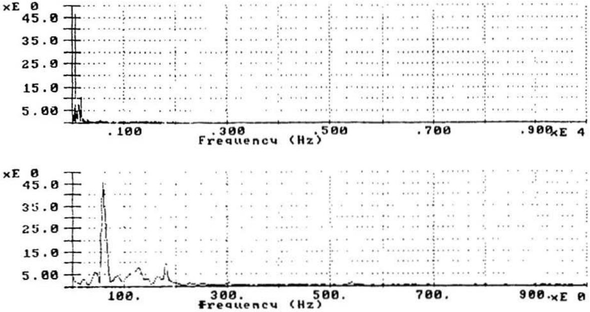
The control semblances for the gillnet samples (g1 and h1) are shown in Figures 19a and 20a respectively. Experimental semblances for these nets are presented in Figures 19b and 20b respectively. The control semblance for the capelin trap sample (ct1) is given in Figure 21a, and the experimental semblance is shown in Figure 21b.

For each net sample, the control readings were composed of noise from the environment and system self-noise, while the experimental recordings were composed of noise from the environment, system self-noise and the net sample. Environmental conditions remained similar for each series of recordings; thus it can be assumed that ambient noise would be constant for any one particular experiment. Any differences between control and experimental

Figure 17

Constructed semblances for the cod trap sample c2. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.

A


xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

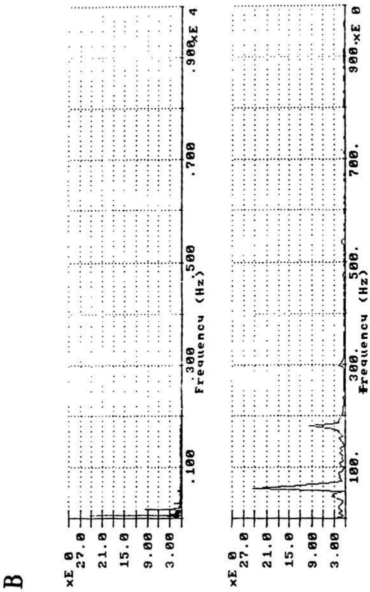
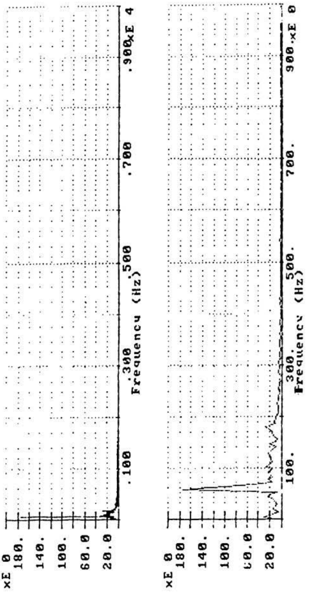

B
xE 0
27.0
21.0
15.0
9.00
3.00
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
27.0
21.0
15.0
9.00
3.00
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

Figure 18

Constructed semblances for a composite cod trap sample, combining all control samples and all experimental samples. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.

A


xE 0
180.
140.
100.
60.0
20.0
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
180.
140.
100.
60.0
20.0
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

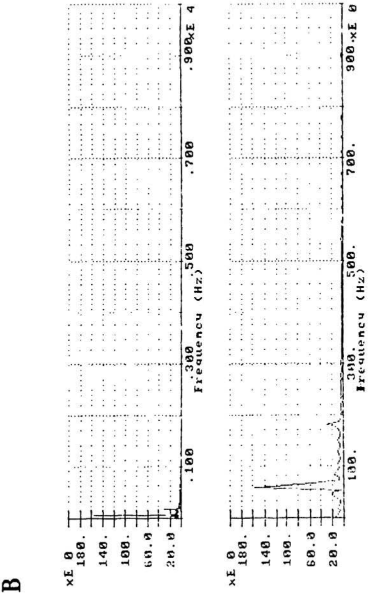
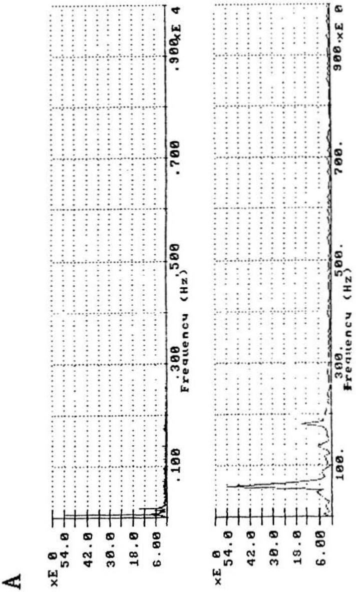

B
xE 0
180.
140.
100.
60.0
20.0
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
180.
140.
100.
60.0
20.0
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

Figure 19

Constructed semblances for the mono-filament gillnet sample g1. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.


A
xE 0
54.0
42.0
30.0
18.0
6.00
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)
xE 0
54.0
42.0
30.0
18.0
6.00
100.
300.
500.
700.
900. xE 0
Frequency (Hz)

B

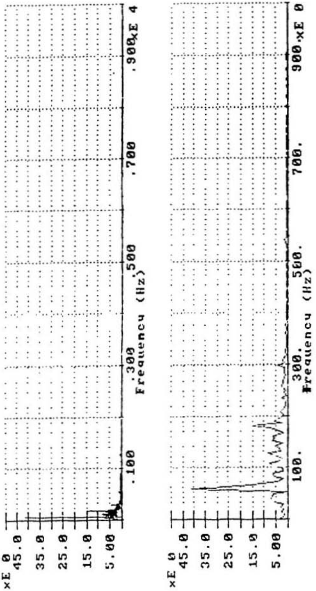
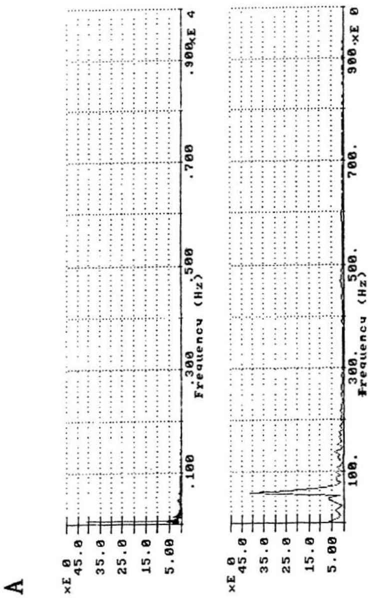

×E 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900
×E 4
Frequency (Hz)
×E 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.
×E 0
Frequency (Hz)

Figure 20

Constructed semblances for the multi-filament gillnet sample h1. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.


A
xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

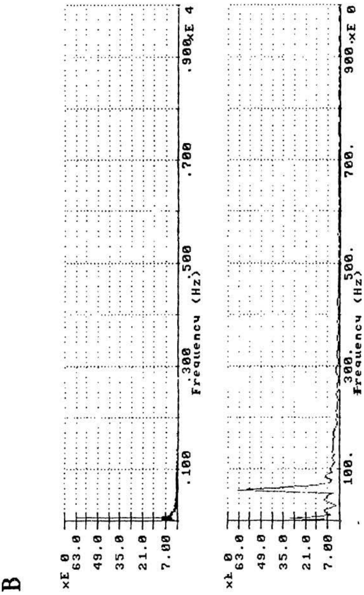
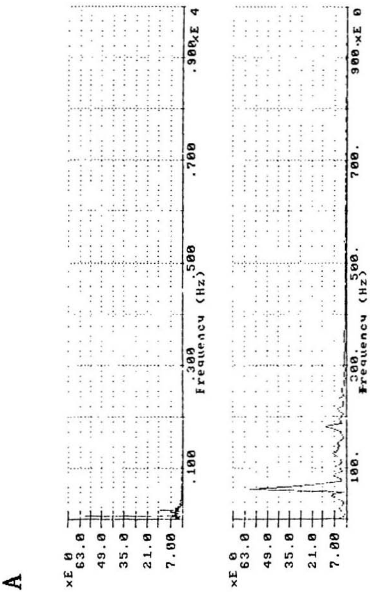
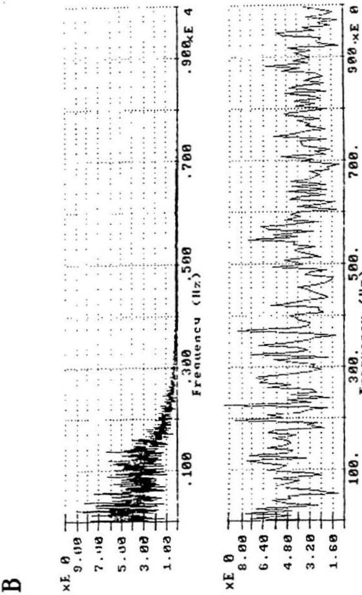

B
xE 0
63.0
49.0
35.0
21.0
7.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
x1 0
63.0
49.0
35.0
21.0
7.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

Figure 21

Constructed semblances for the capelin trap sample ct1. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.


A
xE 0
63.0
49.0
35.0
21.0
7.00
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
63.0
49.0
35.0
21.0
7.00
100.
300.
500.
700.
900.xE 0
Frequency (Hz)


B
xE 0
9.00
7.00
5.00
3.00
1.00
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)
xE 0
8.00
6.40
4.80
3.20
1.60
100.
300.
500.
700.
900. xE 0
Frequency (Hz)

readings were therefore caused by the net sample itself, plus interactions between the three components.

A subtraction programme estimated the acoustic contribution of each net sample, by subtracting the control semblance from the experimental semblance for each net type. The subtractions files can be seen in Figure 22 (for cod trap samples), Figure 23 (for gillnet samples), and Figure 24 (for the capelin trap sample).

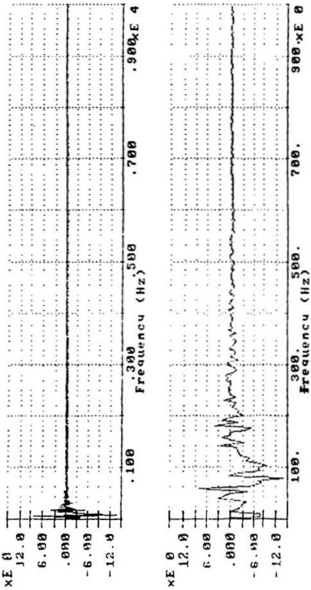
It should be noted that amplitude (on the y-axis scale) is relative when comparing these last three figures. The zero datum line does have an application in that any plot beneath this line represents a lack of that particular frequency in the acoustic signature of that particular net sample. Alternatively, any plot above this datum indicates that the specific frequency constitutes part of the acoustic signature.

The cod trap samples demonstrate mostly negative signatures (see Figure 22a, b, c, d), with the exception of c3 (Figure 22c). It has already been noted, however, that the presence of boat activity may account for the some additional low frequency activity in this particular sample. In the majority of cases, again excluding c3, the acoustic signal consists of low frequencies up to 1 kHz. The composite cod trap signature (Figure 22e) shows a spectrum that is predominantly negative. This estimation represents the sound signals from four nets together; it is presented here only to demonstrate the shape of the spectral curve.

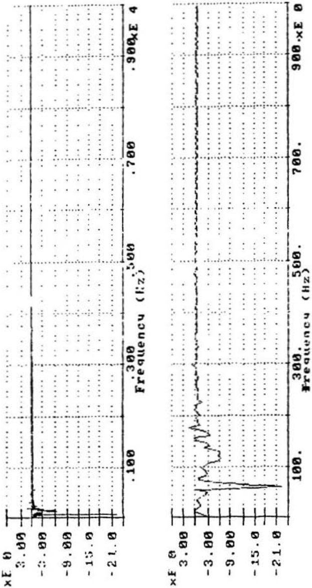
Figure 22

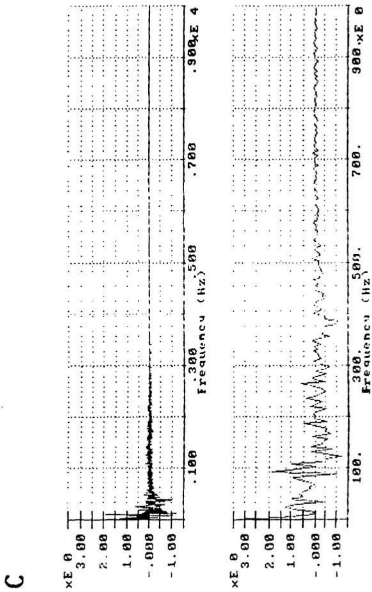
Constructed subtraction files for the cod trap samples. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) c1, b) c2, c) c3, d) c4 and e) composite cod trap (see text).

A

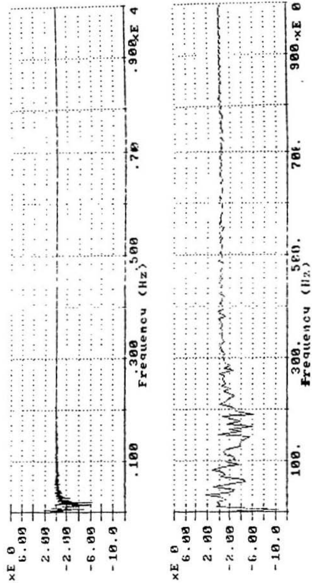

xE 0
12.0
6.00
.000
-6.00
-12.0
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
12.0
6.00
.000
-6.00
-12.0
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

B


xE 0
3.00
-3.00
-9.00
-15.0
-21.0
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)
xE 0
3.00
-3.00
-9.00
-15.0
-21.0
100.
300.
500.
700.
900. xE 0
Frequency (Hz)


C
xE 0
3.00
2.00
1.00
-.000
-1.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
3.00
2.00
1.00
-.000
-1.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

D


xE 0
6.00
2.00
-2.00
-6.00
-10.0
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
6.00
2.00
-2.00
-6.00
-10.0
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

E

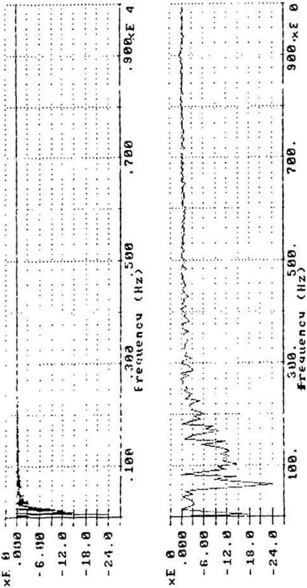
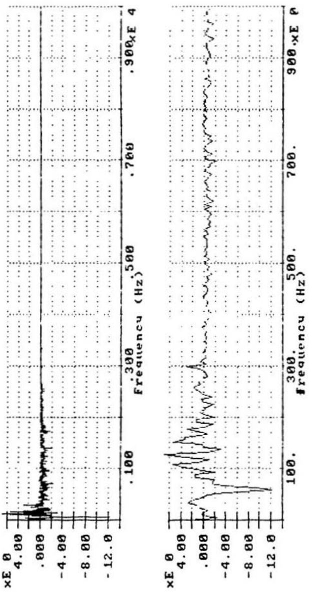

xE 0
.000
-6.00
-12.0
-18.0
-24.0
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)
xE 0
.000
-6.00
-12.0
-18.0
-24.0
100.
300.
500.
700.
900. xE 0
Frequency (Hz)

Figure 23

Constructed subtraction files for the gillnet samples. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) g1, and b) h1.

A


xE 0
4.00
.000
-4.00
-8.00
-12.0
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
4.00
.000
-4.00
-8.00
-12.0
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

B

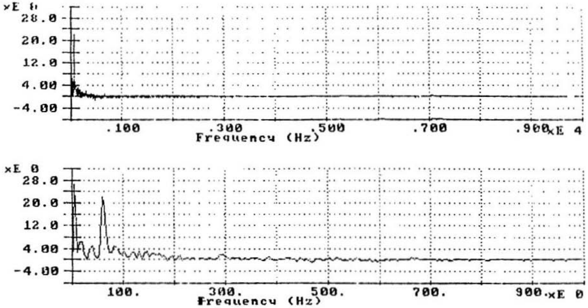
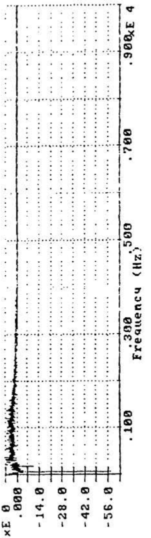
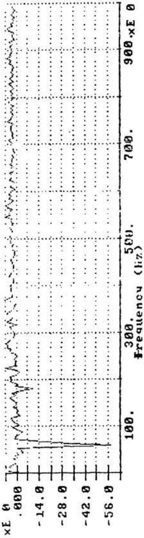

xE 0
28.0
20.0
12.0
4.00
-4.00
.100
.300
.500
.700
.900 xE 4
Frequency (Hz)
xE 0
28.0
20.0
12.0
4.00
-4.00
100.
300.
500.
700.
900. xE 0
Frequency (Hz)

Figure 24

Constructed subtraction files for the capelin trap samples. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz.


xE 0
.000
-14.0
-28.0
-42.0
-56.0
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)


xE 0
.000
-14.0
-28.0
-42.0
-56.0
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

The gillnet spectra (Figure 23) are different in that the signature is of a higher amplitude. The mono-filament gillnet (g1 - see Figure 23a) in particular shows peak frequencies in the range 100 Hz to 300 Hz, although the majority of these may be due to power cycle harmonics. Some exceptionally low frequency activity is evident in the multi-filament net (h1 - see Figure 23b). While the mono-filament net's spectrum is rather more broadband, extending beyond 2 kHz, the multi-filament net's signal does not exceed 1 kHz in frequency.

The most obvious signature is produced by the capelin trap sample (ct1 - Figure 24). The signal is broadband, extending beyond 2 kHz, maintaining a flat residual up to 1.5 kHz.

5. Discussion

5.1. Assessment of the measurement technique

On a gross scale, spectra taken generally had a similar shape. The majority of the signal in the spectra was usually concentrated below 1 kHz, with signal amplitude decreasing as frequency increased; any signal beyond 1 kHz was generally flat, and low in amplitude. As it is likely that ambient noise will constitute the major component in these recordings, the general shape observed here is not unusual. Higher frequencies will be attenuated more rapidly - signals rarely exceeded 2 kHz. Wenz (1962) demonstrated that beyond 1 kHz, the primary factors affecting the shape and strength of the ambient noise curve are meteorological influences. Weather conditions were relatively calm during experimentation; therefore, the noise curve will not show much activity beyond 1 kHz.

Examination on a finer scale reveals that there were noticeable differences between spectra. It can be assumed that these changes in spectral character would be due to: a) changes in ambient noise conditions, b) acoustic changes in the measurement system, or c) acoustic changes in the net system being monitored (as measured by the experiment).

A comparative analysis to identify trends across different acoustic signatures remains a valid and informative exercise, as the equipment has been referenced to a source level (although admittedly this level is not known).

Ambient noise is highly variable (Wenz, 1962). Factors that affect ambient noise were monitored; in certain cases, their effect on the ambient noise curve were easily detected. The presence of precipitation in particular produced an obvious change in spectral character (as seen in Figures C1a, C1b, C2a, and C2c). During periods of rain, time series taken became noisier in nature. The signal also became more broadband, extending (in some cases) up to 7 kHz. Forbes, and Smock (1981) noted that during times of heavy rain, frequencies ranging from 200 Hz to 40 kHz can be affected. The presence of a boat in the recording area was also noticeable (see Figures C3c, C3e, C3f, C3j, and C4c).

It is convenient to discuss the 60 Hz power cycle as part of the ambient noise character of the bay, as it was present in all recordings in St. Phillip's. Its dominating presence was unexpected. As noted previously, the 60 Hz peak and the consequential harmonics at 120, 180, 240, and 300 Hz (as well as higher strata) must be allowed for when interpreting any of the spectra. However, the presence of a signal at these particular frequencies is a constant that can easily be allowed for.

The existence of the power cycle in most, if not all, recordings made at St. Phillip's is particularly relevant when considering spectral files as created by the semblance and subtraction programmes. Spectral input into such programmes would include a assessment of the power cycle's contribution to the overall spectrum at that specific time. Given the temporal variation in amplitude of any cyclic wave, it is unlikely that the spectral peaks due to the power cycle will be directly comparable between spectra, unless the recordings being compared were taken at identical points during the cycle (which is not probable). While the subtraction programme might aid in eliminating common environmental frequencies, it will not consistently reduce the contribution of the power cycle to the overall spectra.

It can be assumed that the subtraction programme removed the effect of ambient noise from a spectrum, however, as environmental conditions remained constant. Therefore, if there are any differences between spectra as recorded, it is probable that these changes are caused by physical/acoustic changes in the target being measured.

5.2. The acoustics of bait and capelin traps

The dominating factor that caused deviations in spectra taken were changes in the net and its catch. In comparing pre- and post-haul spectra, it is more useful to compare on a daily basis, as it is unlikely that environmental conditions varied significantly within a series of measurements. Ambient noise conditions may have changed slightly between series.

In comparing pre-haul and post-haul spectra, it can be seen that there are differences in spectral character between an empty and a full net. Generally, a full net appears to be quieter and narrower band in energy, while an empty net has more noisier, flatter, and broader in band (for example, compare

Figures 4a and 5a for Day 1; Figures 4b and 5b for Day 2; Figures 4d and 5c for Day 4; Figures 4e and 5d for Day 5, at least in the lower frequencies).

Three of the series do not absolutely follow this generality. For the Day 4 recordings, while the post-haul file (Figure 5c) is for the majority of the spectrum higher in amplitude, the pre-haul (Figure 4d) does show an unusually high amplitude low frequency component. In the case of Day 5, the post-haul spectra (Figure 5d) shows some low frequency activity, while the pre-haul spectra (Figure 4e) is more broadband. Finally, one of the series (Day 6) shows the reverse in trend; the pre-haul spectrum (Figure 4f) is noisier than the post-haul spectrum (Figure 5e). This was likely due to the presence of a speedboat during post-haul recordings.

Generally, however, the six pre-haul (Figure 4) and five post-haul (Figure 5) spectra reveal definite changes in the acoustic signature of a capelin trap when full and when empty. Given that environmental conditions may vary slightly on a per day basis, it may nevertheless be valuable to compare semblances of pre- and post-haul spectra (Figures 6 and 7 respectively). Comparing these two spectra, it can be seen that the pre-haul spectra is generally larger in amplitude, and more broad band, extending beyond 3 kHz in frequency, with the majority of the signal within a 1 kHz band focussed in the lower frequencies. The post-haul spectrum, in contrast, only extends to 1 kHz in frequency. The signal's highest amplitudes occur up to 500 Hz .

The data imply that a full net is in fact quieter than an empty net. This seems to be in contrast to what would be expected; that the noise of the fish, together with any noise produced by an empty net, would cause a full net to have a more substantial acoustic signature. Instead, it would appear that the presence of capelin acts to dampen noise as produced by a net.

Net noise can be generated in two ways: by interactions within the frame system itself, and by interactions between the net and the surrounding medium. Within the framing system, certain parts of the net may be hitting other parts, creating 'knocks' or 'bangs'. This would be particularly significant if those parts were metal (for example, links on an anchor chain). Such pulsive noises would increase when the net is agitated in some way (for example, by wave action).

Second, the hydrodynamic nature of a net causes high levels of drag when subjected to a current. Micro-turbulence might be expected in the vicinity of the net/water interface. The resultant eddies and backwash would create noise, from a 'streaming' effect. Also, some of the trap's framelines, set under some tension, might vibrate at particular resonant frequencies when subjected to a current. As capelin traps are always placed close to shore, some tidal current is typically present (except at slack water), and thus streaming will occur for a majority of the time. Volume of noise created would be greatest when the current the net is subjected to is at its highest. While the first method of net noise production might be considered sporadic, dependent on a particular combination of conditions, this second method of production would occur constantly in a cyclic fashion corresponding to the strength of the tide and/or other currents in the area.

It has been shown, however, that the presence of capelin substantially reduces the amplitude of the acoustic signature of a net. There are two reasons why a school of bait would do this. First, the school, as a large body of suspended particles within a transmitting medium, would act to scatter and absorb any sound produced by the net. Second, rather than dampen an acoustic signal already produced, the school would inhibit the production of net noise by changing the hydrodynamics of the net. In underwater observation, capelin traps are often seen to physically distort because of the large number of fish they contain. If a school were placed directly on the inside face of a net panel experiencing some form of current, tidal flush through the net would be reduced, thus decreasing the streaming effect, and consequently, the acoustic signature produced.

The file that resulted from the subtraction of the post-haul spectra from the pre-haul spectra (Figure 8) shows the residual signal caused by the presence of the capelin. It should be remembered that this file is the result of the addition of five separate hauls taken in a period of time in which environmental conditions may have changed (although not to any great extent). Therefore, it is more useful to use this file to describe the general shape of an acoustic signature as produced by capelin, as opposed to a definitive characterization of a capelin school's signature. The fact that the presence of a capelin school dampens the sound produced by a net is shown by the predominantly negative signature, at least up to 1 kHz. Beyond this frequency, the signature is largely positive, up to approximately 3 kHz. This suggests that while capelin may act to alter the low frequencies produced by a net, they do produce a signature between 1 - 3 kHz.

Large numbers of capelin would probably make a more substantial acoustic contribution than smaller schools capelin. Similarly, one might expect differing gender ratios within schools being measured to have a different acoustic effect, because of morphological differences between male and female capelin (for example, the shape of the gas-filled swimbladder in the female changes as it is displaced by the maturing ovaries; Todd, unpub. data). It was not possible, at least from this research, to separate out the effects of gender or size of school, because of the low sample size collected, and because of the unavoidable interaction between the two variables that could not be isolated. In a more ideal experiment one factor would be controlled while the other was varied. It was clearly not feasible to manipulate these variables in this case. Later experimentation in a more controlled setting suggested male capelin produced a louder spectrum than female capelin, although no correlation was found between number of fish and strength of signal, for either gender (Todd, unpub. data).

5.3. The acoustics of net types

Given the problems of interpreting data files with the predominance of an unwanted 60 Hz power cycle, and variations due to changes in the ambient noise environment, the exercise of comparing different net signatures as shown in Figures 22 (c1, c2, c3, and c4), 23 (g1 and h1), and 24 (ct1) is still a valuable one. It is clear that different types of nets produce different types of signature.

It has been shown that capelin mesh produces a broad band acoustic signature, detectable up to approximately 2 kHz. Two possible mechanisms of net self-noise production have also been suggested. Given that primary noise production would involve streaming effects created by the drag of the net, nets of different drag values might vary in the type and strength of signature produced. Further, it might also be postulated that nets of the highest drag produce the strongest acoustic signal, when compared to nets of low drag. The drag of a net is proportional to the surface area exposed to the current (Baranov, 1976). In turn, the surface area exposed of a net, or its solidity (surface area exposed per unit area) is inversely proportional to the the mesh size and proportional to twine diameter (see Appendix B). As mesh size decreases, drag increases (Baranov, 1976). There are further complications to this relationship as caused by smoothness of the the twine, and the size of the knots in the mesh. However, at present these can only be empirically solved (Baranov, 1976).

Cod traps, even though they are extremely large installations, appear to produce very little signature in comparison to other nets. For all net samples, the signal does not exceed 500 Hz; beyond this point, the signal is weak and flat in response. Net sample c3 had the strongest signature (Figure 22c) in terms of amplitude across the spectrum analysed; it also had the second smallest mesh size and the second largest solidity of the cod trap samples. The quietest net, c2 (Figure 22b), had the largest mesh size, and just over half the solidity of c3. Thus cod trap mesh can be characterized as a narrow band, low frequency, weak signal, as shown in the composite subtraction file (Figure 22e).

Gillnet acoustic signatures are louder when compared to cod trap signals. The mono-filament sample (g1, see Figure 23a) shows high signal amplitudes energy up to 300 Hz. Some of these peaks can be attributed to power cycle infiltration; others cannot. The multi-filament gillnet (h1, see Figure 23b) shows a similar amplitude spectrum, with the exception of two outstanding peaks - one at less than 10 Hz, and one at 60 Hz (approx.). The second of these two peaks is obviously caused by a particularly high point in the power cycle.

One might expect differences in smoothness in twine fibre to affect noise level, because: a) smoother twines would result in less surface area, and b) smoother twines present less of a friction coefficient to form eddies (Baranov, 1976). The two gillnet samples tested had solidities of approximately the same magnitude (Table Two), although it should be noted that the calculation of solidity makes no correction for smoothness of fibre (see Appendix B). The multi-filament net was made from three twines wound into a single core, whereas the mono-filament net was constructed of one smooth molded nylon fibre. One can expect, therefore, that the mono-filament's smoother twine might have an effect on amount of drag the net produced.

The fact that the multi-filament net had a slightly higher solidity than mono-filament net explains the slightly higher amplitude signature. Both gillnets were louder than any of the cod trap samples. One explanation for the gillnets' noise might be that they are lighter in mass (see Table 2). Increased flexibility could result in more noise production within the net itself - by mesh doubling back and rubbing against itself, for example. Such net interactions would probably be low frequency in nature (pers. obs.).

The acoustic signature produced by the capelin trap sample was radically different from the other net samples measured. The broad band, relatively high amplitude signature is not seen in any other sample. The capelin trap sample had the smallest mesh size, densest twine, and highest solidity (just under four times higher than the cod trap with greatest solidity), which correlates with the sample also having the most noticeable signature.

Summarizing, capelin trap mesh generates a broad band, noisy signature detectable up to 3 kHz, in comparison to cod trap mesh, which generates a narrow band, low amplitude signature detectable up to (approx.) 1 kHz. Gillnet mesh produces a narrow band, medium amplitude signature, also detectable up to (approx.) 1 kHz.

5.4. Net noise, entrapment and humpback orientation

Entrapments reports over the past decade (Lien *et al.*, 1991) suggest humpback whales may use audition to orientate in the environment. Instances of entrapment may be explained by a failure of the whale to acoustically detect the net.

If capelin traps produce a more detectable signal in comparison to cod traps, then one might expect a differential probability for a whale to hit either type of trap. The cod trap, being the quieter of the two types, would be hit more often. To assess this relationship, catch-effort statistics (compiled by Department of Fisheries and Oceans, Newfoundland region) were examined along with entrapment statistics for the past ten years (Lien, et al., 1989c). Unfortunately, until recently, catch-effort data (in particular for capelin traps) were not collected consistently (Lien, et al., 1991). Consequently, one must assume that cod trap fishing effort has remained constant over the past ten years, at approximately 7,500 traps fished for an approximate mean of 40 days; one must also make further estimates for the capelin fishery (Lien, et al., 1991). It can thus be calculated that the ratio of cod trap effort to capelin trap effort is approximately 10-15:1. Alternatively, the ratio of the number of cod traps hit by whales to the the number of capelin traps hit by whales is approximately 146:1.

Even allowing for the difference between the number of hours cod traps and capelin traps are fished, it can be shown that a cod trap shows a higher probability of being hit by a whale than a capelin trap (Lien, et al., 1991), by a ratio of 10-15:1. While it is acknowledged that this ratio is constructed from estimates of fishing effort, it is clear that there is a differential probability in trap collision. One explanation for this difference would be because of the difference in acoustic 'visibility' between the two types of trap. Whales are more likely to collide with cod traps, which are the least acoustically obvious (Lien, et al., 1991), even though whales are also found feeding in areas where capelin traps are abundant.

Catch-effort data were not collected for gillnet operations; nor were incidences of gillnet entrapment examined as in the above context. It could be predicted that gillnets would exhibit a probability of collision less than cod traps, but not as low as capelin traps, given the sound files as analysed above. Such an examination remains a useful exercise, assuming the existence of a reliable database for gillnetting operations.

The recording of all net samples were done in a specific environment (St. Phillip's), which has its own unique ambient noise characteristics. The signatures presented in this study are referenced to a specific noise level, because the programmes used to isolate the net's acoustic signature accounted for environmental noise. That is, a capelin trap panel is detectable above given noise levels, whereas a cod trap panel is certainly less so. It is to be expected that if the experiment were repeated in an area of higher noise levels, the signature produced by the capelin mesh may be, to a large extent, masked.

Signal masking must be considered when modelling target detection (Forbes and Smock, 1981). If entrapment occurs as a result of failure to detect a net, then one must take into account masking factors by local levels of ambient noise. For example, entrapments of humpbacks have been noted to be more common after a stormy period. This has been previously interpreted as being due to the discovery of the animals following a period of not attending to the nets (Lien, pers. comm.). However, such increases in frequency of entrapment may be due to noise changes in the water. At the height of an intense storm in July 1991, two observations were made of humpbacks colliding with gear. The following day six entrapped humpbacks were reported - an unusually high number (Lien, pers. comm.).

The second section of this study specifically measured net panels. When considering the acoustics of a trap, there are many panels that will contribute to the acoustic signature. In the most simple design of traps, such as the capelin trap, or the traditional cod trap, noise will be produced by any one of the five panels that make the box of the trap, along with the doors and trap leader. Baranov (1976) notes that drag decreases as the angle of the net to a current approaches zero, reaching a minimum when the panel is parallel with the current. Thus it is the panels in a trap that would be closest to a perpendicular angle with the current that would produce the most noise. More complex designs of cod trap - such as the modified, or Japanese cod trap - may be expected to produce a stronger acoustic signature in comparison to a traditional trap made of the same mesh size, since the newer designs consist of more panels. It would follow that the more complex designs of trap have a lower probability of being hit by a whale, because of their increased detectability. Unfortunately, insufficient data exists as to the type of cod trap that is hit. As the more modern designs are used less by Newfoundland fishermen, one would have to account for the low 'n' in sample size. Based on calculations of solidity, while the Japanese and modified cod traps should be theoretically noisier than the traditional cod trap, it is unlikely that they produce a stronger signal than the capelin trap.

Cod traps recently set in the water have a higher probability of being hit by a whale than one which has been in the water for some time (Lien, 1980). Data are inconclusive as to whether the whale is simply 'learning' the position of older nets, and thus avoiding them. A second explanation is that new nets may be more acoustically obvious than older nets. Nets that have been set in the water for a period of time will acquire a layer of biological accretions which would act to increase the surface area of a net. Increased surface area would create a higher drag with respect to water currents, and thus make the net noisier by increasing the 'streaming' effect (although the more impulsive noises created by the interaction of chains and ropes would probably be dampened). No increases in signal strength were observed with the capelin trap that was monitored for seven days at St. Phillip's - it is possible that in this brief span, not enough biological slub had built up to make a significant alteration to the net's signature. Typically, capelin traps are kept in the water only for brief periods of time - perhaps seven to fourteen days. Cod traps are set for much longer periods - because of this, the effects of biological accretion may be more significant in cod trap detectability.

Fishermen commonly observe collisions occur with full cod traps or capelin traps - more often than with empty traps. This may be due to greater production in these areas which, in turn, attracts more whales. However, an alternative explanation suggests that full nets are less acoustically obvious. The preliminary work on capelin traps suggests that schools of fish may reduce noise created by a net. It has yet to be shown that schools of cod possess the same ability when within a cod trap, although the possibility remains since cod traps are of a design similar to capelin traps.

Finally, the fact that capelin reduce noise within a trap provides a direction for future research in whale foraging behaviour. It is clear that a large school of bait is capable of altering the acoustic environment. A whale may use such cues in foraging. Whales may not actively listen for capelin *per se* , but modifications in the acoustic environment which capelin cause.

Evidence suggests, therefore, that humpbacks use sound as a tool in orientation. This, in part, explains the success of various alarm programmes deployed in past years in Newfoundland and Labrador. Alarms improve the 'acoustic visibility' of a net. The 'beeper' device deployed by Lien (1980) and reviewed in Lien et al. (1991) stimulated further research into alarms. The most recent prototype employed appears to have a similar, perhaps stronger, effect in reducing entrapment (Lien, pers. comm.). These findings are in contrast to alarm programmes designed for the smaller cetaceans (Hatakeyama, et al., 1990) which remain, in general, unsuccessful (Todd, & Nelson, in prep.).

The differences in success rate between these two alarm programmes may be because the causes of odontocete entrapment are different to those in mysticete entrapment. It has been shown that some of the smaller cetacean species can detect nets (Au, in prep.; Au, & Jones, 1989; Au, & Jones, in press), and that their entrapment may be due to factors beyond detection of the obstacle (Goodson, pers. comm.). Larger baleen whales may or may not lack the technical sophistication to detect nets.

Although this thesis has shown that the potential for humpbacks to use acoustic orientation with respect to nets exists, it has yet to be categorically shown, in true experimental fashion, that humpbacks can orientate to sound cues. This research is ongoing (Lien, et al., in prep.). Preliminary results have indicated that humpbacks can acoustically discriminate between targets, although to date research has concentrated on the element of passive recognition, as opposed to the potential of the possible active 'biosonar' element that humpbacks might possess.

As a comparative exercise, the study has shown that there should be a differential detection rate between different types and states of net, assuming humpbacks use auditory perception to interrogate the environment. However, to begin to model the ability of humpbacks to acoustically detect nets, source levels of targets will need to be established. In addition, data will be required on detection thresholds and frequency sensitivity in humpbacks.

6. Conclusions

The causes of incidental entrapment remain, to date, unresolved. It appears unlikely that ultimately there will be one solution to minimize whale collisions with fishing gear. Rather, on a species to species basis, one will adopt solutions that fit particular combinations of causes and conditions. Smaller cetacean species appear able to detect nets. Attention and interpretation factors which result in incidental entrapment may be important. However, conditions under which the larger baleen whales can detect nets have yet to be shown. Anecdotal evidence (Lien, *et al.*, 1991) suggests collisions by humpbacks occur, at least some of the time, because of the failure to detect the presence of nets. Fundamental questions of how a humpback perceives the environment have remained unanswered, however, because of the difficulties in studying the larger species of cetacean.

Whereas researchers such as Au and Jones (1989) or Pence (1986) defined the target strength of nets when subjected to a dolphin or simulated echolocation click, this study has investigated the passive, 'self-noise' of a net, and shown that different nets produce different acoustic signatures. While the measurement of net acoustics was attempted in a more controlled environment (Todd, unpub. data), such modelling cannot simulate all the variables that contribute to the ocean's acoustic environment. More valuable information regarding net acoustic behaviour can be obtained when measuring samples *in situ* . In this study, the hanging frame system was successfully used to accomplish this. In particular, the all-rope moorings provided a stable, low self-noise system from which to base measurements.

In this study it has been shown that variations in acoustic signatures are probably caused by the amount of surface area a net provides to a current in the form of drag. The differences in net acoustics have been linked to some entrapment evidence that suggests humpbacks may, partially at least, rely on sound as a navigational tool; entrapment may occur because of a failure to detect the net in time to avoid it.

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Appendices A - D

Appendix A - Technical specifications of equipment used

Hydrophones

Brüel and Kjaer Type 8101:

Usable frequency range;	1 Hz - 120 kHz
Flat response range (+/- 3 dB);	1 Hz - 50 kHz (approx.)
Voltage sensitivity;	-180 dB re 1V/μPa

Amplifiers

Brüel and Kjaer Type 2635:

Frequency range;	0.2 Hz - 100 kHz
Low-pass filter set at;	30 kHz

Recording equipment;

Hewlett Packard Instrumentation Recorder 3964A:

Frequency response (at 7.5 ips);	50 Hz - 32 kHz

Appendix B - Various net calculations

B.1. Calculations of net sample sizes

The hanging ratio (E) is given by the equation,

$$E = \frac{\text{Length of top-rope (frame line)}}{\text{Mesh Size x no. of Meshes}}$$

and represents the ratio between the length of rope that the meshes are hung on and the fully extended length of netting. In practice, the hanging ratio is usually set at 50%, or 0.5. Therefore, the number of meshes per side of a net panel can be estimated by first calculating the width and depth one mesh will occupy in a net panel.

The width of one mesh (b) of bar length a/2 (that is, stretched mesh of length a) in a net panel can be calculated by,

$$b = aE$$

By simple trigonometry, the depth (c) of one mesh in a net panel can be calculated by

$$c = \sqrt{a^2 - [aE]^2}$$

or,

$$c = a\sqrt{1 - E^2}$$

Therefore, the number of meshes either across (H), or down the length (V) of a net panel can be calculated as,

$$H = \frac{\text{length of top rope frame line}}{b}$$

and,

$$V = \frac{\text{depth of vertical frame line}}{c}$$

B.2. Calculating the solidity of a net

In calculating the exposed surface area per unit area, or solidity, of a net sample, two important assumptions must be made. First, that the mesh twine models as a smooth sided cylinder, and second, that the exposed surface area added by the knots at the corners of each mesh is negligible. In reality, both the fact that net twine consists of three to four separate strings twined together, and the fact that the knots in the mesh do make some contribution to surface area exposed, the actual "solidity" of the net may be underestimated by the following method. However, as these restrictions apply equally to all but one of the net panels tested, the below formula should be considered a reasonably accurate measure of the solidity of a net. The one exception to this is the gillnet; because of its construction - from monofilament nylon fibre - its strands are more likely to model a true cylinder.

The surface area (a) of a cylinder of cross-sectional radius (r) and height (h) is given as

$$a = 2\pi rh \qquad [1]$$

If we assume that a net consists of many cylinders, spaced by the length of one mesh bar (L/2) (that is, half the stretched mesh size, L), then the number of cylinders running vertically in a unit area of net panel (that is, 1 m^2), (v),can be given by

$$v = \frac{2}{L} \qquad [2]$$

Similarly, the number of cylinders running horizontally in a unit area of net panel, (h), is given by

$$h = \frac{2}{L} \qquad [3]$$

Therefore, the number of cylinders in a unit area of mesh, (n), can be calculated to be

$$n = h + v = \frac{4}{L} \qquad [4]$$

As each of these cylinders has a known surface area (see Equ'n [1]), the total exposed surface area per unit area (A) is given by

$$A = (2\pi rh) \times \frac{4}{L} \qquad [5]$$

$$A = \frac{8\pi rh}{L} \qquad [6]$$

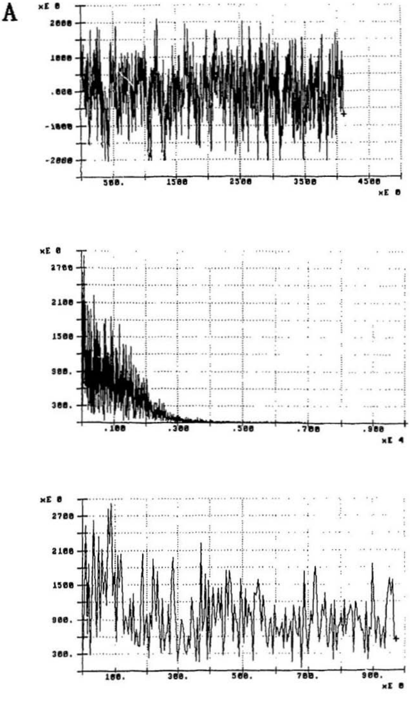
As the length of each cylinder (h) corresponds to the unit area being measured, this equation simplifies to

$$A = \frac{8\pi r}{L} \qquad [7]$$

Appendix C - Additional recordings

Figure C1

Acoustic recordings from the capelin trap on Day 2. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. Recordings presented were taken at (approx.); a) 1210 hrs, b) 1235 hrs, c) 1310 hrs, d) 1400 hrs, e) 1430 hrs (pre-haul) and f) 1600 hrs (post-haul). Note that no high frequency graph is available for 1310 hrs, and no low frequency graph is available for 1400 hrs.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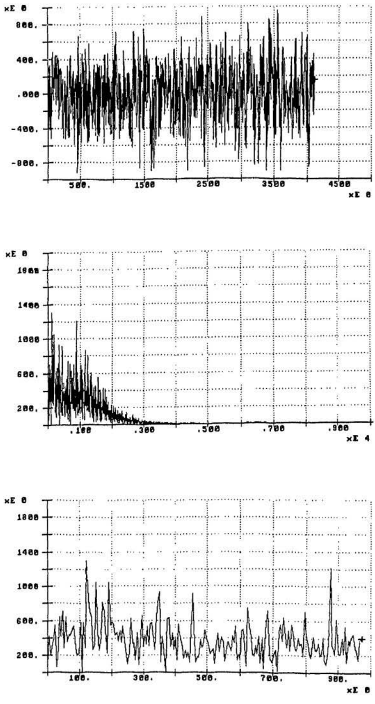
xE 0

B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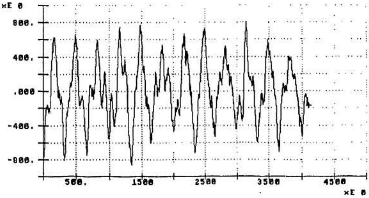
C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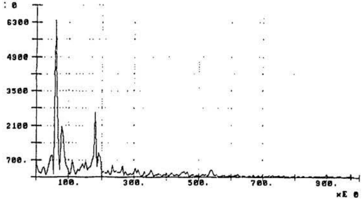
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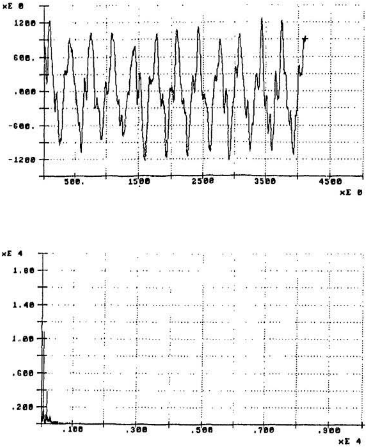
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.700
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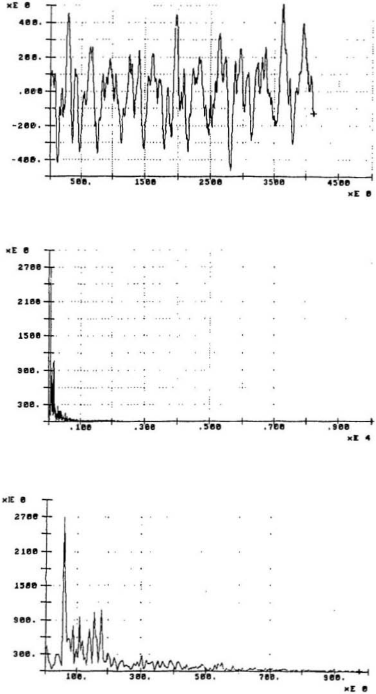
xE 4

E



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xE 0
xE 0
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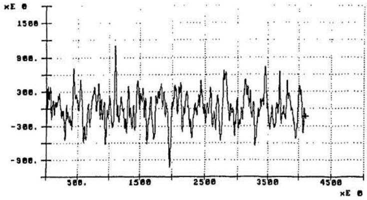
xE 0

F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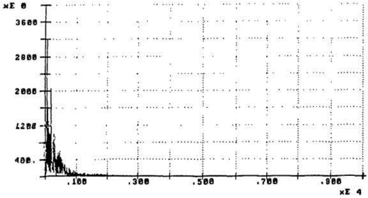
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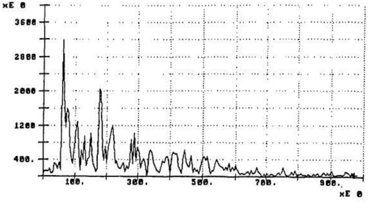
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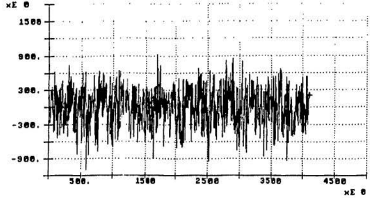
Figure C2

Acoustic recordings from the capelin trap on Day 3. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. No post-haul recording is available for this series. Recordings presented were taken at (approx.); a) 1235 hrs, b) 1300 hrs and c) 1340 hrs (pre-haul).

A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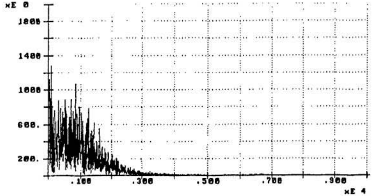
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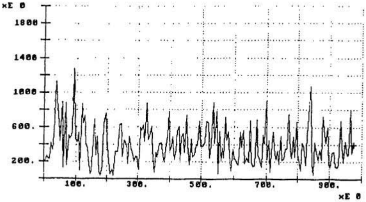
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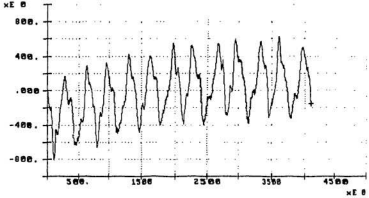
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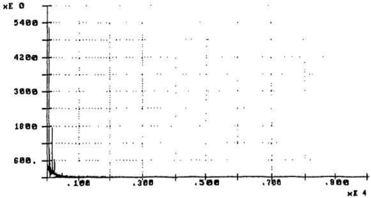
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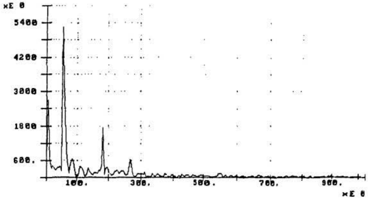
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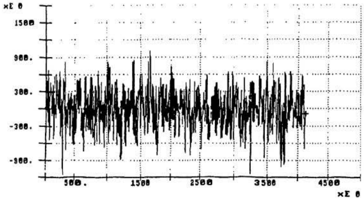
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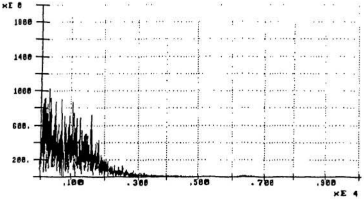
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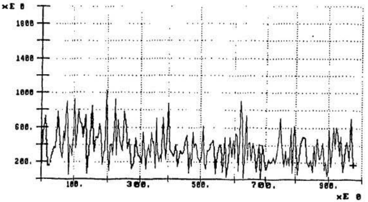
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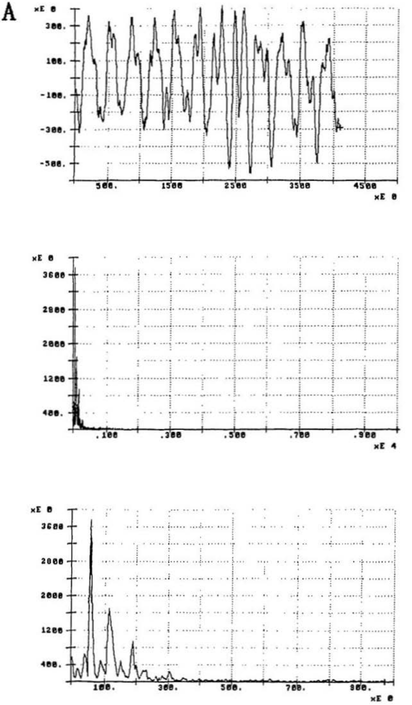
Figure C3

Acoustic recordings from the capelin trap on Day 4. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. Recordings presented were taken at (approx.); a) 0945 hrs, b) 1115 hrs, c) 1150 hrs, d) 1215 hrs, e) 1235 hrs, f) 1250 hrs, g) 1310 hrs, h) 1320, i) 1335 hrs (pre-haul) and j) 1500 hrs (post-haul). Note that no low frequency graph is available for 1215 hrs.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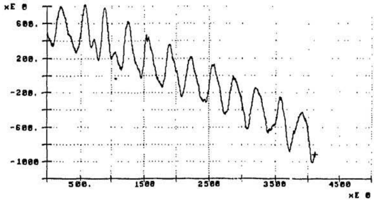
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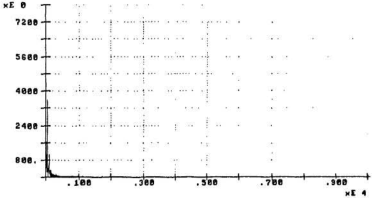
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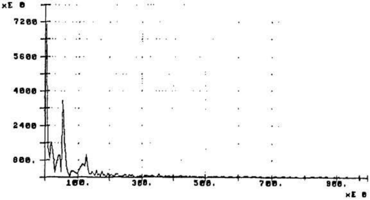
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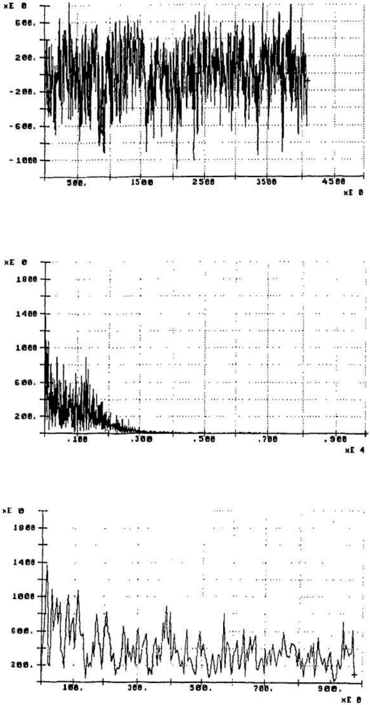
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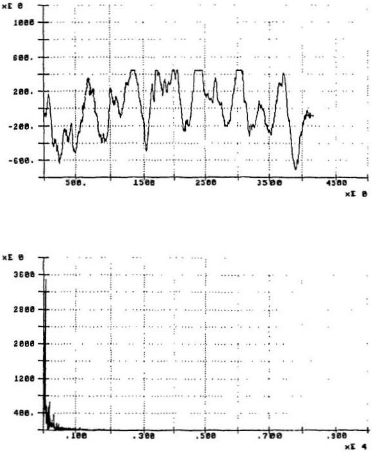
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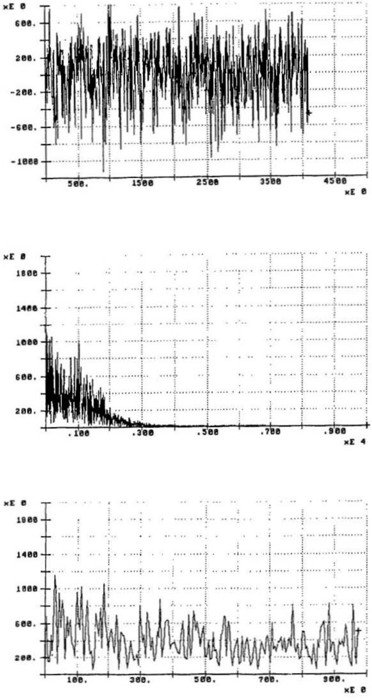
E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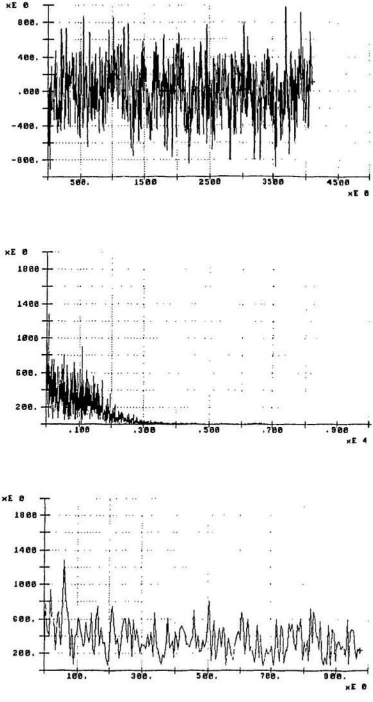
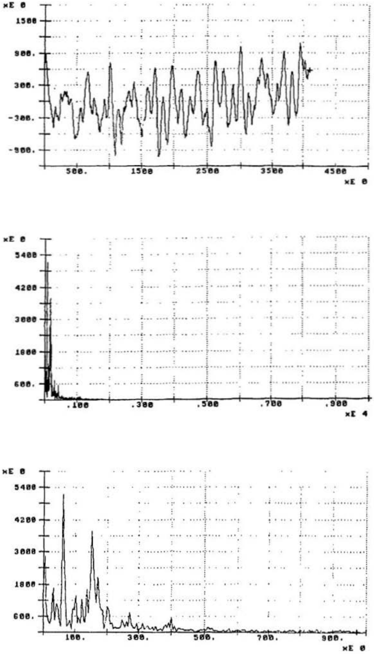
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

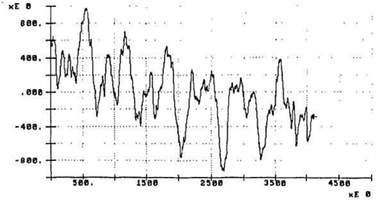
F

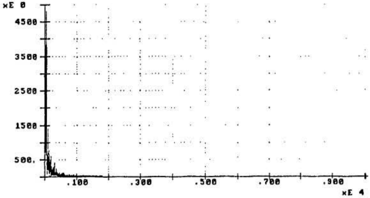

xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4
xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

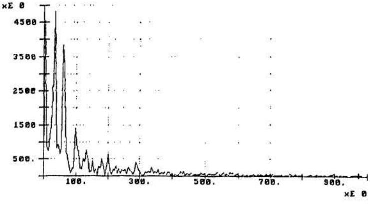
G


xE 0
1500
900.
300.
-300.
-900.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

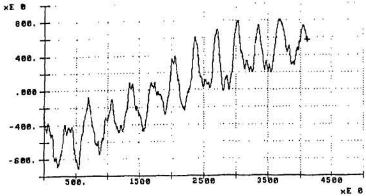
H

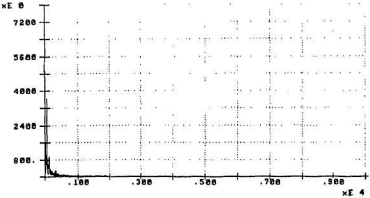

xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0

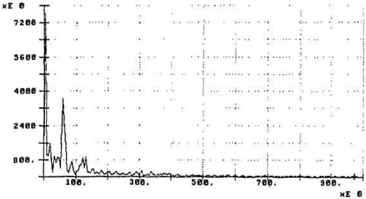

xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4


xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

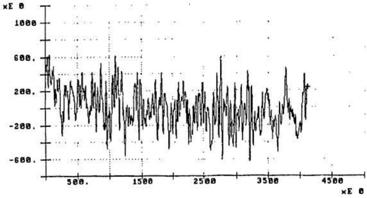
I

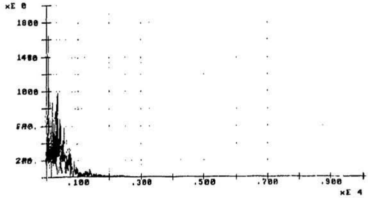

xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0


xE 0
7200
5600
4000
2400
800.
.100
.300
.500
.700
.900
xE 4


xE 0
7200
5600
4000
2400
800.
100.
300.
500.
700.
900.
xE 0

J


xE 0
1000
600.
200.
-200.
-600.
500.
1500
2500
3500
4500
xE 0


xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4

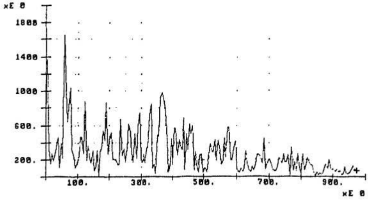
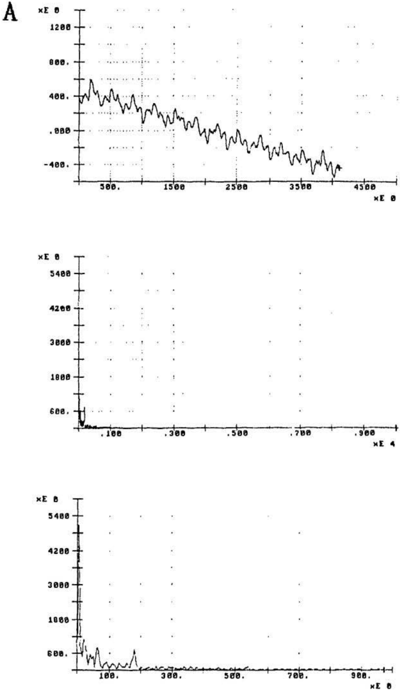
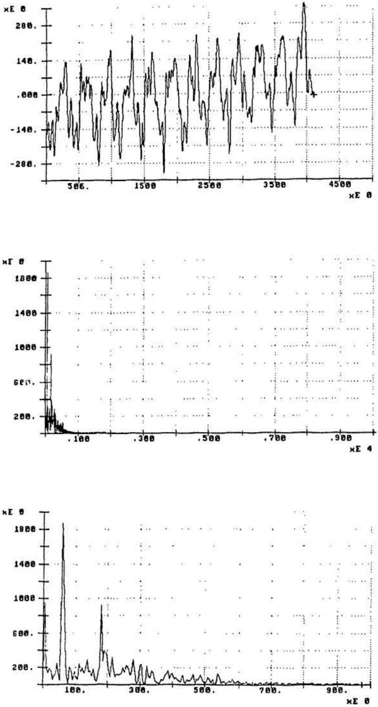

xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

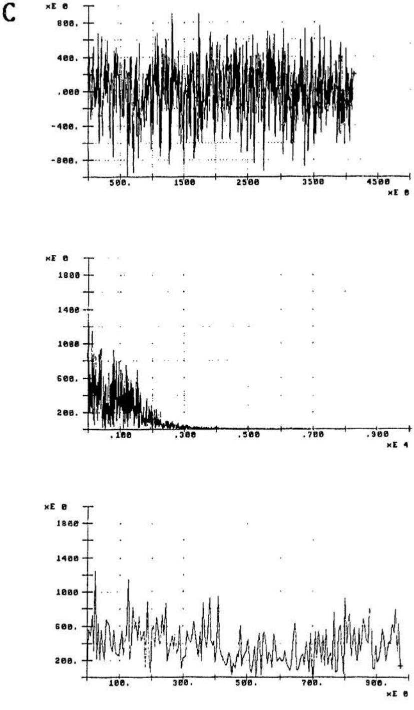
Figure C4

Acoustic recordings from the capelin trap on Day 5. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. Recordings presented were taken at (approx.); a) 1430 hrs, b) 1500 hrs, c) 1530 hrs (pre-haul) and d) 1645 hrs (post-haul).


A
xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

B


xE 0
280.
140.
.000
-140.
-280.
500.
1500
2500
3500
4500
xE 0
xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4
xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0


C
xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 0
1800
1400
1000
600.
200.
.100
.300
.500
.700
.900
xE 4
xE 0
1800
1400
1000
600.
200.
100.
300.
500.
700.
900.
xE 0

D

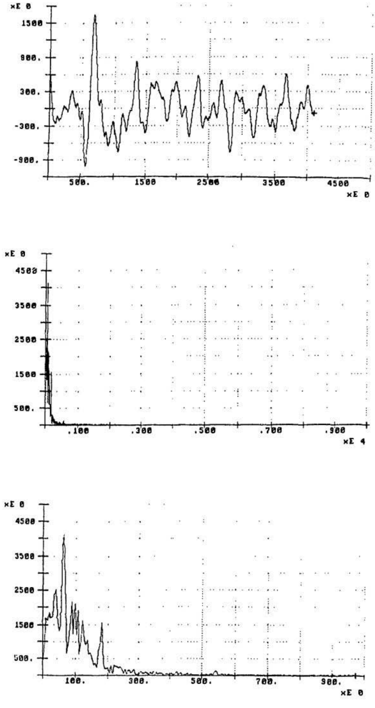
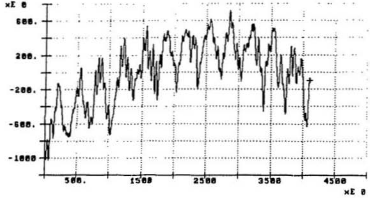
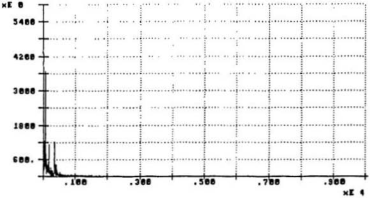

xE 0
1500
900.
300.
-300.
-900.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

Figure C5

Acoustic recordings from the capelin trap on Day 6. Upper graph illustrates a time series taken over a sampled 50ms section. Middle graph illustrates a frequency composition from 0 Hz to 10 kHz. Lower graph illustrates the same frequency composition for low frequencies (0 Hz - 1 kHz). All y-axis are plotted in relative units. Recordings presented were taken at (approx.); a) 0930 hrs (pre-haul) and b) 1115 hrs (post-haul). Note that no time series is available for 0930 hrs.

A


xE 0
600.
200.
-200.
-600.
-1000
500.
1500
2500
3500
4500
xE 0


xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4

B

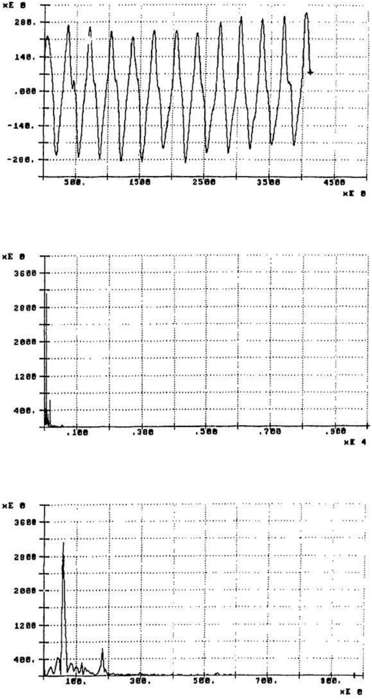
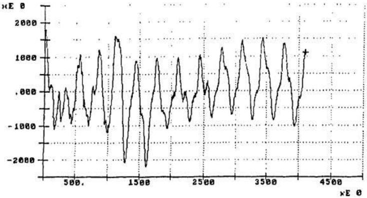
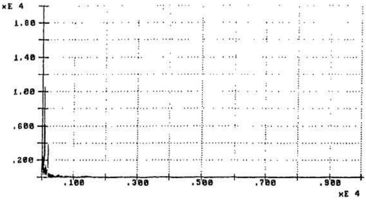

xE 0
280.
140.
.000
-140.
-280.
500.
1500
2500
3500
4500
xE 0
xE 0
3600
2800
2000
1200
400.
.100
.300
.500
.700
.900
xE 4
xE 0
3600
2800
2000
1200
400.
100.
300.
500.
700.
900.
xE 0

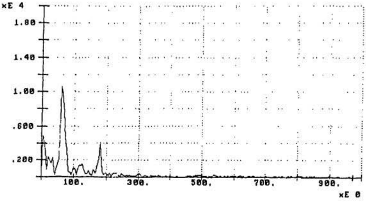
Figure C6

Control readings for the cod trap sample c1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1100 hrs and b) 1130 hrs. Note that no low frequency graph is available for 1130 hrs.

A


×E 0
2000
1000
.000
-1000
-2000
500.
1500
2500
3500
4500
×E 0


×E 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
×E 4


×E 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
×E 0

B

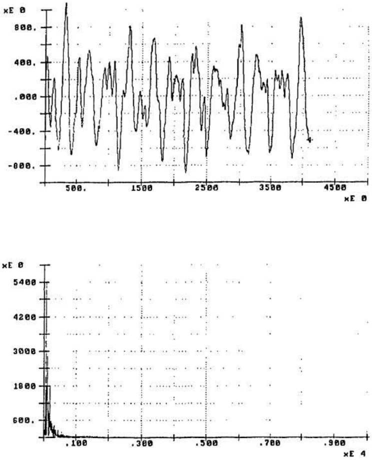
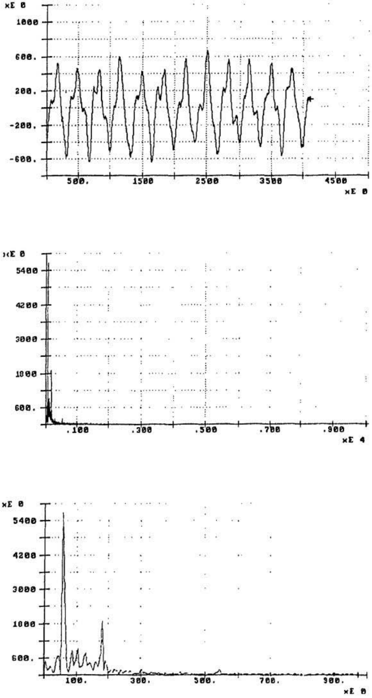

xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4

Figure C7

Experimental readings for the cod trap sample c1. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1330 hrs and b) 1400 hrs.

A


xE 0
1000
600.
200.
-200.
-600.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

B

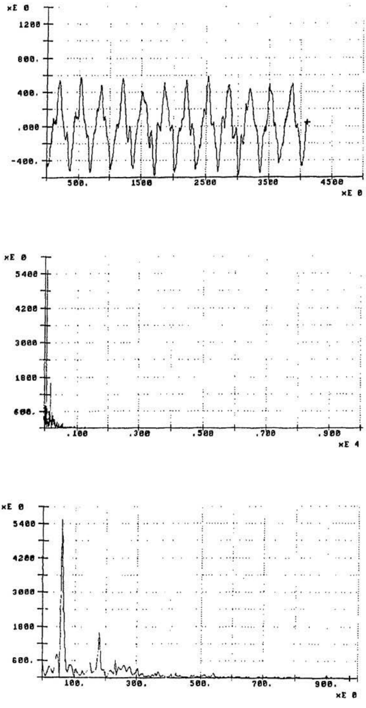
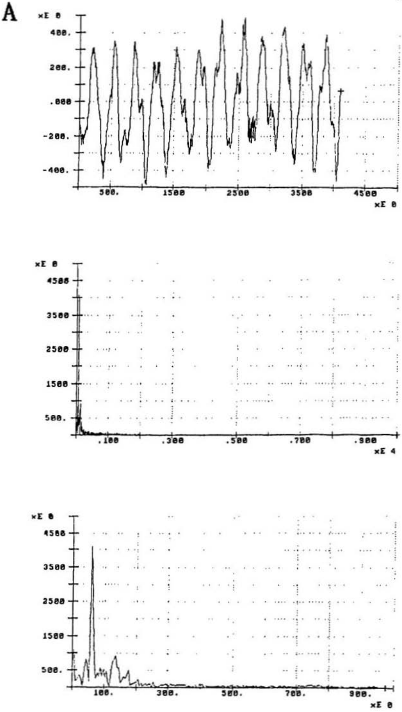

xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
5400
4200
3000
1800
600.
.100
.300
.500
.700
.900
xE 4
xE 0
5400
4200
3000
1800
600.
100.
300.
500.
700.
900.
xE 0

Figure C8

Control readings for the cod trap sample c4. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 0945 hrs and b) 1015 hrs.


A
xE 0
400.
200.
.000
-200.
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
4500
3500
2500
1500
500.
.100
.300
.500
.700
.900
xE 4
xE 0
4500
3500
2500
1500
500.
100.
300.
500.
700.
900.
xE 0

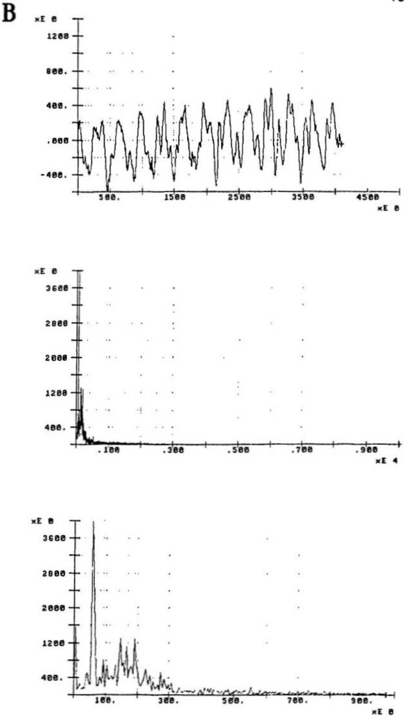
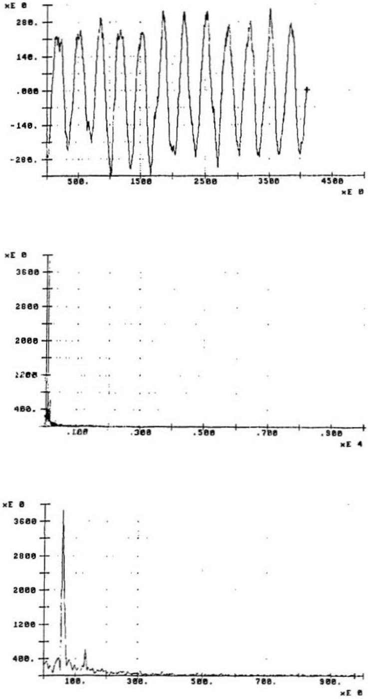

B
xE 0
1200
800.
400.
.000
-400.
500.
1500
2500
3500
4500
xE 0
xE 0
3600
2800
2000
1200
400.
.100
.300
.500
.700
.900
xE 4
xE 0
3600
2800
2000
1200
400.
100.
300.
500.
700.
900.
xE 0

Figure C9

Experimental readings for the cod trap sample c4. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1200 hrs and b) 1230 hrs.

A


xE 0
280.
140.
.000
-140.
-280.
500.
1500
2500
3500
4500
xE 0
xE 0
3600
2800
2000
1200
400.
.100
.300
.500
.700
.900
xE 4
xE 0
3600
2800
2000
1200
400.
100.
300.
500.
700.
900.
xE 0

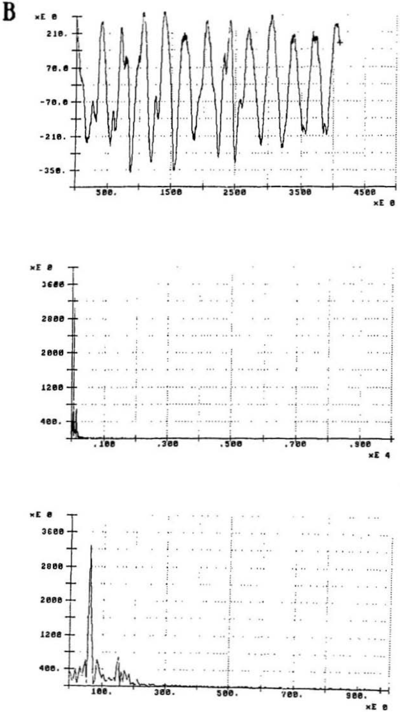
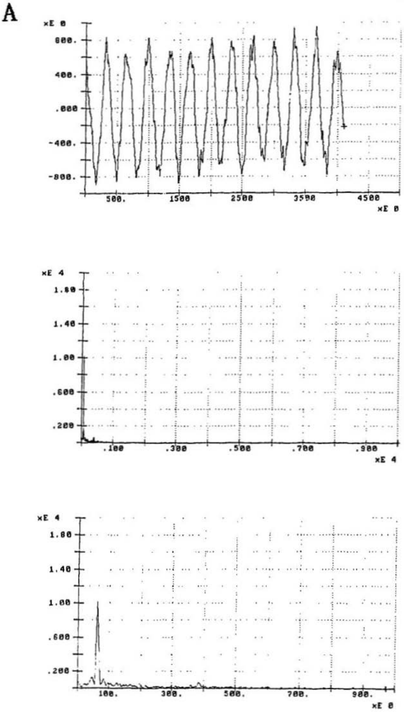
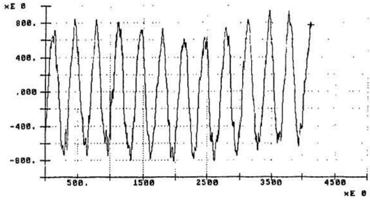

B
xE 0
210.
70.0
-70.0
-210.
-350.
500.
1500
2500
3500
4500
xE 0
xE 0
3600
2800
2000
1200
400.
.100
.300
.500
.700
.900
xE 4
xE 0
3600
2800
2000
1200
400.
100.
300.
500.
700.
900.
xE 0

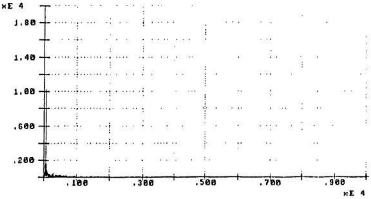
Figure C10

Control readings for the cod trap sample c3. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1100 hrs and b) 1130 hrs.


A
xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0
xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4
xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

B


xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0


xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4

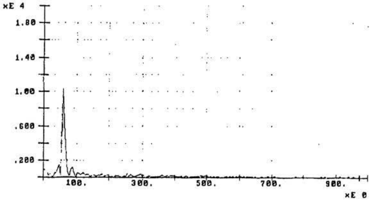
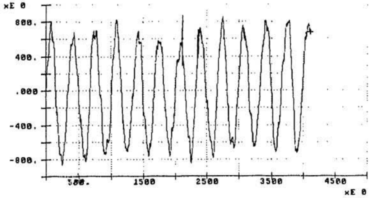
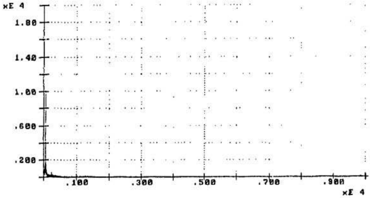

xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

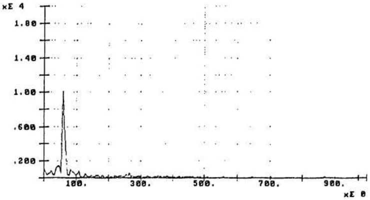
Figure C11

Experimental readings for the cod trap sample c3. Upper graph shows a time series taken over 50 ms. Middle graph illustrates a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings taken at (approx.); a) 1230 hrs and b) 1300 hrs.

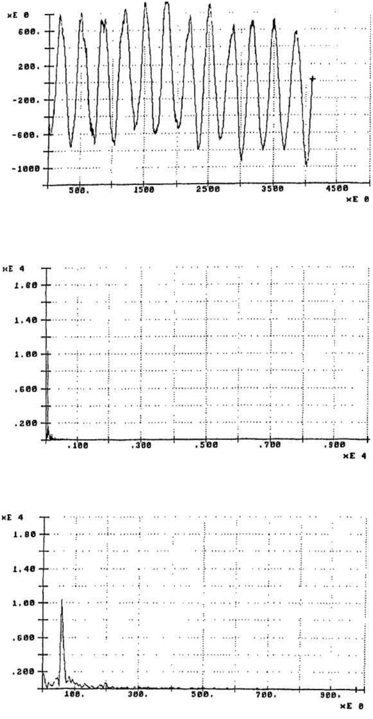
A


xE 0
800.
400.
.000
-400.
-800.
500.
1500
2500
3500
4500
xE 0


xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4


xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

B

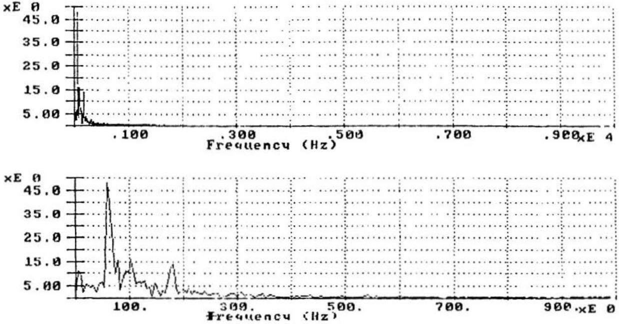


xE 0
600.
200.
-200.
-600.
-1000
500.
1500
2500
3500
4500
xE 0
xE 4
1.80
1.40
1.00
.600
.200
.100
.300
.500
.700
.900
xE 4
xE 4
1.80
1.40
1.00
.600
.200
100.
300.
500.
700.
900.
xE 0

Figure C12

Constructed semblances for the cod trap sample c1. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.

A


xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

B

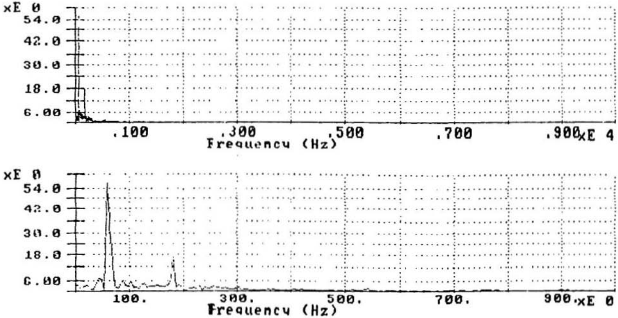
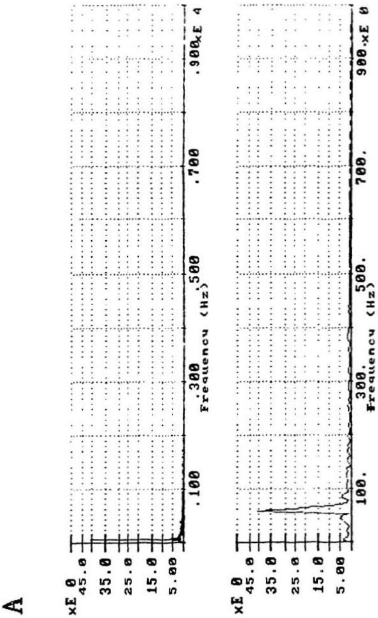

xE 0
54.0
42.0
30.0
18.0
6.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
54.0
42.0
30.0
18.0
6.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

Figure C13

Constructed semblances for the cod trap sample c3. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.


A
xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.xE 0
Frequency (Hz)

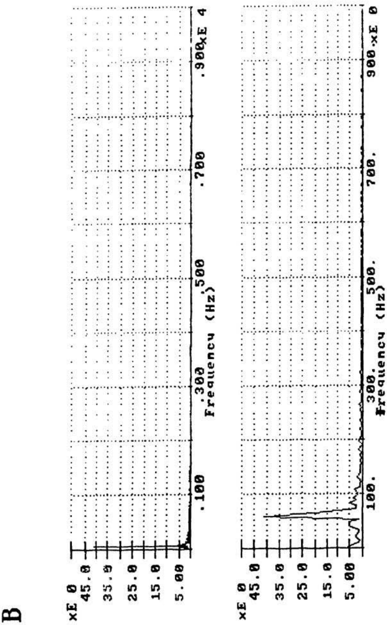
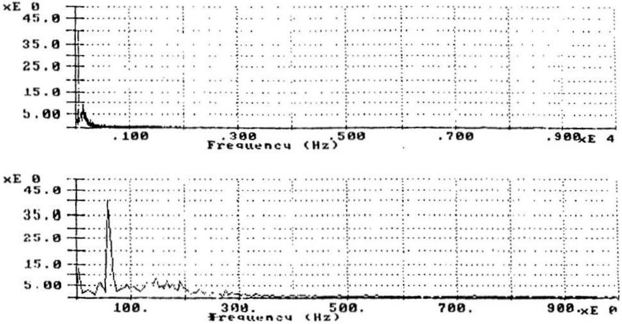

B
xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

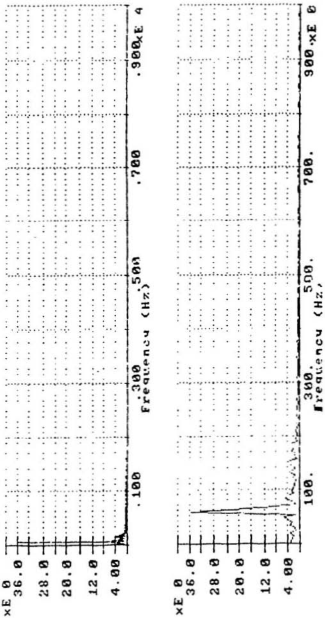
Figure C14

Constructed semblances for the cod trap sample c4. Upper graph shows a frequency composition for the range 0 Hz to 10 kHz. Lower graph shows this range expanded for the bandwidth 0 Hz to 1 kHz. Recordings show; a) control and b) experimental readings.

A


xE 0
45.0
35.0
25.0
15.0
5.00
.100
.300
.500
.700
.900
xE 4
Frequency (Hz)
xE 0
45.0
35.0
25.0
15.0
5.00
100.
300.
500.
700.
900.
xE 0
Frequency (Hz)

B


×E 0
36.0
28.0
20.0
12.0
4.00
.100
.300
.500
.700
.900 ×E 4
Frequency (Hz)
×E 0
36.0
28.0
20.0
12.0
4.00
100.
300.
500.
700.
900. ×E 0
Frequency (Hz)

Appendix D - The acoustic environment with respect to oceanic organisms

This appendix is included as a brief introduction to underwater acoustics. While it is not intended to discuss the field in depth, it serves to introduce the reader to certain physical concepts that may be required in interpreting the results of this thesis.

The acoustic environment of the ocean is remarkably complex. Sound travels at least four times faster in water than on land (Vigoureux, & Hersey, 1962), given dependencies on salinity, pressure and temperature (Urick, 1983). However, the propagation of sound is highly dependent on frequency (Vigoureux, & Hersey, 1962), because of the higher absorption rates for high frequencies. The interaction of various oceanographic factors can have a profound effect on sound transmission. Salient aspects of sound transmission are discussed here, in a sequence similar to the temporal association of each factor on a signal. Since the possibility remains that mysticetes may use their vocalizations in an echolocation or orientative sense, discussion here includes sound production. The processes relevant in the context of either a biosonar or listening system can be considered to be sound production (including amplitude and directionality), sound transmission (including transmission losses due to reverberation, absorption, and reflection), and sound reception (including directivity, directionality of the receiving system, binaural hearing, and masking effects of ambient noise).

D.1. Sound production

Sound is the result of excitation, in a regular fashion, of molecules within an elastic medium (Vigoureux, & Hersey, 1962). Such vibration is communicated to subsequent particles within the medium, causing propagation of the sound wave. Assuming a planar sound wave, the instantaneous pressure (P) is related to the fluid medium density (ρ), the velocity of the particles (u), and the propagation velocity of the wave (c), by the equation given by Urick (1983)

$$P = \rho c u \qquad [1]$$

The constant ρc is often expressed as the acoustic impedance (equivalent in analogous terms to electrical impedance), which is approximately 3500 times higher in seawater than in air; hence the much higher intensity for a given sound source when measured in air rather than water (Urick, 1983).

Instantaneous pressure is measured, for convenience, on a log scale, referred to as decibels (dB). The decibel is defined as

$$L = 10 \log \frac{I}{I_{ref}} \qquad [2]$$

where L refers to a level in dB, I to the measured instantaneous pressure, and I_{ref} to a referenced instantaneous pressure level (Caruthers, 1977). The decibel scale is set so that a gain of +3 dB represents a doubling of the energy within a sound wave, and a loss of -3 dB represents a halving of the energy present within a wave (Caruthers, 1977). Because the decibel is a relative scale, and thus must be referred to a specific level for absolute comparisons, Iref is usually standardized. The most common frame of reference is calculated at a distance of 1 m from the sound source, where 0 dB represents a rms pressure equal to 1 μPa (Urick, 1983).

Most measurements to date in the biological field involve amplitude, or pressure level measurements in terms of instantaneous pressure. Instantaneous pressure is relatively easy to measure (only one calibrated hydrophone is required). Closely related to instantaneous pressure is the measurement of intensity. Unlike instantaneous pressure measurements, intensity is a vector quantity (that is, associated with a specific direction). It is measured as the amount of energy crossing a unit area per second (Horton, 1957), and is broadly defined by the equation

$$I = \frac{P^2}{\rho c} \qquad [3]$$

where I is intensity, measured as Watts.m^{-2} (Urick, 1983). As a vector quantity, intensity measurements require a minimum array of two hydrophones, the pressure differential between the two being mapped as intensity. Intensity measurements tend to concentrate on directional signals, with omnidirectional signals (because they lack net movement in a specific direction) being less emphasized. Thus production source level (SL) can be expressed in terms of instantaneous pressure (dB re 1 μPa), or in terms of intensity (W.m^{-2}, with a negative or positive component implying direction).

The biological literature tends to cite instantaneous pressure levels. Extremely loud sources have been recorded as originating from whales; Beamish and Mitchell (1971) estimate for the blue whale an SL for a reported 21-31 kHz signal of 59.2 ± 1.0 dB (re 1 m). For a minke whale signal of between 4-7.5 kHz, they report a maximum SL of 51 dB (re 1 m) (Beamish, & Mitchell, 1973). Payne and Webb (1971) assume the average level of a fin whale signal to be 80 dB (re 1/dyne cm^2 at 1 yard). Thus it has been demonstrated that some mysticetes are indeed capable of powerful emanations of sound, although little work reports measurements of intensity.

Directionality refers to the directional component of the signal, or the beam-width within which the majority of the energy of the signal lies. Beam-width can be simply defined as an angle originating from the sound source. This angle subtends the boundaries of a 3 dB loss either side of the beam. In other words, a movement of the receiver to a position immediately outside the beam would result in a halving of the power of the signal, for the frequency measured. A small angle implies a narrow beam-width, or a highly directional signal. A large angle implies a wide beam-width, which when taken to extremes becomes omni-, or non-directional.

Directionality is commonly used when describing dolphin systems, which are highly focussed in beam-like projections (Au, Floyd, & Haun, 1978; Au, Moore, & Pawlowski, 1986; Au, Penner, & Turl, 1987). Some references have been made to directionality of sound production in mysticetes, although the lack of rigid experimental design has prevented all but a few speculative comments. For example, Beamish and Mitchell (1971, 1973) note the omnidirectional nature of Blue and Minke whale vocalizations, as do Payne and Webb (1971), of fin whales. While directional signals are less subject to transmission losses, they are harder to produce. The production of highly directional signals in odontocete species is undoubtedly aided by the melon (Norris, 1964; Norris, & Harvey, 1974). No such equivalent structures are found to exist in mysticetes.

D.2. Sound transmission

Transmission of sound is highly dependent on reflection, refraction, selective absorption and interference factors within the water column and the boundaries that contain that body of water (Kinne, 1975). Sound energy in water consists of two basic components: a) the pressure wave component (caused by the regular excitation of molecules), which decreases linearly with distance from the source, and b) the component resulting from the displacement of water molecules, which decreases with distance exponentially (Kinne, 1975). As a result of the interaction between these two components, there comes a point where the amplitude of each component is equal. This point is arbitrarily referred to as the near field/ far field boundary. Outside this boundary, displacement amplitude effects are said to be negligible. It is only the displacement amplitude effects that contain a directional component. That is, sound signals in the far field (due to pressure amplitude only) are non-directional, and cannot be used as orientational cues (Kinne, 1975).

Because of the nature of sound waves, there are inevitably energy losses to the medium through heat. Termed 'absorption', this process is frequency dependent (Urick, 1983), and regarded as a 'true' loss in energy (as opposed to distribution and dissipation through wave front spreading, which may be regarded as other attenuation losses). Absorption is quantified as 'α', measured in dB loss per unit length. Low frequency signals are less subject to heat losses (Urick, 1983). In fact, Payne and Webb (1971), in their theoretical discussions of fin whale communication, note that for a 20 Hz signal absorption losses are probably negligible (assuming spherical propagation).

Non-frequency dependent losses from spreading should also be considered. If we assume a simple spherical spreading model, then transmission loss can be simplified as being proportional to r^2, where r is the distance from the source. Simply stated, transmission loss from spreading (TL_S) can be equated as (Urick, 1983)

$$TL_S = 10 \log \frac{I_1}{I_2} \qquad [4]$$

where I_1 and I_2 represents instantaneous pressure measurements at distances r_1 and r_2 respectively. Assuming r_1 is the reference measurement, then equation 4 simplifies to

$$TL_S = 10 \log r_2^2 = 20 \log r_2 \qquad [5]$$

Alternatively, when transmission is limited by parallel upper and lower boundaries, spreading losses will be cylindrical. Under certain conditions, low frequency transmission can be enhanced by boundary layer conditions. The model presented by Payne and Webb (1971) made use of the so-called SOFAR channel (see Northrop, 1966), where sound can be refracted within a deep water layer without extending to the boundaries of that layer - thus reflection losses are minimized. In this case, transmission loss due to cylindrical spreading, or TL_C, is proportional to the first power of r_2, or

$$TLs = 10 \log r_2 \qquad [6]$$

Assuming a spherical spreading model, one can approximate the combined effects of spreading losses and absorption losses (Urick, 1983) by combining a term for alpha and equation 6;

$$TL = 20 \log r_2 + \alpha r \qquad [7]$$

A final transmission loss results from reverberation. Reverberation is the summed effect of particles scattering acoustic energy (Urick, 1983), and can be divided into volume (reflections from particles or inhomogeneities in the water column), bottom (reflections from the seafloor) and surface (reflections from the sea surface) reverberation. The scattering strength (S) of a body is defined according to the type of reverberation it is describing. Simply stated,

$$S = 10 \log \frac{I_{scat}}{I_{inc}} \qquad [8]$$

where I_{scat} represents the energy reflected from a unit area (in the case of surface or bottom reverberation) or a unit volume (in the case of volume reverberation), and I_{inc} represents the energy in the original signal. To a large extent, the energy reflected is a measure of the angle formed by the incident ray to the normal that lies perpendicular to the surface of the body (Rayleigh's Law) (Urick, 1983).

Reverberation can be considered in some respects to be a useful property of transmission. Sonar systems work on the principle of the reflection of incident energy from a target, and one might assume any mysticete echolocation system (whether in the tradition of an odontocete system, or something of less resolution) would rely on such principles. It has already been noted that mysticetes vocalize at very low frequencies. Long wavelengths (that is, low frequencies) are subject to high levels of reverberation, or backscatter. Consequentially, low frequency sounds can not by their nature carry as much orientation information as that of a high frequency signal, although they can travel much further. They might, under the most ideal conditions, provide non-detailed information for general orientation purposes (Kinne, 1975). Therefore, low frequencies would be of limited use as orientational cues, although feasible.

D.3. Ambient noise

The detectability of a signal is partially a function of the background noise prevalent at time of transmission and reception of that signal (Kinsler, & Frey, 1962). Masking - the 'drowning' of quieter sounds by louder ambient noise - is an important factor when modelling perception processes. As masking effects are most dominant when the frequency of the ambient noise matches that of the signal being masked, one common solution is to use frequencies that are outside the frequency range of the dominant noise (Kinne, 1975). Thus it is necessary to understand the nature and character of ambient noise.

Ambient noise, in brief, is a background level of noise, present across all frequencies (although to varying degrees), that is the result of particular acoustic events (Knudsen, Alford, & Emling, 1948). Sources of noise include tidal effects and waves, seismic disturbances, turbulence, thermal noise, meteorological effects, and in modern times, man-made noise from ship traffic, etc.. Wenz (1962) suggested that the form of the ambient noise curve between the ranges of 1 Hz and 1000 Hz was dependent on several overlapping functions; a low frequency spectrum between 1-100 Hz (caused by turbulence), a non-wind dependent spectrum between 10-1000 Hz (caused by ship/traffic noise), and a wind dependent spectrum between 50 Hz -10 kHz (thought to be produced in part by air bubble cavitation). Biological influence on this spectra would only occur in specific areas of biological activity. In a more recent review, Caruthers (1977) notes that between 1-50 kHz, predominant noise components include oceanic turbulence (1-10 Hz), shipping (10-200 Hz), and wind, waves, foam and spray (200 Hz - 50 kHz). It has also been shown that shallow water noise is more variable than deep water noise, averaging about 9 dB higher (Caruthers, 1977).

The relationship between noise levels and frequency was first summarized graphically by Knudsen et al. (1948) and later by Wenz (1962). Despite minor modifications to the ambient noise spectral curve, Wenz's (1962) curve is accepted as the standard (for example, see Tolstoy and Clay, 1966).

Ambient noise character and level has changed significantly in the last one hundred years (Payne, & Webb, 1971; Urick, 1983). The advent of engine-powered boats has significantly contributed to noise levels now present in the ocean (Payne, & Webb, 1971). Therefore, as Payne and Webb (1971) suggest, if one wants to investigate the mechanics of an acoustical orientation system, one should consider its long-term development across evolutionary time, while taking into account modern problems of noise. It has been noted that ship traffic noise might affect certain communication channels between whale species (Clark, 1990b; Dalheim, et al., 1984; Dalheim, & Ljungblad, 1990; Johnson, 1983; Ljungblad, 1983; Mansfield, 1983). Thus in calculating the potentials of a listening system, one must acknowledge the presence of ambient noise and make appropriate allowances for it.

D.4. Sound reception

Several factors are involved in the successful reception of a sound signal (Kinsler, & Frey, 1962). Apart from the sound's production and successful conduction (allowing for transmission losses and masking effects), there are also factors that are characteristic to the receiving 'array' (the term 'array' should be interpreted loosely here to mean a receiving system). First, the directivity of the receiving system should be noted. Second, like in sound production, where signal energy can be focussed in a beam-like projection, there may be certain areas surrounding the receiving system that are more sensitive to the reception of sound. Third, given that a receiving system is located correctly to receive a signal, it should be sensitive to those frequencies and be able to discern them against background noise.

Directivity is a measure of the ability of a receiving system to discriminate a signal against a background of isotropic noise (Caruthers, 1977). It is summarized by the Directivity Index (DI), and is measured in dB. It refers to the maximum array gain under ideal conditions for a given frequency, and is controlled largely by the dimensions of the array. In the case of an organism, DI is related to the structure and morphology of the ears and other sound receiving organs. Very little is known about directivity in mysticetes.

The ability of mysticetes to perceive frequencies above the levels of ambient noise is a function of the signal-to-noise ratio, and the ability of the receiving system to work at that ratio. While studies on noise masking have been performed on human subjects (Hawkins Jr., & Stevens, 1950), Payne and Webb (1971) comment that mysticetes probably do not require the same sensitivity to sounds that humans exhibit. They note that any acoustic system developed through the pressures of natural selection would probably have been designed within the constraints that masking noise imposes. An example of this can be seen in Dalheim et al. (1984). Also, in their theoretical calculations of fin whale auditory sensitivity, Payne and Webb (1971) state that they "do not feel inhibited about assuming that fin whales have adequate sensitivity at 20 Hz".

Directionality is largely linked to the structure and morphology of the sound reception system. Dudok Van Heel's (1962) anatomical review of the mysticete hearing apparatus leaves little doubt that baleen whales are capable of directional hearing. However, because little opportunity has arisen to experimentally map directional 'lobes' of sensitivity systematically around a whale's head, empirical data is lacking for mysticetes. Payne and Webb (1971) assume that mysticetes work with an omnidirectional receiver. Current studies include an attempt to surgically insert hydrophones into the ear bones of a Minke whale head specimen. Sound of known characteristics was then directed at the head, with the sound source varying its location spatially on a three-dimensional grid system based around the head (Guigné, Todd, Guzzwell and Lien, unpub. data).

For acoustic orientational cues to be used most effectively, the animal must have some form of directional or binaural hearing. Kinne (1975) states

> "Directional hearing is based on (i) the time difference in sound perception by both ears, which depends upon the distance between the peripheral most sensitive sound receiving areas and the velocity of internal sound conduction; (ii) differential sound intensity; (iii) differences in phase and complexity of the sounds; (iv) central nervous interpretations of such differences"

Forbes and Smock (1981) note that, for there to be discrimination and spatial recognition of a sound source, one must introduce the concept of Minimum Audible Angle (MAA). The MAA is defined as,

> "the smallest detectable difference between the azimuths of two identical sources of sound.... the minimal audible angle is the angle joined at the centre of the head by lines projecting to two sources of sound whose positions are just noticeably different, when they are sounded in succession" (Mills, 1958)

Discrimination via the MAA concept is thought, at low frequencies (< 1.4 kHz), to be the result of phase/time differences in arrival of the signal at either ear (Mills, 1958). At higher frequencies (> 3 kHz), head shadowing becomes more effective (Forbes, & Smock, 1981). In the case of mysticete sound production, phase/time differences are of greater importance in locating a sound source (Dudok Van Heel, 1962). Forbes and Smock (1981) also note that, for shadowing differences to be effective, the head must contain tissue relatively impervious to sound. The system becomes far more complex when considering a multitonal, as opposed to the above monotonal, situation.