Multi-frequency acoustic discrimination between gas bubble plumes and biological targets in the ocean

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Dissertation for the degree of philosophiae doctor (PhD)
at the University of Bergen

2015

Dissertation date: 18 June, 2015

Year: 2015

Title: Multi-frequency acoustic discrimination between gas bubble plumes and biological targets in the ocean

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Print: AIT OSLO AS / University of Bergen

Scientific environment

This work was done at the Institute of Marine Research (IMR) and Metas AS. Main scientific environment was the Marine Ecosystem Acoustics group at IMR. The Ph.D. project was funded by the Research Council of Norway and Metas AS (Grant No.: 212113/O30).

Acknowledgements

I would like to express my gratitude to Professor Egil Ona who introduced me to the field of fisheries acoustics well over six years ago and was an inspiring mentor for both my Master's and Ph.D. studies. I would also like to thank Dr. Gavin Macaulay who helped to steer my scientific progress and was an inexhaustible source of in-depth knowledge.

I am grateful to Terje Torkelsen, my supervisor at Metas AS, whose high spirits, restless interest and innovative, skilful equipment designs were both crucial for this thesis work and a constant source of encouragement.

My thanks to all of my colleagues at the Marine Ecosystem Acoustics group (IMR): Rolf, Olav Rune, Atle, Espen, Hector, Sindre, Arne, Nils Olav, John, Lise, Endre, Guillaume, Ronald, Lucio and Martha for their welcome, advice, help and valuable discussions during my stay both as a master's and doctoral student. It was a pleasure to work in such an inspiring and vibrant scientific environment.

My thanks also goes to the staff of Metas AS: Olav, Einar, Jostein, Alejandro and Dionisio for their warm welcome and skilful equipment construction and operation during the data collection.

Galiausiai noriu padėkoti tėvams, Feliksui ir Teresai, ir broliui Valdui už jų meilę ir palaikymą per skaitlingus studijų metus.

Abstract

Seabed-originating gas bubble seeps have been observed worldwide from a variety of sources (e.g. Hovland and Judd, 1988) and are most frequently composed of methane and carbon dioxide. Some seabed gas leaks, such as “melting” methane hydrates, may intensify in the coming decades and are a subject of concern in the context of warming seas (Kvenvolden et al., 1993; Archer, 2007). The subsea gas extraction industry and proposed carbon dioxide storage in geological structures under the seabed are examples of potential manmade sources of gas bubble leaks (IPCC, 2005; DNV, 2010), and require swift and precise leak detection and identification. Active acoustic methods are well suited for rapid and cost effective monitoring of large water volumes. Scientific fisheries echo sounders provide calibrated, quantitative measures and are widely used in fish stock monitoring (Simmonds and MacLennan, 2005). As such, these were chosen within the umbrella R&D projects (AKUGAS and AALDOG), the needs of which shaped the scope and objectives of this doctoral study. Bottom-mounted echo sounders, observing laterally along the seabed are considered suitable for gas leak detection. Gas bubble plumes are easy to detect with echo sounders, but separating them from fish and plankton is not always straight forward, as some required information is lacking both for gas bubble plumes and biological targets. This lack is addressed here via selected case studies.

In **Paper I**, the acoustic backscatter properties and natural body tilt orientation were investigated for a common schooling fish that lacks a swim bladder, lesser sandeel (*Ammodytes marinus*). Its natural orientation distribution was measured using optical measurement methods and is a crucial parameter affecting the acoustic backscattering from animals that are large enough to be directive targets at commonly used echo sounder frequencies. A more advanced stereo photogrammetric method was adapted and improved to fit the needs of this doctoral study in **Paper II**. These were implemented to characterize the natural tilt orientation distribution of euphausiids (*Euphausia superba* and *Meganyctiphanes norvegica*) in several *in situ* and *ex situ* experiments (**Paper II**). Krill natural tilt orientation was measured to have a rather large variability (SD of up to 30-37°). This suggests, but does not prove, that dorsal

and lateral aspect krill acoustic backscatter should not be drastically different due to the variable swimming behaviour and body postures adopted by these animals. Such knowledge will be useful for krill multi-frequency identification and target strength averaging either from models or from empirical data. The stereo photogrammetric measurement method (**Paper II**) was later applied to support fine scale acoustic backscatter measurements on gas bubble plumes (**Paper IV**) and saithe (*Pollachius virens*) (**Paper III**).

In **Paper III**, the lateral aspect acoustic backscatter of saithe was characterised at 70, 120, 200 and 333 kHz. Saithe is a good representative of large, acoustically directive schooling fish that also possesses a gas-filled swim bladder. These can create strong and similar acoustic targets to plumes of free gas bubbles rising from the seabed. Saithe lateral aspect acoustic frequency response (r(f)) was measured based on both schools, single acoustic targets and single target tracks. It was found to have an opposite trend across the acoustic frequency band compared to dorsal aspect saithe r(f) as reported in the literature. The reasons for such discrepancy are discussed along with the implications for acoustic target identification. Similarly, lateral aspect acoustic backscatter properties were characterised for induced methane, carbon dioxide and air bubble plumes at 70, 120, 200 and 333 kHz (**Paper IV**). A distinct gas plume frequency response was measured for gas bubbles of non-resonant size and is significantly different from the lateral aspect r(f) of saithe.

In synthesis, the similarity in acoustic backscattering between a gas bubble and biological targets possessing gas inclusions is discussed, both from a literature review and the investigations included here (**Papers I-IV**). The prospects of acoustic-based gas bubble plume detection and identification are discussed in the context of obscuring and confounding biological targets. Acoustic frequency response, routinely used to identify some fish and plankton for species or taxa (e.g. Korneliussen and Ona, 2002; 2003; Anon., 2005), is discussed for laterally observed seabed gas bubble plumes. Lateral aspect gas bubble plumes and swim bladder bearing fish frequency response was not available and hence was measured in **Papers III and IV**. Based on the available research and that defended here (**Papers I-IV**), it is suggested that behavioural and acoustic backscattering differences can be used to separate gas bubble *plumes* from the most common biological targets, plankton and fish. Gas-filled swim bladder bearing fish are the most similar biological acoustic targets to the gas bubble plumes. Schooling and swim bladder bearing fish that are quite directive acoustic targets can be separated using the acoustic frequency response information (indications in **Paper III**). Smaller, but abundant swim bladder bearing fish, such as members from Myctophidae and Sternoptychidae, can be difficult to separate acoustically from a *single* gas bubble. However, the behaviour of such fish assemblages is substantially different from the gas bubble *plumes*. Using both backscattering frequency response and behaviour traits (at one time instance and over time) are likely to give the best chances for acoustic-based detection and identification of seabed gas bubble plumes.

List of papers

Paper I.[*] Kubilius, R., and Ona, E. 2012. Target strength and tilt-angle distribution of lesser sandeel (*Ammodytes marinus*). ICES Journal of Marine Science, 69: 1099–1107.

Paper II. Kubilius, R., Ona, E. and Calise, L. Measuring *in situ* krill tilt orientation by stereo photogrammetry: examples for *Euphausia superba* and *Meganyctiphanes norvegica.* Submitted to ICES Journal of Marine Science.

Paper III. Kubilius, R., Ona, E. and Pedersen, G. Acoustic frequency response of adult saithe (*Pollachius virens*) observed in lateral aspect. Planned for submission to ICES Journal of Marine Science.

Paper IV. Kubilius, R. and Pedersen, G. Relative acoustic frequency response of induced methane, carbon dioxide and air gas bubble plumes, observed laterally. Submitted to the Journal of the Acoustical Society of America.

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Contents

1. Introduction

Natural gas seeps have been observed by man since the ancient times from a variety of sources and at scales ranging from dramatic events such as erupting volcanos to much more humble bubbles rising towards the surface of a shallow lake. With improving technologies to access and observe marine environments, ocean seabed gas seeps have been found to be common (e.g. Hovland and Judd, 1988). Sources of these natural subsea seeps are diverse, including but not limited to, gas-containing fluid vents (Lupton et al., 2008), “melting” methane hydrates (Kvenvolden et al., 1993; Westbrook et al., 2009), pockmarks (Hovland et al., 1984) and mud volcanos which are responsible for some of the truly enormous subsea gas vents (Greinert et al., 2006). More recent phenomena are manmade seabed gas seeps from subsea natural gas extraction installations (e.g. rupture in the transportation pipe) and proposed carbon dioxide storage sites in geological structures below the sea floor (IPCC, 2005; DNV, 2010). Many of these geographically widespread gas seeps are subject to research and monitoring, often because of the potential influence and contribution to atmospheric gas composition and long term climate change (Judd et al., 2002; Archer, 2007).

One of the best ways to detect a gas bubble rising in the water column at a substantial range is via acoustic methods. Active acoustics is arguably one of the best observation tools for rapid and cost effective coverage of large water volumes. Scientific echo sounders, for example, are rather sensitive tools, which can be calibrated to a high degree of precision and are widely used for fish stock monitoring (Simmonds and MacLennan, 2005). However, there are other objects in the sea than bubbles that can cause significant acoustic backscatter. Countless species of fish and planktonic organisms dwell in the world’s oceans. Some of these are extensively studied using acoustic methods and monitored for absolute or index-based biomass estimates as is the case for some commercially important fish species (Toresen et al., 1998; McQuinn et al., 2005; Simmonds and MacLennan, 2005). The acoustic backscattering properties of these animals are also used for target identification purposes (e.g. Holliday, 1972; Cochrane et al., 1991; Brierley et al., 1998; Kang and Miyashita, 2002), with a reasonable degree of success for some schooling species (e.g.

Kloser et al., 2002; Johnsen et al., 2009; Korneliussen, 2010). From an acoustical point of view fish that possesses a gas-filled swim bladder reflect sound in a rather similar manner as a gas bubble of similar dimensions (Foote, 1980c). However, bladderless fish and planktonic organisms may also bear some similarity to gas bubble plumes when observed by echo sounders (e.g. schools of fish or krill and gas inclusion-bearing plankton).

This particular study is part of continuing work on one of the main challenges to using active acoustics to observe and monitor gas bubble plumes – target identification, with gaseous bladder-bearing fish as potentially the most similar target in the marine environment. The lesser sandeel (*Ammodytes marinus*) was investigated as an example for fish with no swim bladder (**Paper I**). The acoustic backscattering properties of saithe (*Pollachius virens*) were studied in more detail and used as an example of a gas-filled swim bladder bearing fish (**Paper III**). The acoustic properties of gas bubbles have been extensively investigated by other researchers (Leighton, 1997), especially under controlled laboratory conditions, at close range and at relatively high acoustic frequencies. The body of research on acoustic backscatter properties of naturally occurring oceanic seabed bubble plumes observed *in situ*, at range and at appropriately low echo sounder frequencies is considerably smaller. The acoustic backscattering properties of induced gas bubble plumes were investigated in detail to satisfy the specific needs of this study, i.e. defined lateral aspect acoustic frequency response at 70-333 kHz (**Paper IV**). These experiments were conducted using scientific echo sounders, identical to those used to observe and quantitatively study biota in pelagic marine environments. Optic-based measurements were also crucial to supplement and aid the detailed investigations of the acoustic target backscatter properties. The specific optic measurement methodologies used were adapted and certain aspects improved (**Papers I, II**) for the particular applications (**Papers I, II, III, IV**).

There is a wide range of active acoustics tools and methods that could potentially be used to observe gas seeps. The scope of this study was framed and focused by the goals of two R&D projects (AKUGAS and AALDOG[†]) which use a specific approach (acoustic "lander" with lateral acoustic observations along the sea floor), equipment (scientific split-beam echo sounders of practical physical dimensions) and targets (gas plumes and fish schools rather than single targets). In practice this involved the use of readily available Simrad brand split-beam scientific echo sounders with nominal operating frequencies of 70, 120, 200 and 333 kHz, mounted to observe laterally.

[†] AKUGAS and AALDOG –"Technology for Acoustic Detection of Gas Seeps" and "Active Acoustic Leak Detection of Oil and Gas" respectively. Two research and equipment development projects, hosted by Metas AS, funded by Regional Forskningsfond Vest (ES475282), Research Council of Norway (ES471693) and Metas AS.

1.1 Objectives and tasks

The objective of this study was to investigate and characterise specific aspects of the acoustic backscattering properties of induced gas bubble plumes and selected biological targets. And to discuss the feasibility of accurate active acoustic-based seabed gas bubble plume identification. The following steps were followed to achieve this objective:

- Adopt, modify and, if needed, improve optic-based measurement methodologies required to support fine scale acoustic backscatter investigations of the relevant acoustic targets (**Papers I, II**).
- Investigate the acoustic backscatter of free-swimming lesser sandeel (*Ammodytes marinus*) and natural body tilt orientation as an example of swim bladder-lacking fish (**Paper I**).
- Investigate the natural body tilt orientation distribution of krill (*Euphausia superba* and *Meganyctiphanes norvegica*) as an example of large, fluid-like plankton organisms (**Paper II**); to learn the possible implications of orientation on the animal's acoustic multi-frequency backscattering.
- Evaluate the lateral aspect acoustic backscattering of saithe (*Pollachius virens*) as representative for a gas-filled swim bladder-bearing fish (**Paper III**).
- Characterise lateral aspect acoustic backscattering of gas bubble plumes under controlled conditions (**Paper IV**).

1.2 Types of acoustic targets in the ocean

The most common acoustic targets observed in the pelagic water column by active acoustics can be broadly grouped into suspended particles (often of organic origin), phyto- and zooplankton, various types of fish, with or without swim bladder, and near-surface bubbles created by natural wave action (Figure 1). Some of the less common objects detected by echo sounders are gas bubble plumes rising from the sea floor. The acoustic backscatter properties of common acoustic targets, which are most relevant for this study, will be briefly discussed.

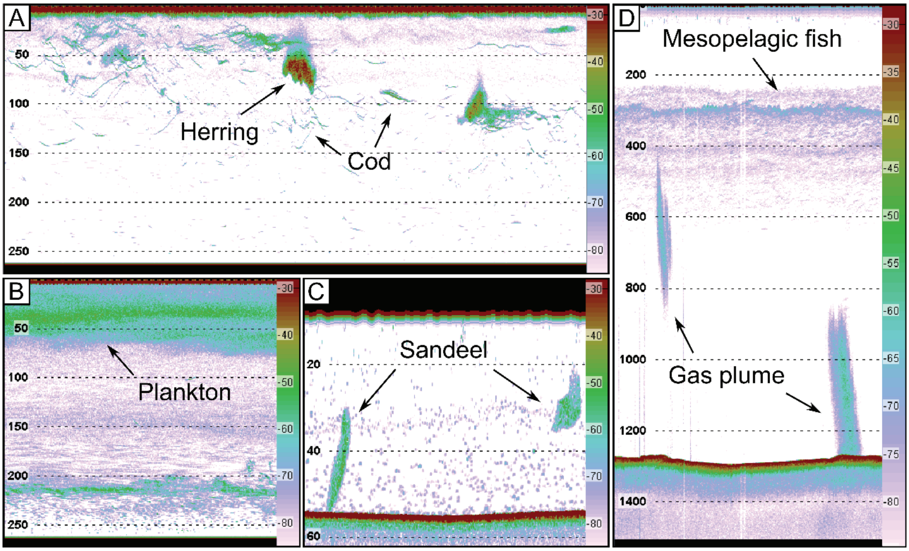

Figure 1. Examples of acoustic targets in the water column observed by scientific fisheries echo sounders. A - schools of Atlantic herring and scattered Atlantic cod, observed ventrally by a stationary acoustic lander (operated at 70 kHz) placed on the seabed north of the Lofoten islands, Norway (LoVe lander 2015.02.19, http://love.statoil.com/). B – LoVe lander recording a near-surface plankton layer (2014.05.15), which may have gas inclusions of a size that resonates at the echo sounder frequency (70 kHz). C – two lesser sandeel schools observed by cruising RV Johan Hjort (2010), one of the schools has a characteristic "connection" to the seabed (38 kHz; data courtesy of Institute of Marine Research, Norway). D - large gas bubble plume rising from the Håkon Mosby mud volcano in the Barents Sea, same plume crossed twice by cruising and then returning on its previous track vessel. The acoustic backscattering signature of the layer at 300 m depth is dominated by gas-filled swim bladder bearing mesopelagic fish. Recorded at 18 kHz by RV G. O. Sars in 2005 (data courtesy of Institute of Marine Research and Bergen University, Norway). Scale on the echogram left-hand side is depth in meters. Colour scale on the right-hand side is volume backscattering strength in decibels.

Plankton

Phyto- and zooplankton are usually the most common biological targets observed by vessel-mounted echo sounders in the water column. These vary in size from microscopic up to macro-zooplankton, such as various species of krill (e.g. up to ~6 cm for Antarctic krill). Plankton is a very broad group of acoustic targets, observed by echo sounders as swarms, aggregations or layers with differing acoustic properties (Figure 1B). The near-surface phytoplankton “blooms” following favourable environmental conditions is one extreme example (Townsend et al., 1994; Joint and Groom, 2000). Not all organisms deemed as plankton are completely at the mercy of the water currents. Some active locomotion-capable planktonic organisms (e.g. siphonophores, copepods and krill) are known to migrate up and down in the water column (e.g. Pugh, 1977; Bollens and Frost, 1989; Vestheim et al., 2014 respectively). The acoustic properties of phytoplankton have been studied (Selivanovsky et al., 1996; Shenderov, 1998), but groups of zooplankton have received considerably more attention. In respect to the acoustic backscatter properties, zooplankton can be broadly grouped into fluid-like (e.g. euphausiids), elastic-shelled (e.g. gastropods) and gas-bearing (e.g. siphonophores) (Stanton et al., 1996). The body density of the fluid-like and elastic-shelled organisms is not very different from the surrounding seawater. This has a profound effect on the acoustic backscatter properties of these targets as the acoustic impedance contrast between the target and the surrounding medium is a crucial determinant of the acoustic backscatter strength. Fluid-like plankton, therefore, has a relatively low acoustic backscatter, generally orders of magnitude lower than the echo from a comparable size gas bubble. Some phyto- and zooplankton, however, do form small gas inclusions in their bodies, which then dominates their acoustic backscatter. The gas inclusion in phytoplankton is generally small in size, but can occupy up to 30% of the cell volume in some cases (Selivanovsky et al., 1996), while acoustic echoes of some siphonophores are dominated by relatively large, ~1-3 mm sized gas inclusion in the pneumatophore (Stanton et al., 1998; Warren et al., 2001). Gas inclusion-bearing plankton organisms generally have limited (e.g. phytoplankton) or somewhat limited (e.g. siphonophores) active locomotion capability and do not form schools or shoals. This parameter is also important to consider when comparing them to the expected backscattering from seabed gas bubble plumes. Moderate size gas bubble inclusions in these organisms can cause resonance effects at one or several commonly used frequencies (e.g. 18, 38, 70 kHz). Due to the gas inclusion, the acoustic properties of some planktonic organisms are somewhat similar to free gas bubbles rising from the seabed.

Direct acoustic plankton species or taxa identification is often not possible, and independent tools, such as net sampling, are necessary in order to validate the acoustic recordings (Simmonds and MacLennan, 2005). However, when the number of species is low, or for some specific groups, such as krill, acoustic identification methods have been successfully applied and are generally based on the backscatter differences at two or more frequencies (e.g. Madureira et al., 1993; Brierley et al., 2006; McQuinn et al., 2013). Brierley et al. (2006), for example, had reasonable success in acoustically discriminating Southern Ocean euphausiids, amphipods and mysids using 38, 120 and 200 kHz. At this point, however, it is enough to note that acoustic backscatter of many planktonic organisms is generally found to be dynamic over the available echo sounder frequency bands, and such may be used for discrimination purposes.

Fish

Fish is another large group of acoustic targets, which may be detected by echo sounders in the pelagic part of the water column. As acoustic targets, fish can be divided into four groups: fish with closed gas-filled swim bladder (physoclistous), fish with open gas-filled swim bladder (physostomous), fish with oil or lipid-filled swim bladder and bladderless fish. Some fish that are bladderless or have a lipid-filled swim bladder when adult may have gaseous swim bladder as larvae or juveniles. Even more generally, these could be split into gas-filled swim bladder bearing fish and fish with no gas inclusions in their bodies. This is because presence or absence of the gas-filled swim bladder has a major impact on the acoustic backscattering from the fish (Foote, 1980c).

Bladderless fish are an abundant group of species, where examples include lesser sandeel (*Ammodytes marinus*) and Atlantic mackerel (*Scomber scombrus*), which are both common in the North Atlantic (Macer, 1966; Iversen, 2004). The lack of a gas inclusion in these fish means that other body structures such as bones, liver and gonads gain a higher relative importance in forming the signature of the total backscattered acoustic energy (see e.g. Ona, 1990; Forland et al., 2014a; 2014d). This also means that the mean acoustic target strength is significantly lower compared to similar sized fish which possess a gas-filled swim bladder (e.g. Clay and Castonguay, 1996; Ona, 2003; **Paper III**). For example, a 30 cm long Atlantic cod (*Gadus morhua*) is expected to have about 66-71 times stronger (~18 dB) mean echo than 30 cm long Atlantic mackerel (Clay and Castonguay, 1996). However, schools of bladderless fish can still be rather strong acoustic targets, which likely can approach the backscatter level of a diffused gas bubble plume. Schools of fish, in fact, are a morphological structure of some similarity to gas bubble plumes, much more so than layers of plankton. Lesser sandeel, for example, is regularly observed forming schools of peculiar shapes, which have a distinct "connection" to the seabed (Figure 1C) and could, therefore, bear some resemblance to a seabed gas bubble plume.

The acoustic frequency-dependent backscattering properties have been described for some common and commercially important bladderless fish species and are now being used for acoustic target identification with a reasonable degree of success. This is true for lesser sandeel (Johnsen et al., 2009) and Atlantic mackerel (Korneliussen, 2010), where schools of both species were found to have a rather distinctive frequency response over the acoustic frequency band used by scientific fisheries echo sounders on research vessels.

Fish possessing a gas-filled swim bladder are also a numerous group, and contain many of the well-known and commercially important fish species, such as North Atlantic cod, Atlantic herring (*Clupea harengus*) and saithe (*Pollachius virens*). These also include small and widespread mesopelagic fish, such as lanternfish (*Benthosema glaciale*) and Mueller's pearlside (*Maurolicus muelleri*) (Gjøsaeter and Kawaguchi, 1980). For fish with gas-filled swim bladders, over 90% of the mean dorsal aspect acoustic backscattering originates from this organ (Foote, 1980c). This is because the acoustic impedance contrast between fish flesh and the gas in the swim bladder is much greater than between seawater and fish flesh. Subsequently, such fish may look as a rather similar acoustic target compared to a free gas bubble of similar dimensions as the gas-filled cavity in the fish. The acoustic backscattering from fish, however, is generally not equal at different frequencies. Gaseous swim bladder bearing fish, such as widespread North Atlantic saithe, Atlantic cod, Norway pout, Atlantic herring and few common species from Myctophidae and Sternoptychidae have been measured to have a frequency-dependent acoustic backscatter (e.g. Gorska et al., 2004; Pedersen and Korneliussen, 2009; Scoulding et al., 2015). The trend, when measured dorsally, is broadly similar between species and negative for increasing frequencies. Bladderless fish, on the other hand, have an opposite, positive trend with increasing frequency, as for lesser sandeel and Atlantic mackerel (Johnsen et al., 2009; Korneliussen, 2010). Both fish types can be quite directive targets at commonly used echo sounder frequencies (18-333 kHz). This means that fish body posture in respect to the acoustic wave front can significantly influence the acoustic backscatter of the fish (Haslett, 1977; Nakken and Olsen, 1977; Foote, 1980a). This relationship is less pronounced for smaller fish (e.g. myctophids) and at lower echo sounder frequencies. In fact, small gas-filled swim bladder bearing mesopelagic fish, such as the widespread lanternfish and Mueller's pearlside, possess a nearly spherical or ellipsoidal swim bladder (e.g. Scoulding et al., 2015) of comparable size to bubbles found in gas plumes (details in the following section). Since the swim bladder of these fish is significantly smaller than the acoustic wavelength (in much of the frequency band common for fisheries echo sounders) the scattering is nearly omnidirectional and, therefore, much less affected by the animal body orientation or the transducer observation aspect. As a *single* acoustic target, the echo from these fish is potentially very similar to the echo from a free gas bubble. Swim bladder bearing pearlsides and myctophids are, on the other hand, known to form layers in deep water and exhibit diel vertical migration cycles involving vertical movements of up to hundreds of meters, as observed with both vessel- and bottom-mounted echo sounders (Godø et al., 2009; Kaartvedt et al., 2009). Individual lanternfish (*B. glaciale*), for example, have been documented to exhibit peculiar, sudden vertical movements with stops, while at other times appeared to be passively carried with the tidal currents, behaving essentially as plankton (Kaartvedt et al., 2009). However, these swim bladder bearing mesopelagic fish generally form layers of varying density (e.g. Marchal and Lebourges, 1996; Luo et al., 2000; McClatchie and Dunford, 2003; Godø et al., 2009; Kaartvedt et al., 2009), which is a substantially different morphological structure compared to gas bubble plumes (Figure 1D).

Gas leaks

Natural seabed gas bubble seeps of various origin have been directly observed worldwide with various types of echo sounders. The origin of these range from pockmarks in the Scotian Shelf and North Sea (King and MacLean, 1970; Hovland et al., 1984; Schneider von Deimling et al., 2010) to deep sea mud volcanos (e.g. Dimitrov, 2002; Greinert et al., 2006; Perez-Garcia et al., 2009) and widespread gas hydrates (Kvenvolden et al., 1993). Most of these gas bubble seeps, especially cold seeps, are dominated by methane gas, less often by carbon dioxide. The bubble sizes, observed for natural methane seeps, are generally about 0.4-18 mm, more commonly 1-10 mm (Rehder et al., 2002; Heeschen et al., 2003; Leifer and Boles, 2005; McGinnis et al., 2006 and citations within; Ostrovsky et al., 2008). Seabed gas seeps have been suggested as important contributors of methane both to the biosphere, the hydrosphere and the atmosphere (Judd, 2003). The sizable amounts of methane that is present and seeps out from the oceanic seabed are still poorly monitored, but are considered important for their likely long-term contribution to atmospheric greenhouse gases (e.g. Judd et al., 2002; Judd, 2003; Archer, 2007). Widespread seabed methane hydrates are prone to “melting”, that is bubbling and dissolving, if conditions with respect to their stability (pressure and temperature) are violated (Kvenvolden et al., 1993; Archer, 2007). The methane hydrate stability zone (HSZ) extends below about 520-540 m water depth (Rehder et al., 2002; Zhang, 2003). It has a large impact on the methane bubble dissolution rate, because hydrate-coated bubbles dissolve very slowly within the HSZ and quite rapidly above it. As an example, methane bubbles of 12-13 mm size released at 230 m depth would be only ≤10 % of their initial diameter by the time they reach the surface (McGinnis et al., 2006). In a similar manner dissolution rate of carbon dioxide bubbles is also affected if below the HSZ boundary depth, which is at about 350 m for carbon dioxide (Brewer et al., 1998).

Anthropogenic sources of seabed gas leaks, such as blowouts in offshore drilling or leaks from gas transportation pipes, are a relatively new phenomena, but indicate a high need for active leak monitoring and timely detection and identification (DNV, 2010). This is also true for proposed carbon dioxide storage reservoirs in geological structures under the seabed (IPCC, 2005). Active acoustic methods have important advantages in detecting and monitoring gas bubble plumes, such as cost efficient, rapid and continuous sampling of large water volumes. As already mentioned, the strength of the acoustic backscatter from a target largely depends on the acoustic impedance contrast between the target and surrounding water. Therefore, seabed gas bubble plumes are favourable acoustic targets, which can be detected at substantial distances or depths. There is a large body of research on the acoustic properties of gas bubbles observed in the controlled laboratory settings (e.g. Leighton, 1997), but *in situ* investigations of the acoustic properties of gas bubble seeps are less abundant and detailed. Active acoustic methods can and have been employed to detect and map gas bubble plumes or associated seabed structures using equipment such as side-scan sonars, multi-beam echo sounders, seismic exploration systems and scientific fisheries echo sounders (e.g. Merewether et al., 1985; Naudts et al., 2006; Westbrook et al., 2009). Only scientific fisheries echo sounders can currently provide calibrated, quantitative acoustic measurements, as well as within-beam position of individual targets. In fact, research on seabed gas bubble plume flow quantification with scientific fisheries echo sounders is already being done (Greinert and Nützel, 2004; Leblond et al., 2014). However, while gas bubbles do return a relatively high acoustic backscatter and are generally easy to detect with fisheries echo sounders, gas bubble plume interpretation and identification is still largely based on manual inspection of echograms and supplementary sampling forms or prior knowledge. Acoustic discrimination techniques, successfully implemented for identification of fish and zooplankton (e.g. Kloser et al., 2002; Korneliussen and Ona, 2002; 2003), are yet to be tested on seabed gas bubble plumes.

Brief account of a bubble

A bubble, in simple terms, is a gas-pocket in a liquid contained by surface tension forces. The size of gas bubbles can range from micrometres to several centimetres or more. Bubble shape is generally size-dependent and can vary widely: spherical, ellipsoidal, skirted ("jellyfish" like), spherical cap, etc. (Clift et al., 2005). Generally, the larger the bubble, the more it deviates from a spherical shape. This is because the smaller the local radii of a bubble surface curvature, the stronger the surface tension forces, which ensure that smaller bubbles are more likely to be spherical and maintain that shape (Leighton, 1997). Air bubbles with an equivalent radius (the radius a bubble would assume if formed into a sphere of equal volume) less than about 0.5 mm are spherical, those of about 0.5-7 mm are roughly ellipsoidal, while larger bubbles have an irregular shape (Leighton, 1997). Larger bubbles tend to be less stable and may split into smaller bubbles. Empirical studies of natural methane gas seeps report bubble sizes of about 0.4-18 mm in diameter. The bubble rising speed is dependent on its size, but may also vary due to the amount of other material on the bubble surface (e.g. hydrate-coated bubbles, oil-coated bubbles, etc.) (e.g. Leifer et al., 2000; Leifer and Patro, 2002; McGinnis et al., 2006). Generally, the rising speed of bubbles peak at 0.30-35 m/s for roughly 1.5 mm diameter bubbles. It is lower for smaller bubbles (<1.5 mm) depending on the amount of drag forces and somewhat decreases for larger bubbles (~2-20 mm), when non-spherical bubbles shapes become common. Bubble rising speed can be lower for its size due to presence and amount of surface-active materials, hydrate- and oil-coating.

The acoustic properties of bubbles, both sound generation and backscatter are quite well described (see e.g. Leighton, 1997; Medwin and Clay, 1997). In general, the acoustic backscattering from a free gas bubble is reasonably predictable and well described (Leighton, 1997). Its acoustic backscatter is affected by a range of factors such as acoustic frequency, equivalent bubble mass, stiffness, damping (thermal, viscous and re-radiation) and other gas- and water-specific properties. The strength of the bubble backscatter is largely determined by the specific acoustic impedance ratio between gas inside the bubble (e.g. 400 kg/m^2s for air at standard temperature and pressure) and surrounding water (e.g. $1.5x10^6$ kg/m^2s for freshwater) (Leighton, 1997).

The impedance variation between different gas types is of lower importance, because the impedance contrast between gas (air, CH_4, CO_2 etc.) and water is so large at shallow depths. Therefore, factors such as bubble size and shape, acoustic frequency and ambient pressure are generally more important in determining the backscatter. A relevant backscatter feature is resonance where at a specific acoustic frequency the bubble size oscillates and generates a much enhanced acoustic return. The acoustic frequency at which this backscatter peak occurs is predictable given bubble size, ambient pressure, density of the fluid and ratio of the specific heats of the gas in the bubble. The first order resonance peak of a gas bubble is sharp and reduced mostly by thermal damping within the frequency range of 1 kHz to 1 MHz (Medwin and Clay, 1997). In general, bubble size at resonance increases with increasing depth for a fixed acoustic frequency. The resonance frequency also depends on bubble shape. For example, prolate spheroid shaped bubbles have a lower backscatter strength and higher resonance frequency compared to a spherical bubble of the same volume (Feuillade and Werby, 1994). The larger the aspect ratio of prolate spheroid bubble, the larger the shift. However, for this thesis it is important to note that: (i) damping of the resonance peak is quite different for bubbles enclosed within the body of an organism and (ii) bubbles of sizes commonly reported for natural, ocean seabed-originating methane seeps generally do not resonate at the frequencies used for this work.

1.3 Acoustic lander concept

Echo sounders employed to study gas bubble plumes are most commonly installed on moving platforms such as vessels, towed bodies or remotely operated vehicles. Temporal gas leak variability is likely to be overlooked by these because costly vessel time limits how long specific locations or seeps can be continually observed. A good example of gas seep variability has been documented by Schneider von Deimling et al. (2010) for North Sea pockmarks, which were observed to have a wide range of temporal gas seep patterns. Stationary echo sounders placed on the seabed (hereafter “landers”) are increasingly used to observe biological targets such as krill (Brierley et al., 2006), jellyfish (Ugland et al., 2014), marine mammals (Doksæter et al., 2009) and fish (e.g. Axenrot et al., 2004; Ona et al., 2007; Kaartvedt et al., 2009). These are most frequently equipped with a transducer pointing vertically upwards, towards the sea surface. However, the acoustic beam can easily be oriented sideways to observe the water column near the seabed, thus increasing the seabed area that is monitored for gas seeps. Furthermore, the transducer of such acoustic landers can be equipped with motors for scanning the water column horizontally and vertically (e.g. Godø et al., 2014). Such motorized systems with a wide horizontal swath angle (Figure 2) may be particularly well suited for detecting and identifying seabed gas leaks. These could also be used to reconstruct the 3-D shape of the bubble plume, which may be useful for leak quantification purposes. Automated versions of such landers would be suitable for detecting and studying temporally dynamic leaks (e.g. Schneider von Deimling et al., 2010). It would also be useful for gas leak detection in the subsea natural gas extraction industry or marine underground carbon dioxide storage, where swift and precise leak detection is critical. Following these needs, an acoustic lander system has been developed within the AKUGAS and AALDOG research and development projects under the framework of which the current study was conducted.

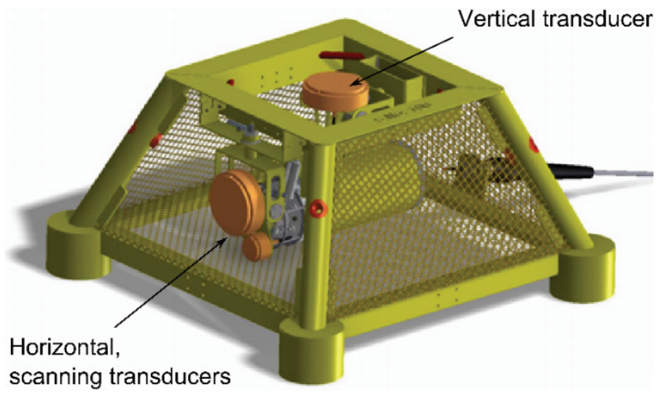

Figure 2. Acoustic lander (1.6x1.6x0.9 m) resting on the seabed, equipped with vertically and laterally oriented transducers, where the latter observe the water column just above the sea floor (drawing by and courtesy of Terje Torkelsen, Metas AS). Transducers for lateral observation are mounted on a motorised platform, enabling the scanning of the water column horizontally and vertically.

2. Discussion

2.1 Detecting subsea gas leaks

Several methods and techniques could be used to locate and identify gas bubble seeps rising from the sea floor. Optics is an obvious choice (e.g. Leifer and Boles, 2005). Remotely operated vehicles equipped with cameras and sonars are sometimes used to identify and observe gas bubble plumes in detail, both close to the seabed and in the water column (e.g. Rehder et al., 2002; Nikolovska et al., 2008). Chemical "sniffers" are another method to identify water masses containing increased concentrations of the dissolved gases generated by seabed sources (e.g. Sackett, 1977; Philp and Crisp, 1982). The later method has an advantage over optic and acoustic methods in some cases as dissolved gases are detected instead of gas bubbles. However, both of the above methods are generally time, labour and cost intensive. The effective detection range of these techniques is also quite limited. Passive acoustics (hydrophones) are also used to detect gas plumes by listening for the specific sounds created by bubbles or the leak and can also locate the source by triangulation (e.g. Leighton and White, 2012). Passive acoustics has a more limited effective range compared to active acoustics when used for bubble detection. Multiple hydrophones are needed in order to locate the gas seep, target identification can be difficult, and some properties of the gas leak can be challenging or impossible to determine (e.g. plume extent in the water column). Active acoustics, on the other hand, provides a rapid and cost effective sampling tool for large water volumes, as is regularly used for fish population monitoring (Simmonds and MacLennan, 2005). The effective range of echo sounders currently used in fisheries acoustics is hundreds to thousands of meters, depending on the acoustic frequency. The strength of the acoustic backscatter largely depends on the acoustic impedance contrast between the target and the surrounding water, which makes gas bubble a highly reflective target. Gas bubble plumes, therefore, are excellent targets for active acoustics and are generally easy to detect. Current scientific fisheries echo sounders can be calibrated to a high degree of precision, which allows the true quantitative measures on targets such as fish, krill (Simmonds and MacLennan, 2005) and perhaps gas bubble flows as well (Leblond et al., 2014).

2.2 Acoustic target identification

One of the main difficulties when employing echo sounders to observe fish and zooplankton is adequate taxa and species identification (Horne, 2000). However, frequency-dependent acoustic backscattering has been used to discriminate between species or target groups since the 1970s. It is long known that fish target strength is depend on fish size, body posture and echo sounder frequency (e.g. Love, 1971). For example, Holliday (1972) attempted to identify fish utilizing swim bladder resonance at low frequencies (0.2-5 kHz). Greenlaw (1977) showed that many common zooplankton animals are both directional scatterers at higher frequencies and that their scattering strength is frequency-dependent. Holliday and Pieper (1980) and Holliday et al. (1989) discriminated plankton into groups by size based on acoustic records at multiple echo sounder frequencies. More recently the comparison of volume backscattering at two or more echo sounder frequencies has been frequently used to separate between groups of targets, such as: between groups of Southern Ocean zooplankton (Madureira et al., 1993; Brierley et al., 1998), fish from zooplankton (Cochrane et al., 1991; Kang and Miyashita, 2002; McKelvey and Wilson, 2006) and between fish groups (Kloser et al., 2002; Logerwell and Wilson, 2004; Jech and Michaels, 2006). Korneliussen and Ona (2002; 2003) used volume backscattering information at multiple frequencies normalized to one frequency in order to construct a simple curve of “relative acoustic frequency response”, the shape of which could then be used to characterise and discriminate between groups of targets. This method is now successfully used to identify schooling fish such as lesser sandeel (Johnsen et al., 2009), Atlantic mackerel (Korneliussen, 2010) and orange roughy (Kloser et al., 2002).

Broadband acoustics, that is transmission and reception over a continuous frequency band, has also been suggested for identification purposes (see e.g. Stanton et al., 2010) and is likely to be implemented in the near future, as broadband transceivers are now available commercially. Today, the most successful acoustic discrimination technique uses the shape of the relative acoustic frequency response (r(f)) curve measured across a range of discreet echo sounder frequencies. Its potential for fish and zooplankton taxa or species identification has been demonstrated (e.g. Kloser et al., 2002; Korneliussen and Ona, 2002; 2003; Anon., 2005) and is now being used to identify targets in regular acoustic surveys for abundance estimation (e.g. Johnsen et al., 2009; Korneliussen, 2010). Therefore, such a technique was the natural choice for acoustic detection and identification of gas bubble plumes (**Paper IV**). This raises the question: how does the backscattering from gas bubble plume compare to the main groups of biological targets and what are the prospects of acoustic discrimination between such targets.

2.3 Comparing gas plumes and biota

The objective of this study was to characterise the acoustic backscatter of selected acoustic targets in order to supplement the discussion and knowledge on acoustic seabed gas bubble plume detection and identification. This is an ongoing work and was by no means finalized by this doctoral study. Furthermore, the study objectives were shaped by the practical needs of two R&D projects, where gas bubble *plumes* and fish *schools* are the most relevant acoustic targets, rather than single bubble or single fish targets. The discussion proceeds with this focus.

Bubbles at resonance

First, let us consider a 2 mm diameter bubble and its basic acoustic scattering traits in two cases: (i) free bubble, a gas-filled cavity in the water, contained by surface tension forces and (ii) bubble immersed in a viscous body of an organism, contained and surrounded by it (e.g. siphonophores, fish larvae, myctophids). The backscatter of a free gas bubble is reasonably predictable for various gas types, environmental conditions, water depths and acoustic frequencies (Leighton, 1997; Medwin and Clay, 1997). Features such as the first order resonance frequency can be calculated with high certainty. A “clean” surface 2 mm diameter methane bubble at 100 m depth, for example, would have a resonance frequency at about 10.4 kHz (Medwin and Clay, 1997; Leblond et al., 2014). The resonance peak of a free bubble is sharp and damped mostly by thermal damping within the frequency range relevant to this work (Medwin and Clay, 1997). The backscattering from a bubble contained within the body of an organism is affected by it, largely due to the different viscosity of the material surrounding the bubble. Furthermore, the large variability in organism body properties and structures surrounding the gas inclusion, which also affect bubble shape, makes it more difficult to accurately predict the backscattering from such a bubble. For example, siphonophore possessing pneumatophore with a single gas inclusion (ellipsoid of size 3 mm x 1 mm) has a resonance frequency that is calculated to be somewhere between 7 and 27 kHz at 100 m depth (Medwin and Clay, 1997), which is also somewhat damped by the viscosity of the material surrounding the bubble. This also applies to fish. For example, mesopelagic lanternfish (*B. glaciale*) have a somewhat wider and lower swim bladder resonance peak (20 kHz for 2.9 mm x 1.3 mm swim bladder, Scoulding et al., 2015) than an equivalent sized free gas bubble. The acoustic backscattering features associated with the resonance frequencies of free gas bubbles and gas inclusion-bearing organisms could potentially be used for discrimination purposes. However, this study considered only echo sounders operating at 70 kHz or higher. This is well above the resonance frequency for the bubble sizes most commonly observed in cold methane seeps (commonly 1-10 mm; Rehder et al., 2002; Heeschen et al., 2003; Leifer and Boles, 2005; McGinnis et al., 2006 and citations within; Ostrovsky et al., 2008). The use of 50 kHz or higher echo sounder frequencies has been suggested for bubble plume investigations down to no more than 1000 m to specifically avoid bubble resonance, which may complicate quantitative gas seep measures (Greinert and Nützel, 2004). For the commonly reported bubble sizes in cold seeps, and echo sounder frequencies considered in this study, bubble resonance is not important.

Bubbles and plankton

The dorsal aspect acoustic backscatter of planktonic, fluid-like organisms, such as medusas, euphausiids and copepods, has a distinct pattern (Figure 3) with a general tendency of increase across the acoustic frequency band commonly used for fisheries echo sounders (18-333 kHz).

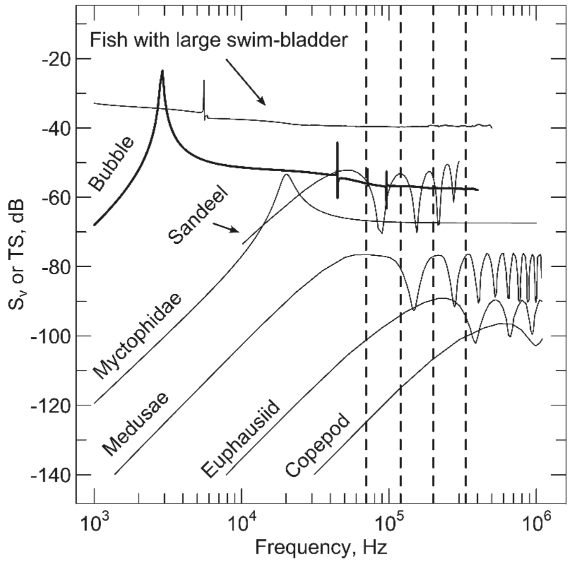

Figure 3. Modelled dorsal aspect acoustic backscatter from some common biological targets, and a gas bubble. The copepod (1.5 mm length), euphausiid (9.8 mm) and medusa (16.5 mm) are redrawn after Lavery et al. (2007). The sandeel (140 mm) is redrawn after Forland et al. (2014d) showing modelled target strength. The modelled target strength of a swim bladder-bearing myctophid (37.4 mm *B. glaciale* with 2.9 mm long ellipsoidal swim bladder at 30 m depth) is redrawn after Scoulding et al. (2015). The "bubble" represents the backscatter for a 2.5 mm diameter methane gas bubble calculated using Anderson's solution (Anderson, 1950). The dorsal aspect backscattering from a large swim bladder bearing fish is approximated here by scattering from a gas bubble (equivalent of 4 cm diameter gas inclusion), the peak at 5.5 kHz is due to higher-order bubble resonance. The vertical dashed lines indicate 70, 120, 200 and 333 kHz.

It is clear that differences in the trend of the frequency-dependent acoustic backscatter of common fluid-like plankton organisms and gas bubbles is a good candidate for discrimination (Figure 3, **Paper IV**). Furthermore, the large difference in backscattering level between the planktonic organisms and a moderate sized gas bubble (Figure 3) means that volume backscatter could also be used as a parameter for discriminating between bubble plumes and zooplankton. Finally, zooplankton is often observed in scattered layers (Figure 1B), that is, with a fundamentally different distribution pattern compared to gas bubble plumes, which often form a distinct shape in the water column (Figure 1D). However, some zooplankton, such as euphausiids, do also form distinct schools. One example is Antarctic krill (*Euphausia superba*), which forms large polarized schools which are detected as strong acoustic targets (Figure 8 in **Paper II**). On the other hand, this is more of an exception rather than a rule for zooplankton. Krill schools are also generally found in the mid to upper layers of the pelagic water column (e.g. Klevjer et al., 2010; Warren and Demer, 2010), while gas bubble plumes may best be observed close to the seabed, not far from the source (Figure 2). In addition, methane, the most common gas escaping from cold seeps, dissolves quite rapidly if above the methane hydrate stability depth (~520-540 m).

Most frequently, zooplankton acoustic backscatter is evaluated or measured from vessels and with vertically downwards oriented echo sounders. Lateral observation aspect is, however, at the core of the objectives for this study. For directive acoustic targets a change in echo sounder observation aspect from dorsal to lateral may have serious consequences for the mean backscattering properties (e.g. Haslett, 1977). This will depend on acoustic frequency, size, shape and composition of the object and on changes in the "average" animal body orientation relative to the acoustic wave front. Broadly speaking, the lower the frequency and the smaller and rounder the shape of the target, the less directive it is. Therefore, acoustic directivity patterns of small sized fluid-like zooplankton are likely to change less from dorsal to lateral observation aspects compared to many of the fish targets. Single-celled phytoplankton organisms are also close to being omnidirectional scatterers at the commonly used echo sounder frequencies. Phytoplankton forming chains of cells, though weak, but can be directive acoustic targets at higher echo sounder frequencies. However, the average orientation of these can be expected to be quite variable in space, thus decreasing target directivity impact on the average backscatter when changing echo sounder observation aspect. Even for larger and actively moving zooplankton, such as copepods and some of the jellyfish, any directivity dependency of dorsal versus lateral echo sounder observation aspect is likely to be diminished or averaged by the variable swimming activity (see e.g. Kaartvedt et al., 2011; Moriarty et al., 2012; Bradley et al., 2013). Euphausiids are directive scatterers at higher acoustic frequencies (Greenlaw, 1977). Krill body tilt orientation have been suggested as the most important contributor to large predicted and observed dorsal aspect target strength variability (Klevjer and Kaartvedt, 2006; Calise and Skaret, 2011; Calise and Knutsen, 2012), with disparities between empirical data and theoretical model predictions sometimes exceeding 25 dB (e.g. Greenlaw et al., 1980; Cochrane et al., 1991; Stanton et al., 1993; McGehee et al., 1998; Demer and Conti, 2003; 2005). The tilt angle distribution of the two most abundant krill species in the Antarctic and North Atlantic oceans (*Euphausia superba* and *Meganyctiphanes norvegica*) were accurately measured in several marine environments and setups, both *in situ* and *ex situ* in **Paper II**. The krill tilt angle distribution was found to be large (standard deviation of up to 30°; Figure 6 and Table 4 in **Paper II**). A large variability in swimming track direction and behavioural patterns (e.g. swimming in loops) has also been reported for individually observed krill (Klevjer and Kaartvedt, 2006). This suggest that the mean dorsal and lateral aspect krill backscatter is not likely to be drastically different due to the variable swimming behaviour and body postures adopted by these animals. Large differences between krill and gas bubble plume frequency-dependent backscatter combined with a sizable difference in echo level (Figure 3) may prove to be sufficient discriminators between these targets.

Plankton, which have small gas inclusions are similar acoustic targets to free gas bubbles. In phytoplankton, these gas inclusions are generally much smaller than the usual bubble size range found in cold methane seeps (commonly about 1-10 mm; Rehder et al., 2002; Heeschen et al., 2003; Leifer and Boles, 2005; McGinnis et al., 2006 and citations within; Ostrovsky et al., 2008). Therefore, already the general echo level may be a feasible candidate for one of the discriminating acoustic features. The echo from gas-bearing siphonophores, on the other hand, is dominated by a single gas inclusion of about 1-3 mm in size (Stanton et al., 1998; Warren et al., 2001). Plankton with gas inclusions generally have somewhat limited (e.g. siphonophores) or no ability for active locomotion (e.g. phytoplankton). Free-floating layers of gas inclusion-containing plankton (Figure 1B) may possibly obscure the gas bubble plumes if at high densities. However, misinterpretation of a plankton layer for a gas bubble plume is thought to be unlikely given the large difference in aggregation morphology and behaviour between the gas-bearing plankton and seabed gas bubble plumes. The effect of possible plankton gas inclusion resonance can increase the apparent echo strength from these gas-bearing organisms at specific acoustic frequencies, but is relatively easy to identify, if multiple echo sounder frequencies are used in parallel.

Bubbles and fish

Fish as acoustic targets can be thought of as two broad groups based on presence or absence of a gas-filled swim bladder. Even though gas-filled swim bladder-bearing fish has more similarity in acoustic backscatter properties to gas bubble plumes, both groups are discussed.

Fish are more complex sound scattering objects than many of the planktonic organisms. This is because the fish body includes additional structures of varying density (e.g. swim bladder, bones, liver) and the generally larger size of fish leads to the significant increase in the acoustic directivity at the relevant echo sounder frequencies. While the above is true for both fish with and without gas-filled swim bladders, the mean acoustic backscattering from swim bladder bearing fish is dominated by the reflection from this organ (Foote, 1980c). The mean dorsal aspect target strength for some widespread and commercially important fish is well described (Armstrong, 1986; Clay and Castonguay, 1996; Ona, 2003; Pedersen and Korneliussen, 2009; **Paper III** to mention a few). Some of the most common schooling bladderless fish in the North Atlantic Ocean are lesser sandeel and Atlantic mackerel, while saithe, Atlantic herring and Atlantic cod are examples of schooling or shoaling bladdered and acoustically directive, strong targets. The dorsal aspect frequency-dependent acoustic backscatter is also well described for both lesser sandeel (Johnsen et al., 2009; Forland et al., 2014d) and Atlantic mackerel (Korneliussen, 2010; Forland et al., 2014a). The frequency response for dorsally observed schools of common bladderless fish has a general pattern of increase across much of the common echo sounder frequency range (Figure 4A). Gas bubble plumes, however, generate an acoustic backscatter that decreases within the same frequency range. This is shown both by modelling and empirical measurements (Figure 3, Figure 4B, **Paper IV**). The same trend is also seen for dorsally measured swim bladder bearing fish, such as saithe, Atlantic cod, Atlantic herring and Norway pout (Gorska et al., 2004; Pedersen and Korneliussen, 2009).

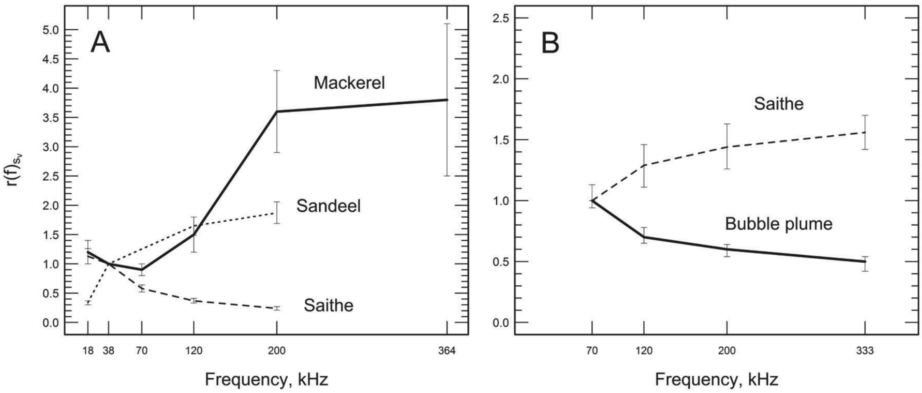

Figure 4. Examples of relative acoustic frequency response (r(f)) measured on several bladderless and swim bladder bearing fish, and gas bubble plumes. A – dorsally measured acoustic frequency response (r(f) normalized at 38 kHz) measured on schools of Atlantic mackerel (redrawn after Korneliussen (2010)), lesser sandeel (redrawn after Kubilius and Johnsen (2010) (unpublished), similar to Johnsen et al. (2009)) and saithe (redrawn after Pedersen and Korneliussen (2009)). B – laterally measured acoustic frequency response (normalized at 70 kHz) of gas bubble plumes and schooling saithe (results from **Papers III and IV**). Vertical bars indicate the variability measures (generally 95% confidence interval or standard deviation).

Considering the available body of research on the dorsal aspect acoustic scattering of schooling fish, it appears that the acoustic frequency response is a strong candidate for acoustically separating gas bubble plumes and bladderless fish (Figure 4). Most confounding targets could be schooling fish with sizable swim bladders, because these have a similar trend of the frequency response as the gas bubble plumes (e.g. Gorska et al., 2004; Pedersen and Korneliussen, 2009; Figure 4A). However, *lateral* aspect observations were emphasised in the far reaching goals of this thesis. It can be argued that acoustic directivity would differ little when changing from dorsal to lateral observation aspect for spherical, round or ellipsoidal targets such as a gas bubble or a small mesopelagic fish possessing similar shaped swim bladder (e.g. some of the Myctophidae and Sternoptychidae). Though abundant and widespread (Gjøsaeter and Kawaguchi, 1980), mesopelagic fish with gas-filled swim bladders are generally observed as layers of varying density (e.g. Luo et al., 2000; McClatchie and Dunford, 2003; Godø et al., 2009). These fish also perform diel vertical migrations, sometimes over hundreds of meters (Godø et al., 2009), while at other times drift with the water currents almost like plankton (Kaartvedt et al., 2009). Dispersed layers of mesopelagic fish have a rather different morphological structure and behaviour compared to gas bubble plumes (Figure 1D). It is also different for large, directive and schooling targets like saithe, herring or mackerel. For larger and acoustically directive fish the body posture relative to the incoming acoustic wave is particularly important (Love, 1971; Haslett, 1977; Nakken and Olsen, 1977). For this reason, measurements of natural fish body posture or tilt orientation distributions have been called for (Foote, 1980a) and measured (e.g. Foote and Ona, 1987; **Paper I; Paper II**). Pelagic fish such as saithe, herring and sandeel have a broadly horizontal average body *tilt* angle with somewhat limited degree of variation (Foote and Ona, 1987; Huse and Ona, 1996; **Paper I**). However, if viewed from the lateral aspect the *yaw* angle of the fish body may vary within the whole 360° range. Thus, the expected average fish body posture relative to the acoustic wave front is substantially different when changing from dorsal to the lateral observation aspect. One might expect that for directive fish targets, the relative backscattering strength at higher echo sounder frequencies would somewhat decrease when changing from dorsal to lateral observation aspect. This would mean that the frequency response curve shape for fish like mackerel and sandeel would become more horizontal and for bladdered fish, such as saithe, r(f) curve would decrease more quickly (Figure 4A). The idea was tested by measuring the lateral aspect frequency response of saithe (**Paper III**). An increasing mean backscattering with increased frequency was now measured (Figure 4B), and with similar but completely opposite frequency response curve shape as for dorsally measured saithe (Figure 4A). This result was positive news for acoustic-based gas bubble plume discrimination from swim bladder bearing fish, because of the large difference in the frequency-dependent backscattering (Figure 4B). An explanation for this behaviour can be sought in the convolution of the directivity pattern of the individual target and its orientation relative to the transducer. Targets much smaller than the acoustic wavelength are omnidirectional scatterers and the orientation of the target relative to the acoustic wave front is not important. On the other side of the spectrum are large targets of elongated shape, such as saithe or Atlantic mackerel, which are very directive targets at the relevant frequency range (70-333 kHz). Furthermore, the acoustic directivity pattern of such fish targets becomes more complex with increasing echo sounder frequency (see e.g. Love, 1969; Haslett, 1977; Horne and Jech, 1999; Towler et al., 2003; Figure 5).

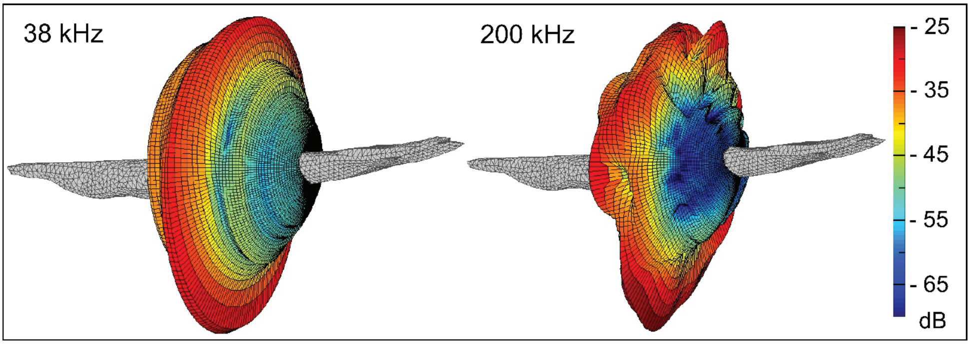

Figure 5. Three-dimensional backscattering model predictions for a 13.3 cm long swim bladder of a 38 cm fork-length saithe at two common fisheries echo sounder frequencies (Geir Pedersen (CMR)). Calculated with the boundary element method (BEM), using the BEM++ library (Śmigaj et al., 2015). Saithe swim bladder shape is digitised from the Foote and Ona (1985).

Fish generate the strongest backscatter when observed at broadside aspect, i.e. the fish body (or swim bladder) is perpendicular to the acoustic axis (Figure 5). Broadside backscatter from saithe is strong for both dorsally and laterally observed fish. However, at higher frequencies it is more complex, variable and includes areas of low backscatter close to broadside aspect (e.g. 200 kHz in Figure 5). Therefore, the average backscatter at higher frequencies close to broadside aspect may be somewhat different compared to lower frequencies. This is the case for dorsally observed saithe as illustrated by the smoothly decreasing dorsal aspect frequency response (Figure 4A). The mean body tilt of saithe is close to horizontal with limited variability (-0.9°, SD=5.4; Foote and Ona, 1987). Laterally observed saithe, on the other hand, have a body orientation relative to the transducer which varies randomly from 0-360°. For laterally observed saithe the mean target strength is higher at higher frequencies (Figure 4B). The backscatter is averaged in the lateral plane over yaw angles with equal probability, and is thus less affected by the backscatter irregularities in the directivity pattern. Recently, a similar increase in lateral frequency response has also been measured for Atlantic herring (Egil

Ona, Institute of Marine Research, Norway). After measuring this peculiar lateral aspect saithe frequency response, the question arises as to what would happen with laterally measured frequency response of bladderless fish, such as Atlantic mackerel or lesser sandeel. This was not measured within this study. However, to follow the line of thought used for discussing the causes of saithe frequency response, the lateral frequency response of bladderless fish, such as Atlantic mackerel (see also Forland et al., 2014a), is also expected to change to a somewhat steeper upwards trend if compared with the dorsal aspect r(f). Confirmation of this is suggested as a topic for future study.

A trait of active acoustics methods that has not yet been explicitly discussed is its ability to sample over time with high resolution. Echo sounder sampling rate (ping rate) is an adjustable setting and can be larger than 5 Hz, depending mostly on the range to the target. The ability to observe targets over time gives an additional discriminator for separating gas bubble plumes from biological targets. Sustained gas leaks would produce an acoustic target in the water column that is persistent over time and would be detected in roughly the same location. Such leaks when observed over time would be quite easy to identify and separate from schools or layers of fish or plankton, which are more likely to move and change their position over time. However, some variability in gas bubble plumes due to water currents is also expected (Schneider von Deimling et al., 2010). Detection and identification of more ephemeral leaks could also benefit from such a discriminator as leaks would reappear in the same position over time.

There are reasons to believe that laterally observed gas bubble plumes could be distinguished from schooling bladderless and swim bladder bearing fish by employing the relative acoustic frequency response technique in combination with backscattering strength and target behavioural traits. The behaviour of seabed gas plumes, which are likely to stay more or less in one place over time or frequently reappear, is also likely to be a strong discriminator when using stationary acoustic landers to laterally observe and monitor seabed gas bubble leaks.

Ascending bubble

Some behavioural traits have been discussed which can be used for discrimination purposes: shape and distribution pattern of fish school or bubble plume and fish or plankton layer. However, another potentially strong behavioural discriminator between gas bubbles and biological targets is the tendency for bubbles to rise in the water column. Rising speed vary depending on bubble size and quantity of other materials on the bubble surface ("dirty" bubbles). It increases almost linearly with bubble size up to diameter of about 1.5 mm for spherical bubbles (0.30-0.35 m/s) and is somewhat lower for larger, irregular shaped bubbles (e.g. Leifer and Patro, 2002; McGinnis et al., 2006). It can be higher for large, intensive leaks generated by high pressure (e.g. a ruptured pipeline) where bubbles at the centre of a plume may experience smaller resistance forces and be carried upwards by the movement of the surrounding water-bubble mixture (Dalen et al., 1986). Water currents, on the other hand, can disrupt this behaviour by advecting bubbles horizontally (Figure 1D). Split-beam scientific echo sounders are capable of tracking single targets with positional accuracy, but only at low target densities. For this reason, split-beam tracking of individual bubbles that are part of a plume is normally not possible at larger ranges. One aspect has not been investigated in this thesis for bubble plumes that are larger than the acoustic beam diameter, and that is inclusion and utilisation of the Doppler effect when characterising and segregating targets. Doppler frequency shift is a change in frequency of a signal backscattered from an object when distance between the target and the sensor is changing due to movement of one or both. Doppler techniques are widely used to track particle motion and water currents (Rowe and Young, 1979). Acoustic Doppler current profilers (ADCP) use scattering from plankton and detritus as tracers of a moving medium (Medwin and Clay, 1997). The movement of bubbles can be tracked in a similar manner. For an acoustic lander system (Figure 2) with an acoustic beam observing laterally at some angle above horizontal, Doppler shift is expected to be detectable for seabed gas bubble plumes. To utilize this technique, an additional acoustic sensor would be needed next to the scientific fisheries echo sounder. Standard ADCP's developed for measuring water velocity may not be directly usable for tracking bubble plumes, because conventional ADCP's use multiple, relatively wide width acoustic beams pointing in different directions at relatively high angles to each other, while a gas plume would likely be a quite localised object. A specially designed system may be needed. A broadband version of the scientific fisheries echo sounder might have the necessary frequency stability and sampling rate to detect Doppler shift, but this would require a separate, future investigation.

Detection range

The echo sounder frequency range used in this study was constrained by the needs for use on lander systems (Figure 2). Fisheries echo sounders with frequencies lower than 70 kHz are large, heavy (e.g. 58 kg for 38 kHz versus 6.4 kg for 70 kHz) and require significantly more power than higher frequencies. Echo sounders with nominal frequencies at 70, 120, 200 and 333 kHz were used to study the frequency response of fish and bubble targets in **Papers III-IV**. These were appropriate for the general target backscatter features and patterns of interest to this work. However, their effective range varies from 600-800 m for 70 kHz to just over 100 m for 333 kHz, depending on ambient noise level, echo sounder settings and target properties. The high frequency echo sounders, such as 333 kHz, will not make a practical bubble plume detector due to this range limitation. In practice, an acoustic lander system (Figure 2) may eventually be equipped with only two frequencies (70 and 120 kHz) with a combined effective range of 300-400 m depending on gas plume size and ambient noise levels. This is the range over which target frequency-dependent backscatter information can be extracted and used for discrimination purposes. For this reason the upcoming calibrated scientific broadband echo sounders are much anticipated (Andersen et al., 2013), which while employing one transducer could extract useful backscatter information over wide frequency range (e.g. 55-95 kHz) with the same, more useful 600-800 m range limitation. The bandwidth of the transducer may also be optimized, if needed, to solve this particular problem, as the wideband transceiver now may transmit 10-500 kHz, limited to 200 kHz bandwidth in one pulse (Andersen et al., 2013).

2.4 Concluding remarks

In this study scientific fisheries echo sounders were used to quantify the lateral aspect acoustic frequency response of induced gas bubble plumes (**Paper IV**) and saithe, as representative gas-filled swim bladder bearing fish (**Paper III**), while also employing an adapted stereo photogrammetry methodology for optical measurements (**Paper II**). The acoustic properties and swimming behaviour of bladderless lesser sandeel were also investigated (**Paper I**). The similarity in the acoustic backscattering of a gas bubble and biological targets possessing gas inclusions was indicated and discussed based both on the literature review and investigations included here as **Papers I-IV**. Based on the available research and that defended here (**Papers I-IV**), it is suggested that behavioural and acoustic backscattering differences can be used to separate gas bubble *plumes* from the most common biological targets, plankton and fish. Gas-filled swim bladder bearing fish are the ones with the closest backscatter spectrum relative to a gas bubble plume. The gas-filled swim bladder is often much larger than the acoustic wavelength for common schooling fish such as saithe, Atlantic herring and Atlantic cod. These acoustically directive targets, when observed laterally, can be separated from gas plumes using acoustic frequency response information (indications in **Papers III-IV**). Smaller, but abundant and widespread swim bladder bearing fish, such as Myctophidae and Sternoptychidae, can be difficult to separate acoustically from gas bubbles, but the behaviour of such fish assemblages is substantially different from the gas bubble plumes (Figure 1D), and the behavioural traits may be then used as separators.

The research in this doctoral thesis represent some initial steps for this potential tool and does not provide the final answers on acoustic detection and identification of gas bubble plumes originating from the seabed. Future work should include more measurements of lateral aspect frequency response on other schooling or aggregating and swim bladder bearing fish (e.g. Atlantic herring, Atlantic cod, Norway pout and mesopelagic fish) and some common bladderless fish (e.g. Atlantic mackerel and lesser sandeel), as well as *in situ* lateral aspect r(f) measurements on naturally occurring seabed gas seeps and at a higher detection range than was practical in **Paper IV**. The next step would be to employ statistical methods, such as discriminant analysis, to test which combination of acoustic backscatter and behavioural traits delivers sufficient discriminatory power for separating gas bubble plumes from biota. Looking to the future, calibrated, split-beam, broadband echo sounder technology should be the natural next step. Broadband technology has a significant potential to improve the acoustic frequency response-based target identification of fish, plankton and other targets. Current frequency response analysis on fish and plankton species or taxa identification is based on just a few points across the acoustic frequency band (e.g. 18, 38, 70, 120, 200, 333 kHz). Broadband echo sounder technology promises continuous measurement over tens or even a hundreds of kilohertz within a single ping, as has been tested and illustrated for single small size gas bubbles in a seawater-filled tank (Figure 6).

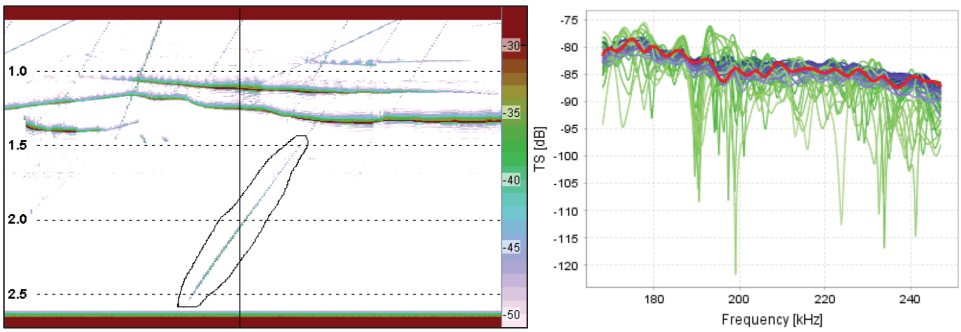

Figure 6. The continuous acoustic frequency spectrum target strength measurement of a single gas bubble with experimental broadband echo sounder (Simrad EK80); an illustration of soon to be available technology and some of its capability. Left – echogram (200 sec) with a track of a single gas bubble (~1 mm, enclosed by black line) rising in a seawater-filled tank (Ø2.2 m, 4 m deep) and several Atlantic cod larvae tracks above it. The scale on the left-hand side is in meters of tank depth, colour scale on the right-hand side is in decibels. Right – the bubble target strength measurements across the acoustic frequency spectrum (165-255 kHz) are plotted for 40 pings around the vertical black line mark in the echogram. Data shown is uncalibrated, neither absolute echo level nor relative target strength change over the acoustic frequency band are necessarily exact. Data courtesy of ECHOEGG project, Institute of Marine Research, Norway. Plotted by LSSS acoustic data post-processing software.

However, some challenges with employing broadband echo sounders are already apparent. For example, management and processing of large quantities of data collected per unit of time, which is several hundred times larger than for discreet frequency fisheries echo sounders. Another challenge could be the interpretation of the apparent large variability in bubble frequency-dependent target strength (Figure 6), which was somewhat unexpected for such small sized and roughly spherical individual bubbles. The likely reason, however, is the fluctuations in shape of the rising bubble. The backscatter, therefore, may change on a ping-to-ping basis, and effectively track the wobble of a bubble. The potential to extract useful information from the broadband backscattering of bubbles is anticipated to be a productive area for future research.

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