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190 Report of a Workshop on

Fish Behaviour in Response to Seismic Sound

Held in Halifax, Nova Scotia, Canada
March 28-31, 2011

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December 2011

Executive Summary

This report is a summary of the proceedings of a workshop held to discuss the design of studies to assess the effect of seismic sound[1] sources on fish behaviour held in Halifax, Nova Scotia, Canada. The workshop was funded by the Environmental Studies Research Funds (ESRF), the Offshore Energy Environmental Research Association (OEER), and the Sound and Marine Life Joint Industry Program of the International Oil & Gas Producers Association (OGP). Workshop attendance was by invitation only and was drawn from an international audience of researchers, regulators and stakeholders. Twenty-seven participants attended.

The 2011 workshop built upon three previous workshops and meetings:

- a 2000 workshop in Halifax sponsored by the Environmental Studies Research Funds examining the behavioural effects of seismic sound on fish and fisheries on the East Coast of Canada (Thomson et al. 2000);

- a 2005 meeting in Halifax that was largely responsible for the formation of the Joint Industry Program (JIP) "E & P Sound and Marine Life" on May 18, 2006 to fund research on behavioural impacts; and

- a 2009 workshop in Stavanger Norway, which was the first OGP workshop that focussed on the effects of seismic sound on fish (http://www.soundandmarinelife.org/ Site/index. html).

The objectives of the 2011 Halifax workshop were:

1. to examine the current and future technologies required to assess the impact of Exploration and Production generated sound on fish behaviour that could lead to significant population effects or effects on fish catch;

2. to derive specifications for experimental design that include the hypotheses to be tested, the methods to be deployed, and the statistical analyses that will be required both before and after any field work;

3. to develop research strategies to address key questions of concern to the sponsors and further to determine the limitations and pitfalls associated with field experiments; and

4. to further understand the technologies available to measure fish behaviour on different geographical scales and how these technologies may be used to measure behavioural changes due to sound exposure in the open marine environment.

The 2011 workshop was designed to build upon the 2009 Stavanger workshop and prior workshops. To avoid the necessity of revisiting the Stavanger discussions, a series of background papers was prepared on the range of study methodologies considered potentially relevant. Following a thorough roundtable review of these background papers, participants themselves introduced a summary table from the 2009 workshop and built upon it to construct the primary outcome from the 2011 workshop.

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[1]   Seismic sound refers to underwater sound used in exploration and development for the oil and gas industry primarily to provide geophysical information on subsurface geology.

To specifically define "the current and future technologies required to assess the impact on fish behaviour" background papers covered:

- acoustic monitoring, sonar, and acoustic tags to assess fish behaviour;

- video monitoring, including LIDAR, for observing fish behaviour;

- use of biomarkers, including pathology and endocrinology, for assessing behavioural impacts; and

- use of fishery statistics in assessing larger-scale effects of changes in fish behaviour over time.

The Day 1 agenda focussed on workshop objectives and the presentation and discussion of background papers. After some discussion on Day 2, consensus was reached to use the output table from the Stavanger workshop as a starting point for defining ecological groupings for discussion. Summary tables dealing with research issues and methods associated with potential studies and species produced on Day 2 were reviewed and a consensus was solicited during the final morning of the workshop.

The background papers and most of the discussions throughout the workshop focussed on examining current and future technologies required to assess the effect of seismic sound on fish behaviour (Objective 1). Key points flowing from the discussions included examining the composite sound in the environment (soundscape) and the role seismic plays within that, assessing changes in time budgets for various behaviours, as well as simple changes in short-term behaviour. New large-scale waveguide technologies, such as the Five Octave Research Array (FORA), may have a role in future studies to provide a snapshot of dynamics at a regional level.

Participants agreed that specifications for experimental design (Objective 2), including test hypotheses and statistical analysis, could only be defined once a specific project was identified, that projects would vary by region for specific areas, and that this workshop focussed on broader conceptual issues governing experimental approaches. Statistical design of studies at the population level is complicated because reliable indicators measuring relevant responses are frequently unknown. In addition, local population level statistics derived from fisheries' catch statistics are often unreliable. Even when good population change measures are available, it is frequently impossible to differentiate the effects of exposure to seismic sound from other changing environmental variables.

Statistical design and analysis in telemetry tagging studies were discussed specifically. It was pointed out that in some cases the data from a single tag provides important information. The number of tags required to produce the desired level of statistical rigour should be determined prior to the background study.

The issue of statistical rigour (Objective 2) was raised specifically in relation to studies done before, during, and after exposure to seismic sound. There are often limited or no replicates and thus an insufficient measure of variability for the results is obtained. It was recognized that building replicates into the experimental design is complex, at least in part because of the variability within the test environment, and it is extremely costly.

The output from the workshop focussed on Objective 3, the design of research strategies. A consensus was reached that studies should be solicited within general ecological categories combined with general behavioural categories, specifically:

- benthic, territorial species;

- benthic, dispersal species;

- pelagic, schooling species;

- pelagic, large species; and,

- coastal/estuarial species.

It was concluded that there are sufficient common elements within these groupings to develop competitive study proposals based on a specified scope and defined criteria.

Views of the relative value of field and laboratory studies (Objective 4), similar to issues of large-scale and small-scale study, were not uniform between participants. For some organisms, particularly commercial invertebrates such as snow crab, laboratory studies have rarely been able to detect behavioural responses similar to the startle responses often observed in fish, even at high exposures. It was generally agreed that it is very difficult to simulate open ocean conditions in a laboratory, or even in a cage. However, in other cases, laboratory work for species such as coastal/estuarine organisms, especially larval forms, can be helpful to define parameters to be measured in the field.

The main outcome of the workshop is the set of recommendations associated with future studies summarized in Table 2 in Section 5 of this report. This table was reviewed and agreed upon by all workshop participants in the closing session of the workshop.

Sommaire exécutif

Ce rapport est un résumé des résultats d'un atelier organisé à Halifax, en Nouvelle-Écosse, Canada, afin de discuter de l'élaboration d'études visant à évaluer les effets des sons de sources sismiques[2] sur le comportement des poissons. L'atelier était financé par le Fonds pour l'étude de l'environnement (FEE), l'association *Offshore Energy Environmental Research* (OEER) et le programme industriel conjoint sur les sons et la vie marine de l'*International Oil & Gas Producers Association* (OGP). Les participants à l'atelier étaient acceptés sur invitation seulement et étaient choisis à partir d'un bassin international de chercheurs, de responsables de la réglementation et d'intervenants. Au total, vingt-sept spécialistes ont participé à l'atelier.

L'atelier de 2011 s'inspirait de trois ateliers et réunions tenus précédemment :

- un atelier organisé en l'an 2000 à Halifax et commandité par le Fonds pour l'étude de l'environnement afin d'examiner les effets comportementaux des sons sismiques sur les poissons et la pêche sur la côte Est canadienne (Thomson et al. 2000);

- une réunion qui a eu lieu en 2005 à Halifax et qui a fortement contribué à la mise au point du programme industriel conjoint (PIC) « *E & P Sound and Marine Life* » le 18 mai 2006 afin de financer la recherche sur les impacts comportementaux;

- un atelier organisé en 2009 à Stavanger en Norvège, qui fut le premier atelier de l'association OGP à mettre l'accent sur les effets des sons sismiques sur les poissons (http://www.soundandmarinelife.org/Site/index, html).

Les objectifs de l'atelier de 2011 à Halifax étaient les suivants :

1. examiner les technologies actuelles et futures permettant d'évaluer l'impact des sons générés par les activités d'exploration et de production sur le comportement des poissons qui pourraient entraîner de graves répercussions sur la population des poissons ou des effets sur les prises;

2. mettre au point des spécifications aux fins de conception expérimentale, afin d'y inclure des hypothèses à mettre à l'essai, des méthodes à déployer et les analyses statistiques qui seront requises tant avant qu'après tout travail sur le terrain;

3. élaborer des stratégies de recherche afin de répondre aux grandes questions qui préoccupent les commanditaires et déterminer ensuite les limites et les pièges en lien avec ces expériences sur le terrain;

4. mieux comprendre les technologies disponibles qui permettent de mesurer le comportement des poissons à différentes échelles géographiques et comment ces technologies peuvent être utilisées afin de mesurer les changements comportementaux attribuables à l'exposition aux sons dans le milieu marin à circulation libre.

L'atelier de 2011 avait pour but de tirer parti de l'atelier de 2009 à Stavanger et des ateliers précédents. Afin d'éviter de reprendre les discussions de Stavanger, des documents de référence ont été préparés sur les diverses méthodologies d'études considérées comme potentiellement

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[2]   Les sons sismiques concernent les sons sous-marins utilisés en exploration et développement pour l'industrie pétrolière et gazière, principalement en vue de fournir des renseignements géophysiques sur la géologie subsurface.

pertinentes. À la suite d'un examen exhaustif de ces documents en tables rondes, les participants ont eux-mêmes présenté un tableau récapitulatif de l'atelier de 2009 et sont partis de ce tableau pour élaborer les objectifs principaux de l'atelier de 2011.

Dans le but de définir spécifiquement « les technologies actuelles et futures requises afin d'évaluer l'impact sur le comportement des poissons », les documents de référence ont couvert les points suivants:

- surveillance acoustique, sonar et marqueurs acoustiques afin d'évaluer le comportement des poissons;

- surveillance vidéo, y compris lidar, pour observer le comportement des poissons;

- utilisation de biomarqueurs, y compris pathologie et endocrinologie, afin d'évaluer les impacts comportementaux;

- utilisation de statistiques sur la pêche afin d'évaluer les effets à plus grande échelle des changements dans le comportement des poissons au fil du temps.

L'ordre du jour de la première journée était concentré sur les objectifs de l'atelier et la présentation des documents de référence ainsi que sur des discussions à leur sujet. À la seconde journée, après discussions, tous ont convenu d'utiliser le tableau des données de l'atelier de Stavanger comme point de départ afin de définir les regroupements écologiques aux fins de discussions. Les tableaux récapitulatifs traitant des enjeux liés à la recherche et des méthodes associées aux études et aux espèces potentielles produites lors de la deuxième journée ont été passés en revue pour en arriver à un consensus au cours de la dernière matinée de l'atelier.

Les documents de référence et la plupart des discussions qui ont eu lieu au cours de l'atelier se sont concentrés sur l'examen des technologies actuelles et futures nécessaires afin d'évaluer l'effet des sons sismiques sur le comportement des poissons (1er objectif). Parmi les points importants qui ont découlé des discussions, l'on note la nécessité d'examiner le mélange des sons dans l'environnement (environnement acoustique) et le rôle joué par la composante sismique dans cet environnement, l'évaluation des changements dans les budgets d'heures pour divers comportements ainsi que des changements simples dans le comportement à court terme. De nouvelles technologies à guide d'ondes à grande échelle, comme le Five Octave Research Array (FORA), pourraient jouer un rôle dans les futures études afin de fournir un aperçu de la dynamique à l'échelle régionale.

Les participants ont convenu que l'élaboration de spécifications en matière de concept expérimental (2e objectif), y compris d'hypothèses d'essais et d'une analyse statistique, ne serait possible qu'après avoir identifié un projet spécifique; ils ont également convenu que les projets varieraient d'une région à l'autre pour des régions spécifiques et que cet atelier se concentrait sur des enjeux conceptuels plus vastes, liés à des approches expérimentales. Il est compliqué de procéder à la conception statistique d'études au niveau de la population car souvent, les indicateurs fiables de mesure des réponses pertinentes sont inconnus. De plus, les statistiques à l'échelle de la population locale qui proviennent des statistiques de prises des poissons sont rarement fiables. Même lorsque de bonnes mesures de changement de la population sont dispo-

nibles, il est souvent impossible de différencier les effets de l'exposition aux sons sismiques des autres variables environnementales changeantes.

On a discuté plus spécifiquement de la conception et de l'analyse statistique dans les études par marquage télémétrique. On a pu remarquer que dans certains cas, les données d'un seul marqueur offrent d'importants renseignements. Le nombre de marqueurs requis afin de produire le niveau désiré de rigueur statistique devrait être déterminé avant d'entreprendre l'étude de base.

L'enjeu relatif à la rigueur statistique (2e objectif) a été soulevé, particulièrement en lien avec les études menées avant, pendant et après l'exposition aux sons sismiques. Souvent, les répliques seront limitées ou il n'y en aura tout simplement pas, ce qui occasionnera une mesure insuffisante de la variabilité pour les résultats. On a reconnu qu'il était complexe de créer des répliques à l'intérieur du concept expérimental, du moins en partie en raison de la variabilité au sein de l'environnement d'essai; de plus, l'exercice est extrêmement coûteux.

Les résultats de l'atelier se sont concentrés sur le 3e objectif, l'élaboration de stratégies de recherche. On a convenu de solliciter des études à l'intérieur de catégories écologiques générales combinées à des catégories comportementales générales, plus spécifiquement :

- espèces benthiques territoriales;
- espèces benthiques dispersées;
- espèces pélagiques rassemblées en bancs;
- espèces pélagiques de grande dimension;
- espèces retrouvées le long des côtes/estuaires.

Il a été possible de conclure qu'il y avait suffisamment d'éléments communs au sein de ces regroupements pour élaborer des propositions d'études concurrentes selon une portée spécifique et des critères définis.

Les points de vue sur la valeur relative des études en laboratoire et sur le terrain (4e objectif) n'étaient pas uniformes parmi les participants, comme ce fut le cas pour les enjeux liés aux études à petite échelle et à grande échelle. Pour certains organismes, particulièrement les invertébrés commerciaux tels que les crabes des neiges, les études en laboratoire ont rarement permis de détecter des réponses comportementales similaires aux réactions de sursaut souvent observées chez les poissons, même à expositions importantes. Il a été généralement convenu qu'il est très difficile de simuler des conditions de haute mer dans un laboratoire, ou même dans une cage. Toutefois, dans d'autres cas, les travaux en laboratoire pour des espèces telles que les organismes côtiers/estuariens, plus particulièrement les formes larvaires, peuvent être utiles afin de définir les paramètres à mesurer sur le terrain.

L'atelier a permis en premier lieu de déterminer une série de recommandations en lien avec de futures études résumées au tableau 2 de la section 5 du présent rapport. Ce tableau a été revu et approuvé par tous les participants à l'atelier lors de la séance de conclusion.

Contents

Preface

This report describes the general consensus and intent of discussions leading to the main outcomes from the workshop; it is not a transcript of the sessions nor are statements attributed to individual participants. Referenced background reports on specific study methodologies were provided by experts in specific topic areas who also participated in the workshop. In addition, most of the comments made by participants are expert opinions and were provided without reference to specific literature. Thus, citations and/or attributions are not generally provided for statements in the main body of the report. Summaries of background material in the report reflect as accurately as possible the emphasis provided by the authors during their participation in discussions, but the full background papers are also appended to this report for reference.

Proceedings of the workshop were not recorded verbatim, but two CEF Consultants staffers took notes during all discussions. These notes served as an overall basis to provide an accurate record of the proceedings. The main outcome of the workshop is the set of recommendations associated with future studies that are summarized in Table 2 in Section 5 of this report. All workshop participants reviewed and agreed on this table during the closing session of the workshop.

Draft copies of this workshop report were distributed to <u>all</u> participants for comment. Their comments are incorporated in this version of the report as fully as possible; however, any errors or omissions are the responsibility of the primary author of this report, Norval Collins.

Glossary

ESRF   Environmental Studies Research Funds – a fund for environmental and social studies research related to oil and gas exploration and development on Canada's frontier land. Initiated in 1983, funds are provided through levies on frontier lands recommended by a joint government, industry, and public Management Board and administered by Natural Resources Canada.

OEER   Ocean Energy Environmental Research – a not-for-profit corporation dedicated to fostering offshore energy and environmental research and development including examination of renewable energy resources and their interaction with the marine environment. Formed in 2006, membership includes representatives from the Nova Scotia government and universities.

OGP   International Association of Oil & Gas Producers – formed in 1974, members include most of the world's leading publicly-traded, private and state-owned oil and gas companies, oil and gas associations and major upstream service companies.

JIP   Members of the OGP agreed to fund a cooperative **J**oint **I**ndustry **P**rogram to support research that focuses on sounds produced during the exploration and production (**E & P**) phases of offshore oil and gas operations and the effects these sounds may have on marine animals. The Joint Industry Program (JIP) "E & P Sound and Marine Life" was initiated on May 18, 2006.

Acknowledgements

1. INTRODUCTION

This report is a summary of the proceedings of a workshop held in Halifax, Nova Scotia, Canada to discuss the design of studies to assess the effect of geophysical survey seismic sound sources on fish behaviour. The workshop was funded by the Environmental Studies Research Fund (ESRF), the Offshore Energy Environmental Research Association (OEER), and the Sound and Marine Life Joint Industry Program of the International Association of Oil & Gas Producers (OGP). Workshop attendance was by invitation only and was drawn from an international audience of researchers, regulators and stakeholders (see Appendix A for a listing of workshop participants).

Seismic (geophysical) surveys employing air guns to produce underwater sound pressure waves[3] for geophysical mapping of the ocean subfloor are a common component of oil and gas exploration operations. This report presents the outcome of a workshop of international experts in fishing, fish behaviour, and oil and gas operations and regulation.

1.1 Background

The 2011 ESRF/OGP/OEER workshop in Halifax, Nova Scotia, was the latest in a series of workshops focussed on the effect of seismic survey sounds on marine organisms and fishing. Two earlier workshops, one in 2000 and one in 2009, provided prior insight into the issues discussed during the 2011 workshop. In addition, a marine mammal workshop held in Halifax in 2005 was largely responsible for the framework of the subsequent E & P Sound and Marine Life Joint Industry Program (JIP).

1.1.1 Halifax ESRF Workshop 2000

Forty-six people, including experts in fisheries and seismic research, attended a workshop in Halifax on September 7 and 8, 2000 focussed on the design of studies to assess the impact of seismic survey operations on fisheries off Canada's east coast. The workshop began with presentations on hearing in fish, ocean acoustic environments, and fish behaviour. Based on a Norwegian risk assessment, participants agreed that studies of seismic effects on fish eggs and larvae were of lower priority and were not considered in subsequent discussions. Study groups discussed:

- small-scale (e.g. caged animals or laboratory) experiments on fish and shellfish;
- studies of behavioural responses to seismic noise; and
- the effects of seismic noise on the 'catchability' of fish.

Small-scale and laboratory experiments, as well as large-scale field studies were recommended to study the effects of seismic sounds on shellfish, various demersal fish species, large pelagics, and spawning activities.

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[3] In addition to pressure, sound energy contains particle acceleration, velocity and displacement components.

1.1.2   Halifax Marine Mammals Workshop 2005

In 2004, following extensive discussions with representatives of the oil and gas industry on the topic of sound and its interaction with marine mammals, it became clear that there were significant knowledge gaps. A review of existing information was commissioned and the resulting report was discussed at a workshop held in Halifax in September 2005. This workshop lead to more than 30 key questions that drove subsequent development of the E & P Sound and Marine Life Joint Industry Program. This workshop and the following phase of the JIP focussed on marine mammals.

1.1.3   Stavanger Norway Workshop 2009

A workshop on fish behaviour was held in Stavanger Norway April 19-20, 2009 as part of the OGP's JIP Sound and Marine Life Programme. While no recommendations for the design of future studies were made, it was recommended that the JIP pursue the discussions further, with a view to designing possible studies of fish behaviour in response to exploration and production sounds.

Day 1 of the workshop dealt with earlier studies related to the effect of seismic sound on fish in the US, Scotland and Norway. Day 2 discussions covered the concerns of regulators, the advantages and limitations of study methods, and priorities for future research. Presentations were made by regulators or representatives from Norway, Brazil, and Canada. Discussions on study technologies included sonar, tagging, video, physiological changes, and assessment of changes in catch.

Presentations were made on:

- field studies of behavioural responses of fish to seismic sound (e.g. rockfish off California, small pelagic fish distribution and density off Norway, and Scottish studies);
- aquatic telemetry study of post-smolt migrations in Norway; and
- field studies on the effect of seismic sound on commercial catch rates off Norway.

With regards to survey design, workshop participants highlighted the following criteria:

- the study must have control of the seismic vessel, not just operate in the vicinity of a seismic survey as a study of opportunity;
- the need for a good description of the background conditions, such as other vessel noises and fish activity (feeding, spawning, migrating, etc.);
- measurement of the exposure signal rather than the signal at the source is very important;
- although it is possible to conduct some studies on fish behaviour in a fiord, it may be difficult to extrapolate the results to open waters;

- since fish react differently to different situations, it is difficult to make general rules for fish behaviour; and

- fish in cages may react very differently from free-swimming fish, and therefore may give rise to false interpretations.

While prospects for collaborative work were raised, relatively few studies on the effects of seismic sound on fish have been conducted in the recent past. Discussions from the first day of that workshop were summarized as follows (Gausland 2009):

- *"The fish ear consists of a system of accelerometers – not all fish detect sound pressure and those that do use particle acceleration to determine sound direction. Therefore the right measurements are important, i.e. measurements of the kinetic components of the sound. Seismic sources at the surface generate shear waves at the sea bottom. The impact of this on fish close to the seabed is a big unknown.*

- *The presentations and discussions have been very interesting. To an oil company this has both medium and long-term interest. With operations in many parts of the world, and in very different conditions, we need to have information to give to both regulators and local fishermen. How can we operate and still protect nearby fish farms? What received decibel levels are acceptable for a safe zone?*

- *The Norwegian fishermen claim an 18 nautical miles safe zone – what can we do to document a necessary distance better?*

- *… Is it sound propagation, is it effect, or is it response in the fish. If we find the answers to these questions, future survey designs can be much better. These are important topics, and regulatory bodies have a role to play and should be involved with project planning.*

- *Have discussed technical issues that must be solved. Secondly, it is important to have the answer in areas where the industry is working. Third is a regulator requirement – any study we plan should be referred to regulators for comments.*

- *We need a multidisciplinary approach, and knowing airgun signal is important. Differences between fiords and, for instance, the Barents Sea may give valuable data.*

- *Fish behaviour can be studied in fiords or labs, but for the big issue one has to go out in the open waters and study commercial species."*

The workshop concluded that studies of different types of fish would require different sets of questions. A possible matrix of combinations of species, habitats and sensitivities was proposed by Tony Hawkins as a summary of proceedings and is reproduced here as Table 1 because it formed the starting point for discussions at the 2011 Halifax workshop. The Stavanger workshop described Table 1 as follows(Gausland 2009): "There will be a different set of questions for different types of fish. A possible matrix of combinations of species, habitats and sensitivities was proposed by Tony Hawkins…"

Table 1: Groupings of Fish by Sensitivity to Seismic Sound and Ecological Association

Fish Categories Arranged by Sensitivity to Sound	Ecological Associations					
	Large Pelagic	Small Pelagic	Demersal	Reef	Shallow/Estuary	In River
gas bladder connected to ear		Herring Sprat Shad	Weakfish Deep-sea cod	Squirrel-fish	Catfish Carp Goldfish	Dace Minnow
gas bladder close to ear			Cod Haddock Saithe	Red Snapper		
gas bladder distant from ear	Dorado	Horse Mackerel	Spot	Wrasse	Sand-smelt	Salmon Eel
no gas bladder	Sharks	Mackerel	Plaice Sole		Flounder	
fish eggs and larvae	Dorado larvae	Herring Larvae	Cod larvae	Red Snapper larvae	Catfish larvae	Salmon eggs

Note: This table is a work in progress and suggestions for other fish species to be incorporated in the various categories are encouraged. Furthermore, the species identified are examples only and should not be interpreted as a set of research priorities either individually or collectively. Source: after A.D. Hawkins, OGP Fish & Seismic Workshop Stavanger Norway (2009).

1.2 Workshop Objectives and Agenda

Following the 2009 Stavanger workshop, there was general agreement that the type of future studies that would be most useful to answer the questions raised could be further clarified by another workshop. The 2011 ESRF/OGP/OEER workshop in Halifax was therefore, in part, a continuation of discussions at Stavanger.

The objectives for the 2011 workshop were as follows:

- to examine the current and future technologies required to assess the impact of Exploration and Production generated sound on fish behaviour that could lead to significant population effects or effects on fish catch;

- to derive specifications for experimental design that include the hypotheses to be tested, the methods to be deployed and the statistical analyses that will be required both before and after any field work;

- to develop research strategies to address key questions of concern to workshop attendees and sponsors and further to determine the limitations and pitfalls associated with field experiments; and

- to further understand the technologies available to measure fish behaviour on different spatial scales and how these technologies may be used to measure behavioural changes due to sound exposure in the open marine environment.

The initial agenda (Appendix B) was based on these objectives and supplemented by the background papers on study methods prepared in advance of the workshop. The agenda was intended to be flexible from the start and included numerous points where feedback was requested and agenda changes were solicited. The agenda was followed relatively closely on Day 1; on Day 2, participants agreed to focus discussions specifically on the definition of studies to assess fish behaviour building on the Stavanger table (Table 1) as a starting point. The final morning, summary tables produced on Day 2 were reviewed and a consensus was solicited. These summary tables provide guidance on suggested studies for assessing behavioural effects on different species within different broad habitat preferences, as well as potential evaluation criteria for reviewers of study proposals. Participants came to a consensus that developing further site specific requirements or costing was not appropriate for this workshop, due to the regional specificity of such requirements and details.

Background papers covered these topics:

- acoustic monitoring, and sonar and acoustic tags to assess fish behaviour (*Dr. Tony Hawkins*);

- video monitoring, including LIDAR, for observing fish behaviour (*Dr. David Mann*);

- use of biomarkers, including pathology and endocrinology, for assessing behavioural impacts (*Dr. Jerry Payne*); and

- use of fishery statistics in assessing larger-scale effects of changes to fish behaviour over time (*Robert O'Boyle*).

A copy of each of these background papers is provided in Appendix C. Summaries of the papers and the outcomes of related discussions are included with the discussions by topic area (fishery statistics, hearing, video, biomarkers, fishing gear, acoustics, and tagging) in Section 3.

2. ROUNDTABLE OF OBJECTIVES AND OUTCOMES

The workshop began with a review of the objectives and a roundtable discussion of the outcomes the participants hoped to achieve from their deliberations. The following summaries endeavour to encapsulate the key ideas raised during this discussion that helped set the stage for the remainder of the workshop.

- Stakeholders concerned with monitoring the impacts of seismic sound include the public, scientists, regulators, interest groups, as well as the fishing and oil and gas industries. Members of the public and interest groups outside of the fishing and oil and gas industries were not specifically represented at the workshop; however, reference was made to broad stakeholder interests during discussions. The topics of study and desired outcomes were felt to vary depending on the stakeholder's point of view. Regardless of individual perspectives, buy-in from most, if not all, stakeholders and moving forward together was viewed as essential in designing specific projects.

- Different geographical scales and differences between jurisdictions must be considered in the design of studies to assess the impact on fish behaviour of seismic sound that could lead to significant effects on population or fish catch.

- The interpretation of workshop objectives and outcomes reflected the participants' backgrounds. Some felt that a focus on changes in fishing success did not adequately reflect the desired emphasis on fish behaviour. However, most participants agreed that a connection to ecosystem concerns should be considered in all studies. Thus, monitoring at the population and ecosystem levels should be a key consideration. At the same time, defining a common, acceptable definition of the biological significance of effects is a challenge.

- The biological significance of an effect varies depending on who interprets the observations; for example, some may consider a temporarily frightened and/or displaced fish significant while others may feel a consequent reduction in reproductive potential is more significant. Time scales of studies and effects are also important. Short-term studies may address specific critical issues, while long-term monitoring programs are likely required to assess population and ecosystem effects, which may also be critical.

- Laboratory experiments and other localized studies frequently do not scale up reliably, requiring longer-term, large-scale field studies. In some cases it may be difficult to separate the effects monitored from sound exposure from changes in the environment. For example, fish can become habituated to sounds or adjust to confinement, resulting in changes to their behaviour and responses to sound. Confined spaces complicate sound propagation and measurement because of conditions like reflection and other boundary effects. It is also difficult to replicate open ocean conditions in a laboratory.

- A defensible baseline of fish behaviour parameters, including variability, is also required as a foundation. It was deemed important to avoid reinventing the wheel and to focus instead on building upon previous studies.

- Different fish species have different hearing abilities; some fish react more to the pressure component of sound and tend to have a greater hearing sensitivity, while others respond mainly to the particle motion component of sound.

- Understanding ambient noise (general background noise for which the exact sources are not identifiable) and the propagation of seismic sound energy along the sea bottom from direct and indirect paths such as reflection and refraction are important components.

- The highest quality research is desired, but cost, statistical analysis, and design are all important factors. Defining uncertainty and relating observations to uncertainty and biological significance are key considerations. Understanding available technology and methodologies is critical to designing feasible experiments with adequate statistical power.

- Each available technology has particular limitations and the resolution of most questions about behavioural response will require integration of a number of different methods. For example, identification of species can be a problem with some acoustic equipment, requiring netting to verify species and size.

This workshop aimed to address these issues by clarifying the types of studies that would help improve our understanding of fish behaviour response to seismic sound.

2.1 What are we measuring?

At this workshop, the term fish applied to finfish and invertebrates, particularly those of commercial or ecosystem importance. Initial roundtable discussions looked to identify how differences between potential impacts or methodologies dealing with finfish, shellfish, or other invertebrates might influence discussions and how these issues should be addressed procedurally.

Overall, it was felt that including invertebrates as fish would not significantly impact discussions. Behavioural and other sublethal responses of finfish to seismic sound can differ by age, size, species, type (e.g. pelagic or demersal), and activity (e.g. migration, spawning or feeding) – invertebrate responses simply fit within the broad spectrum of responses observed in fish. Effects on organisms such as zooplankton may also affect fish and crustacean behaviour and distribution as well. Technologies are emerging that can be better integrated, improving our ability to study multiple systems simultaneously, such as predator/prey dynamics in fish and zooplankton.

Much of the information documenting the effect of sound on individual fish was obtained from caged or captive subjects. This includes study of themes like hearing thresholds or exposures that produce specific responses, such as stunning, in individual fish. The following

factors limit the applicability of observations obtained from captive or controlled studies to wild fish behaviour and populations:

- captive fish are not free to exhibit the broad range of potential natural behaviour, including avoidance to reduce the level of exposure;

- a specific marine species of interest may not behave in a similar fashion to different species previously studied; and

- sound propagation and exposure in captivity are rarely directly transferable to sound propagation in open water.

In addition, while participants agreed that fish behaviour needs to be studied in their natural environment, they also agreed that much of the information from large-scale field studies to date is inconclusive or conflicts in magnitude or duration. With impacts resulting from variations in ocean temperature that have occurred over time, some participants felt it may become more difficult to separate longer-term population impacts from shorter-term impacts related to specific sources, such as seismic sound or vessels.

Measuring the sound levels at the point of exposure is always important because of potential variations in propagation between the source and the target. As was noted at the 2009 Stavanger workshop, "*seismic sources at the surface generate shear waves at the sea bottom, and the impact of this on fish close to the seabed is a big unknown.*" Particle motion at the sea bottom and its effect on shellfish, particularly crab, was also determined to be important by some participants.

3. BACKGROUND ON MONITORING METHODS

This section summarizes the background papers and the discussions that followed. A summary of each background paper was presented by the author. A wrap-up discussion of fishing as a fish behaviour monitoring tool or technology was led by a small panel of participants: R.N. O'Boyle, S. Loekkeborg, A. d'Entremont, and G. MacDonald.

3.1 Fishery Statistics

A synopsis of the scientific literature on fish behaviour studies using fishery statistics since the1960s was used to review the utility and design of these studies of fish exposure to seismic sound. Generally the literature on fish is more abundant than on invertebrates, but six studies of fish and five studies of invertebrates were reviewed in detail. The design of studies has progressed from the opportunistic use of available data to specific experimental design and hypothesis testing. Sources of other information and methods, including acoustic survey mapping, tagging, and video, have been increasingly integrated into these studies.

For finfish, short-term responses in behaviour (e.g. startle or flight response) have affected catch rate but results have been variable[4]. The existence of population effects have been suggested if, for example, migration is affected, but the potential for measurable population effects to occur are highly uncertain. Invertebrate response is less obvious and few conclusions can be drawn. Population effects are more difficult to assess due to confounding factors such as natural variability, habitat changes, fishing, and migrations.

Objectives will have to be clearly stated in future studies, and local, short-term, and population level studies, as well as long-term studies will likely be required. Each study will face a unique set of challenges, requiring different approaches. Elements to be addressed in future studies include:

- ensuring that the sampling grid comprehensively covers the study area, including rationale for study area size;

- sound source monitoring, including measurement of received levels at the target;

- modelling, including standardization of data; and

- sampling design with appropriate sample units or observation data cells, including stratification if sub-areas differ.

An advantage of using fisheries data in local, short-term studies is that they can provide insight on fish and invertebrate behaviour at a relatively low cost (Appendix C, O'Boyle, page18). At the same time, incorrect conclusions may be drawn if all confounding factors are not understood. To date, study suggests that the effects of seismic sound are localized and short-term, but little work has been done to determine if these studies inform the broader implications of seismic energy on fish or invertebrate populations. At the population level, cumulative effects from seismic sound may not be readily measurable compared to other impacts, especially if a species is relatively mobile, e.g. seasonally shifting concentrations over tens of kilometres.

Some participants expressed concern about the reliability and relevance of catch data to behaviour studies. Fisheries experts agreed that fishing gear and vessels can introduce bias into the data which needs to be considered during analysis and modelling. For example, catch of a species other than the target species can introduce further issues in terms of misreporting and discarding of unwanted catch. Many jurisdictions use comparative fishing and other studies, such as onboard observers, to adjust fisheries data. Commercial catch data are seldom used as the primary input to population modelling because catch is highly influenced by regulation and enforcement – stock analysis relies mainly on research trawl survey catch data. The quality and use of catch per unit effort (CPUE) in fisheries management varies by country.

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[4] Worcester (2006) reviewed the literature to date of laboratory and *in situ* studies on the behavioural, physical and biochemical responses of fish to sound, focussing primarily on impacts of airgun sources. Based on the limited number of studies available, she considered that there is a high probability that some fish within the general vicinity (i.e. hundreds of metres) of a seismic survey would exhibit a startle response, changes in swimming speed or direction, and changes in vertical distribution, with recovery likely within minutes to hours after exposure. There is a lower but still reasonable probability that seismic surveys will influence the horizontal distribution and 'catchability' of some fish under certain conditions.

Separating potential effects of seismic sound from natural and other anthropogenic sources is critical and limited by available technology. The complexity and variability in the natural environment needs to be considered in the design of monitoring, data analyses, and use of these data in risk assessments. In addition, new advances in fish population and ecological modelling were suggested as a possible avenue to simulate and isolate seismic impacts.

3.2 Hearing

Sound consists of both sound pressure and particle motion. Sound pressure is a scalar quantity and acts in all directions. A measurement on a single, stationary sound pressure sensitive hydrophone cannot determine the direction of a sound. However, particle motion, which can be described in terms of displacement, velocity or acceleration, is a vector quantity acting in a particular direction. Particle motion can be measured directly by means of an appropriately designed accelerometer. Or it can be estimated from the pressure gradient, using two pressure sensitive hydrophones. To specify the axis of particle motion three orthogonal accelerometers, or four sound pressure hydrophones are necessary. Much of the research related to seismic sound has focussed on sound pressure. Many fish and most, if not all, invertebrates are sensitive to particle motion, and to gain a full understanding of the effects of sound on these animals it is necessary to measure or estimate the particle motion.

Hearing mechanics in fish and invertebrates, hearing sensitivities, and hearing shift/loss after exposure to seismic sound were reviewed. Both otoliths in fish and statocysts in invertebrates act as accelerometers. In addition, the distance and connections between the ear and the swim bladder affects hearing in some fish. Specifically, fish with a swim bladder coupled to the ears that tend to have more sensitive hearing.

All fish species detect particle motion. However, some species can detect sound pressure and this gives them greater sensitivity and a wider frequency range. Particle motion may be a more appropriate measure of potential impact for many species. Audiograms are not necessarily a good predictor of the effects of seismic sound. For one thing, fish reactions may be subtler than indicated by an audiogram and vary depending on whether the fish is feeding, spawning or resting. In addition, many audiograms have been obtained under poor acoustic conditions in the laboratory, and have failed to measure particle motion.

Exposure of fish to high-level sounds may result in loss of sensitivity through the loss of hair cells within the ear. Generally, hearing loss in fish recovers over time because the lost hair cells regenerate. However, any loss of these cells may temporarily affect the ability of fish to detect the direction of a sound source.

3.3 Video

Video can provide helpful information on species identification and behaviour but it has many limitations, especially in relation to the distance over which observations can be made and potential disturbance of the subject. Limitations to video as a monitoring tool include:

- limited field of view;

- limited depth of field;

- poor performance under low light levels;

- time consuming analysis with poorly developed automatic detectors;

- may require many cameras; and

- may require divers to place cameras on the sea bottom.

However, video also has the advantage that it allows the observer to see and identify species and clearly describe behavioural responses, providing the subject remains in the field of view. Video can also capture audio simultaneously.

Monitoring methods can affect behaviour, including the presence of things like video equipment housing and lights and also vessel movements. Much work may be required to develop a reliable baseline that allows the effect of a disturbance to be separated from normal behaviours. Assuming good visibility, video can be most helpful with sedentary species or in rivers where a species occurs within a confined area.

In addition to recording the different categories of behaviour observed, development of time budgets (i.e. the amount of time an animal engages in a particular activity) can provide useful additional information. Time budgets may change in response to sound exposure and these changes may be more meaningful than quantification of separate behavioural responses.

3.4 Biomarkers

A biomarker is defined as a change induced in the biochemical or cellular components of a process, structure, or function, that can be measured in a biological system. However, it is important to note that all biomarkers are not equal in importance. For instance, histological changes in the hair cells of fish ears or the hepatopancreas of crustaceans would generally be considered of greater importance than a transient change in cortisol or enzyme levels in the blood.

Biomarkers can be used to detect sublethal effects that may indicate acute exposure to environmental perturbations potentially linked to population or community impacts. A constraint of biomarkers is that they indicate exposure but may not be directly linked to a behavioural response of interest. Biomarker studies can be carried out in the laboratory or similar controlled conditions and are used extensively in many areas of biological monitoring. Biomarkers can be useful for screening issues of concern but are less able to directly predict population impact.

Most sublethal effects result in change in some health indicator, which may be measured to determine thresholds or severity of effect. The direction of change in an indicator is not always as anticipated. Sometimes behaviours change unexpectedly after exposures to sound (e.g. increase or decrease in food consumption). The duration of behavioural effects can also be longer than anticipated (e.g. cod remained at the bottom of the tank for over 2 weeks after exposure, see Appendix C: J. Payne). Thus, in some cases, biomarkers or health

indicators may provide additional information to assess whether an effect is linked to a particular source and continuing over time.

Biomarkers have been used more extensively in studies of seismic effects on invertebrates than fish. Studies on fish have focussed more on behavioural responses of interest or concern. Behavioural responses to sound exposures in the laboratory for invertebrate species like snow crab have been less pronounced than in most fish species. For example, a startle response similar to that obtained with fish is generally not observed.

Studies of other sound stimuli can also be relevant, such as those associated with pile driving due to the localized, acute, and highly repetitive nature of the activity. Even with pile driving, there is little evidence of impact on invertebrates unless at very close range. Results from studies of related stimuli suggest that long-term effects from chronic exposure to noise from large ships could be similar in magnitude to less frequent seismic sound sources.

3.5 Fishing Gear

The type of fishing gear used affects the resulting catch qualitatively and quantitatively. Success with different gears depends on different fish behaviours; thus, some types of fish behaviour can be inferred from catch data. With baited gear (e.g. longline and traps), the kind of bait can affect the catch and, as recent information suggests, also the size of the catch. Operating conditions, including type of vessel, time of day, and type of gear, all affect the catch and need to be standardized. Gear-related behaviour indicates that fish must be feeding for successful longline catch, moving around for gillnet catch, and in the targeted water column depth for trawl success.

Much of the current information on the effect of seismic sound on fish populations was generated by fish catch. For example, multiple gear types have been used to help assess whether fish left an area following exposure to seismic sound. In addition to providing information relevant to fish behaviour (e.g. changes in response to bait or gear), the effects on commercial fishing operations can be viewed as important in and of themselves.

As much as a large amount of data on fish catch is available and catch has been a rich source of information in the past, traditional fishing methods are not necessarily the best way to obtain information on fish behaviour. For example, fish catch may drop because of reduced 'catchability' from behavioural changes other than flight from the area, leaving questions about the interpretation of results. It can be argued that obtaining information through fishing is a biased sampling method and more objective tools are available today, such as an increasing range of acoustic technologies.

Generally, commercial catch is not a good indicator of population effects because so many different variables can affect catch rates, including regulations. When the fishing industry develops a new method of fishing, it can take ten years of data to develop an adequate baseline to create confidence in catch trends. However, fishing, particularly trawling, is used widely as a research tool to provide population estimates for fisheries management.

3.6 Acoustics

In addition to the vertical echo sounders traditionally used to estimate numbers or biomass, multi-beam and omnidirectional sonars can observe fish in three dimensions. Some sonars (e.g. Kongsberg, Simrad, Furuno and others) are capable of operating in horizontal (parasol) and vertical (swath) mode, while others (e.g. Didson™ by Sound Metrics, SeaBat™ by Reson AS, or MS1000™ by Kongsberg Simrad) can observe individual fish in real time. Sonars can also be used to estimate fish abundance with fewer disturbances than in trawl surveys. Where fish are large and dispersed, the actual numbers can be counted if the instrument senses a response. More commonly, echo-integration is used to sum all the echoes within a sampling volume to estimate total biomass.

Sonars are used to assess some fish stocks, especially pelagics such as herring. Not only can fish movements be documented, but numbers or biomass can also be estimated, including plankton. While acoustics can be used to study behaviour, such as feeding and fright responses, quantification of results remains difficult. Problems with sonar include:

- images which may be incomplete and require interpretation;

- identification of species is usually uncertain; and

- the fact that sonar must often be attached to a ship, may itself generate considerable noise.

3.7 Tagging

Electronic tags allow researchers to monitor and store data on movement and local environmental conditions. It is important to ensure the tag does not load or stress the fish or result in injury or infection. Some tags are limited to operation near the water's surface, but new generation tags are allowing for operation under broader environmental conditions. Tagging can also affect the behaviour of the organism, especially if the tag is cumbersome or the organism is removed from the natural environment for extended periods and/or moved to a different location.

Tags can track individual fish and relay data to an array of bottom-mounted or buoy-mounted receivers. These receivers can record fish movements, including depths and physiological information, and later be released to the surface or captured in other ways for data extraction and analysis. Other tags can transmit to satellites or other receivers, but may require the animal to be near the surface of the water to transmit and receive data.

The use of acoustic/ultrasonic tags is increasing globally with data sharing through numerous receiver and data networks. For example, the Ocean Tracking Network (OTN) encourages data sharing to look at the larger, sometimes global, picture. A worldwide network and infrastructure could provide a constant picture of important aspects of marine life and ocean conditions around the globe.

4. OVERARCHING ISSUES

4.1 Relative Importance of Behavioural Responses

The relative importance of the behavioural responses of fish to seismic sound concerns the potential for the following:

- being driven from preferred areas, such as feeding and spawning grounds;

- escape reactions and associated increased energy expenditures;

- disruption of migration;

- suppression of spawning behaviour; and/or

- masking or blocking of important sound reception.

These effects may have negative impacts on fish populations and may also lead to reduced condition, health, survival, or reproductive success of a large number of individuals. Fish may not avoid the disturbing stimuli or react strongly, even though they are adversely affected. Rather, they may show compensatory behaviour patterns. Furthermore, time budgets rather than immediate responses may be a preferred tool for study (e.g. percent of time gobies remained in their shelter). Observing behaviours in the wild is critical because captive fish are unlikely to express a full range of potential responses. In addition, sounds are difficult to reproduce under laboratory conditions because of reflection and reverberation from tank walls.

A fish's response to disturbance may be context-dependent: the resultant response may be a trade-off between avoiding disturbance and engaging in other fitness-enhancing activities, such as feeding, mating, or migration. In addition, behaviour can change dramatically over time and life stage. For example, young cod may stay within a small home range (200 m) when feeding on crustaceans, but, as they grow and start feeding on fish, they may travel long distances.

Passive listening to the sounds fish make is a specific type of monitoring useful in studying some species. For example, some species, such as haddock, make sounds during spawning that are thought to be critical to spawning success.

4.2 Sensitivity Issues

Research topics can be prioritized according to species, behaviour and habitats. Considerations include:

- sensitivity of fish to sound;

- habitats that are more or less prone to noise; and

- behaviour that may be dependent on sound, which, when disrupted, may represent a population level risk.

Available evidence suggests that invertebrates are less sensitive than fish to air gun discharges (see Appendix C, Payne, pages 5-6), but subtle physiological effects could still impact the population.

Species that are representative of a group of similar fish are good candidates for study. Broad habitat groupings considered at the workshop included pelagic, demersal or benthic, and coastal/estuarial types. Within these habitat groups, basic behaviour patterns were also considered a useful grouping factor, specifically (i.e. whether or not a species is a territorial or schooling type). Species like herring, red grouper, and cod were suggested as example representative species. Herring can be considered representative of small pelagic schooling species, red grouper representative of territorial demersal species, and cod representative of non-territorial and widely dispersing (within a stock or stock complex) demersal species. Some groupings also address time scale issues to a certain degree, because small pelagic species, such as herring, are short-lived, and not well suited for long-term studies. These species groupings also tend to reflect differences in ecosystem considerations.

4.3 Scale of Study

Participants expressed contrasting views of how best to use laboratory experiments. One view favoured initial study in the laboratory at a small-scale to get a preliminary sense of acute effects, which would then allow proper design of larger-scale experiments in the wild. Another view favoured initial study in the wild with fine-tuning of specific aspects in the laboratory. It was agreed that both laboratory and field studies had merit depending on the issue and species involved. For some species of invertebrates, such as snow crab, laboratory studies may be required to identify specific avenues of effect and response that can be incorporated into field studies. Laboratories may be the only way to study some effects on larval stages.

Measurement of the population or ecological effects will generally require long time scales and a mix of analytical methods, including laboratory and field study. New sonar technologies, such as the Five Octave Research Array (FORA), may have a role in future studies to help define more of a system view (bigger picture). In some instances, progress could be enhanced by having a specialized team working in a specific area over a span of years. A *centre of excellence* would be one way of maintaining adequate skills and resources along with special coordination and funding. Existing centres with expertise in certain areas, such as research on behaviour of small pelagic species, can already provide a starting point for longer term studies.

4.4 Soundscape

The soundscape of an area is composed of highly variable ambient sounds. Sound sources such as rain, wind, waves, biological sources, vessel traffic, and various other natural and anthropogenic sources in combination with factors that affect sound propagation, such as surface and bottom roughness or water column stratification , all contribute to the soundscape.

It is important to understand the soundscape because a seismic signal in a noisy environment will be perceived and elicit responses differently than the same source level in a quiet environment. Understanding the soundscape also makes it possible to assess the proportion of time a fish would naturally be exposed to sound levels over a certain threshold. This in turn provides the proper context for interpreting behavioural responses to received levels of seismic sound.

The soundscapes of most environments are not known, but interest in characterizing them is increasing. For example, a Quiet Oceans experiment may be conducted in which as many anthropogenic sources of sound as possible are shut down to allow study of the full spectrum of remaining sounds. This type of information would help understand natural variations in ambient sound and aid in distinguishing between chronic and acute exposures.

5. POTENTIAL FUTURE PROJECTS

The workshop made it clear that more work is needed to improve our understanding of the direct and indirect effects and possible ecological consequences of seismic (exploration and production) sound on fish, including shellfish.

Two of the objectives of this workshop were to try to derive specifications for experimental design and to develop research strategies to address key questions of concern to the sponsors. While the workshop was able to address these objectives to a certain extent, it made it clear that detailed design was better left to specific study initiatives. Nonetheless, this report highlights issues to be addressed in future studies (see particularly Table 2), as well as potential methodological approaches to dealing with them that have been developed and that will provide guidance to those who wish to pursue these studies.

The workshop sponsors, as well as other potential funders, may choose individually or jointly to solicit proposals for specific research projects that fit within topic areas described in this report. The kinds of studies needed to address the issues considered at the workshop are technically complex, logistically challenging and, as a result, potentially costly.

Like many funding mechanisms for this kind of research, ESRF, OEER and OGP have structured mechanisms such as focussed Request for Proposals (RFP) to solicit and evaluate the scientific merit and feasibility of studies under consideration for funding. Funding processes begin with the identification of high priority research areas within which research topics fall, followed by the solicitation of specific research projects through a call for proposals within a topic area or a request for proposals against a specific scope of work. Proposals are then evaluated from technical, logistical, and financial perspectives; this is usually done by qualified technical advisory groups. Studies approved to go forward are normally overseen by standing or ad hoc oversight committees made up of subject matter experts and stakeholders (e.g. industry and public) and, in some cases, regulatory agencies. Supporting these functions are program managers and administrative functions to help ensure technical and financial due diligence, as well as mechanisms to ensure study results are peer reviewed both before and during the funding agency's publication processes.

5.1 Obtaining Sound Sources

Obtaining a full-size seismic sound source typical of the oil and gas industry was raised as a critical element in conducting fish behaviour research, especially in relation to availability and costs. In some parts of the world, Norway was cited as an example, researchers have been offered appropriate seismic survey vessels at a relatively favourable cost, but in other areas seismic survey vessels are in short supply, expensive, and must be booked well in advance. A survey company may amalgamate jobs from a number of clients to make a visit to an area affordable. The cost of a source vessel for a large-scale project may be in the millions of dollars. These costs are largely associated with the receiver arrays and processing equipment onboard the survey vessel and not the sound source *per se*. A vessel equipped with only a sound source would be comparatively inexpensive but is not generally available to researchers.

One suggestion by workshop participants was that JIP or another appropriate agency could obtain compressors and airgun arrays that could be used to produce sound sources equivalent to typical commercial sounds. This equipment could then be made available to people interested in conducting environmental effects monitoring as part of a proposal submission process.

5.2 Recommendations for Future Studies

Most of the second day of the workshop was spent discussing the potential categorization of research studies most needed to further advance our understanding of the effects of seismic sound on fish behaviour. It was felt that it was important to maintain flexibility in defining future studies in order to take advantage of other studies and equipment availability, particularly seismic sound sources, as well as available funding. It was also felt that the overall emphasis should be placed on the population or ecosystem level, longer-term studies that integrated methodologies, but that small-scale, localized studies could also be useful in certain instances.

Participants felt that future studies should be solicited on the basic habitat and behaviour combinations, as discussed in Section 4.2. Categorizing study types using a fine resolution of issues such as hearing sensitivity or possession or lack of an air bladder was discussed, but it was felt that the breakdown by habitat and general behaviour classification (e.g. territorial or schooling) was more suitable. The final categorization of research types is presented in Table 2 along with example species, suggested methods of studies, and primary issues of concern.

Table 2: Categorization of Research by Type of Habitat and Species Behaviour

TYPE OF STUDY	SPECIES	ISSUES	METHODS
Benthic – territorial	Groupers Rockfish Tilefish Lobster	• Fishing gear types are frequently restricted, e.g. trawling unlikely, longlining individuals • Study should be focussed broadly on the the animal's repertoire of behaviours (e.g. time budgets) • Habitat usually includes topography and small home ranges • Number of tags/samples determined by power analysis at design stage (previous studies useful)	• Tags (acoustic, standard, archival) – capture and tagging of individuals • Fishing may provide some primary behaviour information • Ground truth – fishing (changes in CPUE, biological indicators) • Echo sounder/sonar to track movements • Passive acoustics for specific behaviours, e.g. spawning • Video has more applications with territorial species
Benthic – dispersal	Cod Haddock Flatfish Snow crab Skates and some sharks (e.g. dogfish)	• Potential rate of movement increases size of study area and costs • Acoustic transponder tags can allow vessel tracking of individuals • Fishing allows collection of additional biological data • Assessment of abundance usually relies on standardized gear types (e.g. trawls) but behaviour requires multiple gear types • Echo sounders have limitations close to the bottom • Number of tags/samples determined by power analysis at design stage (previous studies useful)	• Tags (acoustic, standard, archival) – capture and tagging of individuals • Fishing may provide some primary behaviour information • Ground truth – fishing (changes in CPUE, biological indicators) • Echo sounder tracking of movements • Passive acoustics for specific behaviours such as spawning • Special attention on particle motion along bottom may be required (e.g. snow crab)
Pelagic – schooling (e.g. herring)	Herring Capelin Anchovy Mackerel Shrimp Alaskan pollock	• When and where – during what life stage or behaviour? • Scale is flexible, and confined space may be cheaper • Ship noise may be a confounding stimulus • Document ambient and equipment noise • Monitoring must be close and far requiring two observation platforms • Similar methodology to sampling zooplankton in some cases (e.g. patchiness) • Can population effects be studied (short-lived species may be easier but may be more difficult than some demersal species)? • Number of tags/samples determined by power analysis at design stage (previous studies useful)	• Biomass assessment – quantitative acoustics – sonars and echo sounders • Behavioural monitoring – specialized acoustics • Supplemented by tagging for individual movements / physiology • Ground truth – fishing or observation acoustics – (biological indicators collected by fishing) • Long range acoustic waveguide may allow 3D large scale assessment in the right area and conditions but quantification may be difficult (expensive)
Pelagic – large	Tuna Swordfish Dorado Some sharks (e.g. porbeagle)	• Reasonable baseline in large scale movements for most species • Hard to control exposure to these animals, but exposure is more easily recorded (with tags) • Number of tags/samples determined by power analysis at design stage (previous studies useful)	• Pop-up and satellite tags most likely method (long tradition) • Multiple types of tags will likely be useful • Acoustic tags (ultra-long life) become more useful as networks grow • Large size allows tagging to monitor acoustic exposure • Ground truth less critical – fishing (changes in CPUE, biological indicators) • Active acoustics (special horizontal sonars to observe response)
Coastal/ Estuarial	Shad Salmon Striped bass Eel Sturgeon	• Some species (Alosa sp. and menhaden) are difficult to sample because they swim away from ultra-sound • Number of tags/samples determined by power analysis at design stage (previous studies useful)	• Acoustic/telemetry tags are primary study method • Active acoustics may be used in river monitoring of migrating species like salmon • Opportunities to use existing fisheries for groundtruthing (e.g. striped bass and eel) • Biological indicators may provide useful information

5.3 Evaluation Criteria for Future Project Designs

Participants proposed a number of criteria for comparison or evaluation of potential projects within the basic habitat types provided in Table 2. Potential priorities were discussed within a number of general topic areas that could be used in project selection. Topics areas suggested for possible use in evaluation of project proposals were as follows:

- ecological importance (integration with multi-species and/or population studies, timing or life stage considerations, risk);

- scale of study (laboratory versus field, short-term versus long-term, geographic scope);

- statistical design/rigour;

- impacts related to commercial fishing;

- team make-up; and

- links with on-going studies.

These considerations were discussed as they applied to potential studies of small pelagics and gadoids as examples of how these topics could be applied more generally.

5.3.1   Ecological Importance

One of the overriding issues from available information is that questions remain concerning actual population or ecological impacts of observed behaviours. The time of year and location can have major impacts on the validity of studies. Different size classes or year classes of fish occupy different areas at different times, and this can affect the ability to detect individuals and document behaviour. Some issues, such as the potential for disruption of spawning, are difficult to assess in a large-scale study because of the potential ramifications of the impact. These may be cases where small-scale localized studies or laboratory studies can help clarify issues and concerns. It is important to understand the stage and behaviour of the fish at the time of study, as well as the population or ecological risk of disrupting that behaviour.

Few studies to date have attempted to integrate studies of predator-prey relationships or potential food or plankton into studies of fish behaviour. Seismic sound can affect other organisms such as zooplankton or predators, which can in turn affect their vertical distribution as well as the distribution of fish, with implications for predator-prey interactions. These types of studies will likely be necessary to improve our understanding of population or ecological impacts. For example, this could include studies of redfish in conjunction with cod and haddock studies, or complementary studies of zooplankton and herring. These studies could also incorporate examination of other valuable life stages of marine organisms in plankton, such as eggs and larvae.

5.3.2   Scale of Study

Scale issues include short-term versus long-term study, laboratory versus field experiments, and the spatial or geographic scale of the particular program. Investigation of full-size arrays on benthic dispersal species, such as cod and haddock, may require study over tens of kilometres to determine the degree of movement out of an area. On the other hand, study within a confined area, such as a fjord, may help lessen the need for large-scale deployment of resources. The spatial scale may be left open and information extrapolated to the population level, but it is unlikely that it will be possible to eliminate the need for large-scale field studies.

Some species are more suited to short-term rather than long-term study. For example small pelagics, such as herring, are short-lived. In some cases studies are limited to a few days or weeks. Other species, such as cod and haddock, are longer lived (usually over a decade) and may be more suitable for longer-term studies. Many invertebrates, such as snow crab, are also relatively long-lived (over a decade).

Some studies, such as those on eggs, larvae, and zooplankton, can be virtually impossible to conduct in the field. However, the behaviour of larger and more complex organisms like fish can be misleading unless conducted in the field. For example, one of the key questions with gadoids has been effect distance and duration from a full-sized array.

5.3.3   Statistical Design/Rigour

The overall design should capitalize on the results of previous studies, especially those conducted in the target area, which can help define the sample size needed to produce conclusive results. When studies incorporate before, during and after exposure components, it should be recognized that the degrees of freedom to determine statistical significance may be low. Preliminary studies can be useful to determine potential variability for refining the statistical design, but the statistical design must be established prior to the main study. Having a good statistical analysis component is critical for any study.

5.3.4   Impacts on Commercial Fishing

Addressing commercial fishing may be important in most, if not all, studies of fish behaviour in response to seismic sound. One of the major reasons for this is that effects on commercial fishing may be connected to ecological impacts and, indirectly, to other valuable species (for example, through bycatch). In most marine environments, fishing is a major part of the system. Traditional and logistical knowledge provided by the fishing industry can almost always be of assistance in designing or conducting these studies. That being said, it may also be important in a particular study to isolate the study from the effects of commercial fishing to the largest extent possible. Whatever the approach, it will be important to examine how a particular study interfaces with commercial fishing in the area.

5.3.5   Team Make-up

Some studies may be best carried out by centres with proven experience in conducting the type of study required and the resources to continue work over a number of years. In other cases, it may be necessary to establish a centre of excellence to support long-term research. A seismic airgun source could be part of such a study centre.

Regardless of the study and approach, a marine ecologist should be part of any team from the beginning to ensure population/ecological considerations are adequately addressed.

5.3.6   Links with On-going Studies

It will be important to link new studies with the existing information baseline and with other concurrent studies. These workshops and the participants are an important part of that linkage to ensure that information is shared and new studies address important outstanding issues in a cost-effective manner.

6. REFERENCES

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.

Appendix A: Final List of Workshop Participants, March 29, 2011

First Name	Surname	Affiliation
Steve	Bettles	Canadian Association of Petroleum Producers
Robert	Branton	Dalhousie University Ocean Tracking Network
Chisa K.	Brookes	ExxonMobil
David	Burley	Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB)
John	Campbell	International Association of Oil and Gas Producers (OGP)
John	Christian	LGL Limited
John	Dalen	Institute of Marine Research, Norway
Alain	D'Entremont	Scotia Harvest Seafoods
Ingebret	Gausland	Consultant to Statoil, Norway
Roger	Gentry	E&P Sound and Marine Life Joint Industry Program (JIP)
Anthony	Hawkins	Loughine, UK
Frank Reier	Knudsen	Kongsberg Maritime - Simrad, Norway
Svein	Loekkeborg	Institute of Marine Research, Norway
Gordon	MacDonald	Crab Fisher
Maxine	Madison	ConocoPhillips
David	Mann	University of South Florida, College of Marine Science
Jennifer	Matthews	Offshore Energy Research Association, Canada
Jennifer	Miksis-Olds	ARL Penn State/JIP OGP
Lars Petter	Myhre	Statoil
Robert	O'Boyle	Beta Scientific Consulting Inc.
Jerry	Payne	Fisheries and Oceans Canada
Kimberly	Skrupky	Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)
Dave	Taylor	Environmental Studies Research Funds (ESRF)
Eric	Theriault	Canada-Nova Scotia Offshore Petroleum Board (C-NSOPB)
David	Wallace	Wallace & Associates
Joe	Warren	Stony Brook University, School of Marine and Atmospheric Science
Gary	Wolinsky	Chevron

Workshop Coordinators		
Norval	Collins	CEF Consultants Ltd
Anne	Muecke	Griffiths Muecke Associates
Ashley	Sprague	Workshop Coordinator

Lunch Speakers		
Jeremy	Broome	Acadia University, Centre for Estuarine Research
Hilary	Moors	Fisheries and Oceans Canada, Species at Risk

Appendix B: Halifax Workshop Agenda

ESRF/OGP/OEER Workshop   All events except dinners are at the Lord Nelson Hotel, 1515 South Park Street, Halifax

Monday, March 28
18:30 - 20:00	Icebreaker Reception	Victoria Suite, Lord Nelson Hotel
20:00 -	Dinner - on your own	

Tuesday, March 29   Admiral Room, Lord Nelson Hotel
07:30 - 08:30	Breakfast	
08:30 - 08:45	Opening and Introduction	
08:45 - 09:00	Objectives, Outcomes and Agenda – An emphasis on science	
09:00 - 09:45	What is our primary measure of effect and what methods are available?	
09:45 - 10:30	Fish and/or Invertebrates - how do our concerns change?	
10:30 - 10:50	Break	
10:50 - 12:15	Fishery Statistics - use and misuse	R. O'Boyle
12:15 - 13:15	Lunch	Presentation: *H. Moors, Acoustic Monitoring of Scotian*
13:15 -13:30	Networking - Agenda Changes?	*Shelf Bottlenose Whales*
13:30 - 14:15	Monitoring Methods - Video	D. Mann
14:15 - 15:00	Monitoring Methods - Biomarkers	J. Payne
15:00 - 15:20	Break	
15:20 - 16:00	Monitoring Methods - Fishing Gear	Panel Discussion
16:00 - 17:15	Monitoring Methods - Acoustics & Tagging	A. Hawkins
19:00 - 21:00	Group Dinner	McKelvies Seafood Restaurant

Wednesday, March 30   Admiral Room, Lord Nelson Hotel
07:30 - 08:30	Breakfast	
08:30 - 09:30	Are there non-science issues that must be considered?	
09:30 - 10:30	How do we document experience and knowledge?	
10:30 - 10:50	Break	
10:50 - 12:15	Geographic Perspectives	
12:15 - 13:15	Lunch	Presentation: *J. Broome, Monitoring in the Bay of Fundy*
13:15 -13:30	Networking - Agenda Changes?	
13:30 - 14:30	Scale Issues - what can we do small, what needs large scale study?	
14:30 - 15:10	Blend of Methods - what components/elements do we need in all studies?	
15:10 - 15:30	Break	
15:30 - 16:30	How do we separate scientific research from applied monitoring?	
16:30 - 17:00	Agreeing on Priorities	
18:00 - 21:30	Group Dinner	Halifax Dinner Theatre

Thursday, March 31   Admiral Room, Lord Nelson Hotel
07:30 - 08:30	Breakfast
08:30 - 09:45	Monitoring Methods - Primary Issues
09:45 - 10:30	Integrating Statistical Analysis into Reporting
10:30 - 10:50	Break
10:50 - 12:00	Risk, Investment and Potential Benefits in Monitoring
12:00 - 12:30	Wrap-up

ESRF   OGP   OEER

Appendix C: Background Papers

Contents

Observing fish behaviour

By acoustical methods

A briefing paper prepared for a
JIP Fish Behaviour Workshop
March 2011: Halifax

Anthony Hawkins
Loughine Ltd

Observing fish behaviour

By acoustical methods

Anthony Hawkins
Loughine Ltd

The importance of behaviour

Much of the work done so far in assessing the impact of sounds on fish has been concerned with defining sound exposure levels that result in the death or injury to fish. Such impacts can be relatively easily determined. Death rates can be evaluated and criteria for injury readily be defined by pathologists. Similarly, changes in hearing sensitivity can be demonstrated following exposure to sounds, either by showing a change in threshold to a particular sound (temporary threshold shift or TTS), or by demonstrating injury to the sensory hair cells of the inner ear. It is also possible to ascertain whether sound exposure has caused a physiological response, in terms of elevating the levels of stress hormones in the tissues, or evoking a change to the heart rate or breathing rhythm.

Such responses have been observed from fish under both laboratory and field conditions, and have been especially useful in helping to define the levels of sound which are capable of affecting individual fish adversely.

Often, however, our concerns not whether a sound causes physical or physiological damage to individuals but whether exposure results in changes to the behaviour or distribution of fish. That is:

- are fish driven away from preferred areas, like feeding grounds;

- do they expend more energy in movement and escape reactions;

- are their migrations disrupted;

- is their spawning behaviour suppressed; or

- is their ability to detect important sounds blocked or masked?

All these changes can have major effects upon fish populations, reducing the feeding rate and growth rate of fish, preventing their reaching spawning areas at the appropriate time, or interfering with reproductive success. Changes in behaviour may also affect fisheries by impairing the ability of fishers to catch fish.

Damage and injury to fish can be examined with captive fish under controlled conditions in the laboratory. However, studies of the behaviour of fish cannot readily be conducted under controlled conditions.

Captive or free-living fish?

There are many advantages to carrying out experiments on fish under carefully controlled conditions; i.e. in tanks in the laboratory or in cages in the wild. A fixed installation at a carefully chosen location, with measuring instruments precisely positioned, can yield definitive information on responses to sound. Detailed observations can be made of the behaviour of the captive animals by means of TV or other observation systems. The fish can be examined before and after the experiments and *post-mortem* examinations carried out. The full history of the experimental fish is often known.

However, it has become increasingly evident that the behaviour of many fish in tanks and enclosures is distorted. It may be nothing like the behaviour they show in the wild. Often, their repertoire is severely restricted in captivity. They will not feed, or they will not spawn. Fish unaccustomed to being enclosed may damage themselves against the sides of tanks or through contact with netting. They become habituated to the repeated presentation of sounds and cease responding to them. Background noise levels may be high from pumps and other machinery and detection of sounds by the fish, including the sounds they make themselves, may be impaired or masked.

It is more meaningful to conduct behavioural studies in the wild, where fish behaviour is natural, and less influenced by artificial conditions. It is only in the wild that a full repertoire of behaviour is seen. Predators behave like hunters and may range widely in search of prey, or they may hide in order to ambush vulnerable food organisms. Prey can protect themselves by adopting cryptic habits or by joining together in large schools. Nomadic fish can range more widely in their movements, while territorial fish can defend a selected home range. Only when fish are showing their own distinctive behaviour patterns in a natural habitat, under quiet ambient noise conditions, can we expect them to express their full range of responses to the sounds presented. Moreover, under these conditions fish can be exposed to man-made sounds under more appropriate acoustic conditions. Sounds are difficult to reproduce under laboratory conditions, where the fish may be close to reflecting boundaries and where sounds may propagate very differently.

There are therefore very good reasons for looking at the behavioural responses of fish to sounds in the wild, rather than in an aquarium or sea cage. It is preferable to examine free-swimming wild fish, unconfined by walls or netting and unaffected by the trauma of capture, and handling.

The problems in examining fish in the wild are formidable however. How can we best observe and record the behaviour of free-swimming fish?

Requirements of any system for observing fish

It is inherently difficult to observe fish in the wild. Although it relatively easy to look at the behaviour of fish which live in small streams or shallow pools, like guppies or some fresh water members of the carp family, it is exceedingly difficult to observe marine fish at depth in the ocean. We humans are essentially visual creatures. We mainly use our eyes to observe the world around us but our eyes do not work well underwater or in the dark. We can look at fish doing their own thing in daytime, using SCUBA gear or by snorkelling, but we are not

really at home in the aquatic environment, especially at night. We are forced to use instruments and aids which can be deployed in water for long periods, under a range of light levels, at significant depths.

Such underwater observation instruments:

- Have to be robust, waterproof and capable of operating at considerable depths

- Should not influence the behaviour of the fish being observed. Ideally they should not emit light at wavelengths which can be seen by fish or emit sounds which can be heard. They should not constrain the movements of the fish.

- Must be capable of providing a clear and unequivocal measure of behavioural change

Options for observing fish

Observations by eye or by camera have been used frequently to observe and record fish behaviour. However, water is much less suited to making visual observations than air. It is less transparent and behaves as a filter, taking out red light and leaving yellow and green. It is often full of particulate material, which scatters and absorbs light and results in fog-like conditions. Contrast is poor and light levels, especially at depth, are low. It is difficult to see any distance, and almost impossible to see fish at night or at extreme depths. Nevertheless, in daytime, visual observations can provide detailed information on the behaviour of shallow water fish, and under these conditions cannot be rivalled by any other technique. In tropical waters the behaviour of fish can be observed in detail, especially if they show limited movements.

Sound travels well through water and forms the basis for many underwater observing systems. Although sound cannot provide the detailed images created by light-sensitive cameras it can be used to observe fish over much greater distances. Through the use of sonar the behaviour of fish can be observed and recorded at great depths. In particular the movements of schools of fish can be plotted in two and even three dimensions, often against background images of the seabed and other features.

In addition, small electronic devices can be attached to fish and used to follow their movements. In rivers and shallow lakes radio-transmitters can be used to track fish by means of mobile or fixed receivers. In the sea, ultrasonic transmitters can serve a similar function. Some electronic recording tags can also store data on various environmental parameters for months, and when retrieved can allow the movements and behaviourof fish to be reconstructed.

Visual observations

Visual observations of fish have often been made by divers and from manned submersibles, both towed and under their own power. Pioneering observations were made on the response of fish to fishing gears by means of diving techniques (Wardle, 1983; Urquhart and

Stewart, 1993 and Graham et al., 2004). However, the short duration of a scuba dive, the restriction of the technique to relatively shallow water, and the noise and general disturbance generated by the diver severely limits the value of direct observation for describing the detailed movements of fish.

Underwater cameras placed at fixed positions, towed or carried by a submersible vehicle can replace direct visual observation and can allow prolonged periods of observation. One method is to observe a small area of seabed with a camera for long periods, noting the detailed behaviour of fish within it, their interactions with one another and their association with particular features of the environment. One disadvantage is that many fish may only be passing through the area, and can be glimpsed only for a short period. A mobile camera can follow individual fish, or a diver can move along a line transect to look at many individuals and gain an idea of the distribution and variety of behaviour shown; but there is always a risk that movement of the camera may affect the behaviour of the fish.

As an example of the successful use of underwater cameras we have the early experiments used to describe the response of sharks to sound (Figure 1). Studies in the wild have shown that both coastal and oceanic sharks approached underwater speakers broadcasting low frequency, pulsed sounds from several hundreds of meters (studies reviewed by Myrberg 2001). In contrast, sudden loud sounds evoked startle responses, with sharks turning away from the source. Sharks often habituated to the stimuli after several presentations.

Figure 1: Underwater movie camera image of sharks attracted to a loudspeaker broadcasting low frequency pulsed sound.

Stereo cameras have particular advantages where the positions of fish within a school or in relation to habitat features are required (e.g. Harvey et al., 2002). Stereo imaging permits the location of fish in 3-D and allows the size and swimming speed to be determined. Commercially available systems have been developed which use robust, low light video cameras and purpose-written software to give non-intrusive monitoring of fish size at aquaculture installations (Sheih and Petrell, 1998). So far, this technique has not been

widely applied to the analysis of fish behaviour but it has the potential to provide detailed examination of the movements of fish in three dimensions.

The visual field of a single camera in water is often narrow. Arrays of cameras with overlapping visual fields can expand the area that can be monitored.

Visual observations at night, or at depths where light penetration is poor, require light. Ultra-violet and infrared are heavily absorbed by water and their use is limited to short-distances. Infrared light has been used to observe fish under the assumption that fish are insensitive to this wavelength, but has a very limited range in water. Wherever artificial light is used there is strong backscatter from suspended particles in the water. Moreover, fish may react to the lighting itself. It is especially difficult to observe pelagic fish, living in open water, by optical means as they react to the presence of the camera.

Laser scanning systems can increase the range attainable by conventional optical instruments, while retaining relatively high-resolution image quality. They have been successfully used in place of traditional side-scan sonar to map benthic habitats (Rhoads et al., 1997; Carey et al., 2003). Other applications have included assessing king crab populations (Tracey et al., 1998) and the assessment of kelp forest fish communities (Heilprin and Carey, 1994). However, such lasers are visible to fish, which may react to the presence of the light.

The use of sound - sonar

General features

Acoustic devices for the detection of underwater objects are known as **sonar** (the acronym derives from sound navigation and ranging). Sonar has been used widely to locate fish, map their distribution, and evaluate their numbers and biomass. A short pulse of sound or ping is generated by the sonar system, which travels out from the source and is then reflected by individual fish or groups of fish, with the received echoes providing information on the distance and angular location of the reflectors (Figure 2). Different tissues within the fish reflect sound to a differing degree. The gas-filled swim bladder is an especially good reflector and fish with swim bladders like the cod and herring provide stronger echoes than those fish lacking internal gas volumes, like the mackerel.

The world's first patent for an underwater echo ranging device was filed at the British Patent Office by Lewis Richardson one month after the sinking of the Titanic (Hill, 1962). Within a few years sonar had been developed by several navies to enable the detection of submarines. The earliest commercial sonars were simple depth sounders, where the main echoes were received from the seabed. However, "false" echoes were often observed above the seabed and were subsequently attributed to cod, herring and other fishes (Rallier du Batty, 1927; Kimura, 1929). Fishers began using echo sounders to locate fish (e.g., Sund 1935; Balls 1948). Sonar has now become a vital tool for commercial fishers, enabling them to find fish concentrations and to manoeuvre their vessels to catch them. In the scientific field, improvements in computer and electronic technology have resulted in the quantitative use of sonar to count individual fish or estimate fish biomass. In addition, sonar can be used

to observe the behaviour of fish. Simmonds and MacLennan (2005) provide a full description of the variety of sonar systems applied to fisheries.

The essential function of any sonar is to transmit a sound, and then receive, filter, amplify, and analyse any echoes received. Most sonars use the same transducer to transmit sounds and receive them, but more sophisticated system use separate transmitter and receiver arrays. The time from transmission of the leading edge of a sound pulse to reception of the echo is measured and converted into the range by knowing the speed of sound in water. Simply pointing the beam of the sonar in different directions, and comparing the amplitudes of the received signals may determine the bearing of a fish or fish school. However, the relative arrival time or phase of the echoes at several receiving elements of the transducer array may also be processed to derive the directions from which echoes are returned.

The common depth-sounding sonar uses a downward directed beam of sound (Figure 1), but many types of sonar have their transducers mounted so that the sound beam can be pointed in different directions. Some sonars use single, wide beams, while others use narrow beams. Some have multiple beams while others can rapidly scan a beam across a sector. The sonar transducers can be attached to the hull of a ship, mounted on a pole, or towed behind or alongside the ship. The directional sound beam is often conical in shape, but shaped beams are also commonplace. Echo amplitudes are usually greater on the acoustic axis than on the edges (Urick, 1983). The beam cut-off may not be sharp and side lobes may be generated which can interfere with the precision with which targets are located.
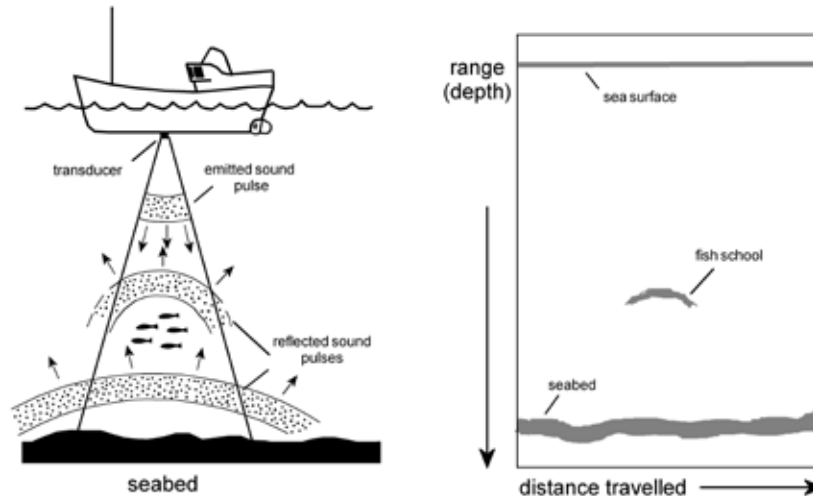
Figure 2: A simple, single-beam sonar sends out a short sound pulse at an ultrasonic frequency, which travels through water at a fixed speed. Reflected echoes are received at times depending on their range. A simple display shows the depth of the fish and the depth of the seabed.

Sonars usually transmit sound pulses at ultrasonic frequencies – well above the hearing range of fish. The choice of acoustic frequency for sonar is critical. Lower frequencies have greater transmission ranges and sampling volumes than higher frequencies; however, the

latter have higher resolution and are able to detect smaller targets (Simmonds & MacLennan, 2005). Sonar systems suffer limitations near reflecting boundaries, such as the sea floor or sea surface, which return strong echoes. As echoes from fish are often very weak in comparison with the emitted sound pulse or any seabed reflections various devices like the blanking out of stronger reflections and the application of time varied gain are used to improve performance.

Most simple depth sounders operate at frequencies of 20 to 200 kHz, which allows long-range transmission and large sampling volumes. Higher frequencies (up to 300 kHz) are used in scientific sonars, which require narrower beams and greater precision in resolving sound scatterers. High precision scanning sonars may operate at even higher frequencies but the higher the frequency the shorter the range over which the sonar will detect fish targets. Such simple sonars give clear images of fish schools and individual fish below the moving vessel (Figure 2)
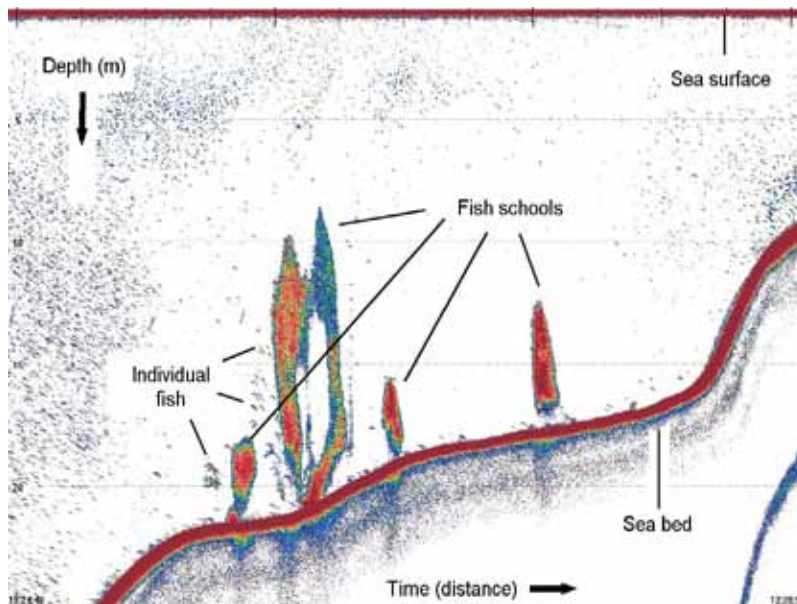

Figure 2. An echosounder may give clear and detailed images of fish schools and individual fish. This particular scientific sounder (Simrad EK60) operated at 200 kHz

A small number of military sonars, and sonars for examining the topography of the seabed, operate at low and mid frequencies. These may transmit at frequencies that fall within the hearing range of fish and may therefore influence their behaviour. Some devices emit long chirps rather than short, single frequency pulses. These sonars are not generally used to observe fish behaviour. However, they can detect fish and can demonstrate the movements and behaviour of large schools at considerable distances, although their effectiveness depends on prevailing conditions for sound propagation. The GLORIA long-range side scan sonar, designed by the UK Institute of Oceanography, is contained within a towed body. It operates at frequencies around 6.2 and 6.8 kHz and can detects returns from a range of up to tens of kilometres on either side of the sonar. It is capable of the long-range detection of fish schools (Figure 3), although its primary function is to determine the topography of the ocean floor. Other side-scan sonars operate at higher frequencies and are used to look at hard objects on the seabed, like wrecks and pipelines, as well as to describe seabed

topography. The sonar is often towed behind the ship, which moves along a straight line so that the echogram shows a rectangular area to one side of the survey track. Such sonars have been used to map the distribution of pelagic fish schools. Doolittle and Patterson (2003) adapted a 600 kHz side-scan sonar to study the behaviour of fish in relation to fishing gears.

In the earliest sonars a moving strip of paper marked by a stylus provided a permanent record of each echo, the distance across the paper indicating the depth. There was usually some means of recording time or the distance travelled by a moving vessel. Nowadays the display is on an electronic screen, using a wide variety of configurations.
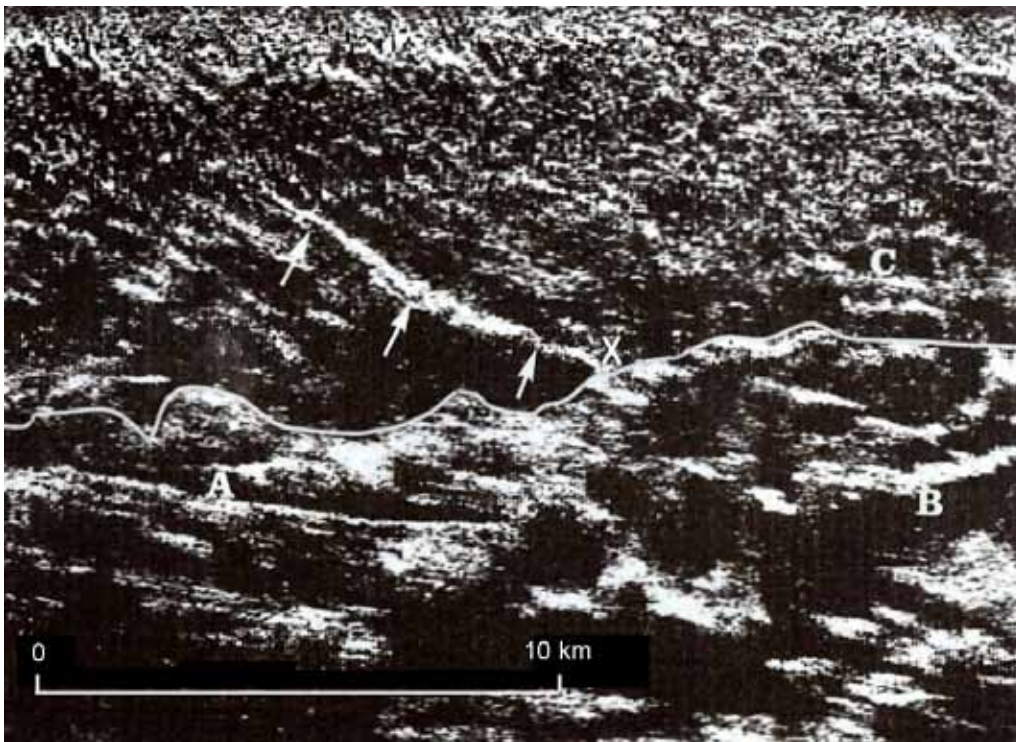
Figure 3: Display from a long range towed side scan sonar (GLORIA) showing a large school of herring *Clupea harengu*s, many kilometres long, off Hawes Bank in the of the Hebrides. The edge of the bank is marked with a white line and the school by a series of arrows. A cross marks the spot where a purse seine vessel caught part of the school. A, B and C indicate conspicuous bottom features. Image courtesy of Stuart Rusby

Observing fish using sonar

Keeping a narrow sonar beam in contact with a single moving fish can be difficult (although it is not impossible, see below), and it is more usual for sonar to be used to track large schools, which present much larger targets and hence enable wider beams to be used. Much of the development work that has gone into sonar has been concerned with enabling fishing vessels to locate, track and manoeuvre their nets around large schools of fish. Simple searchlight sonars operate in the same way as depth sounders but the sound beam can be trained in different directions, both in the vertical and horizontal planes. The targets

are shown on a plan position indicator display, giving both bearing and range. A skilled operator may maintain contact with a school of fish for long periods. Because of the need to wait until an echo is returned before a further pulse can be emitted, mechanically scanning the sonar can be slow.

In more elaborate sonar systems the transmitting and receiving transducers are more complex, with several directional transmitting and receiving beams, or a single narrow beam, which is scanned or swept from side to side electronically. The received signals are stored and the display continuously updated. Information from the ships navigational instruments or from a GPS system can be combined to show the movements of a school relative to the ship, or the movements of the school relative to the seabed. Displays depicting the fish and seabed in three dimensions are now commonplace.

Responses of fish to a single seismic air gun (Figure 4) have been observed with a simple, primitive depth sounder mounted on a moored vessel (Chapman and Hawkins (1969). Indeed, quite complex behavioural reactions (Figure 5) can observed from fish with quite simple sonar systems (Knudsen et al., 2009).
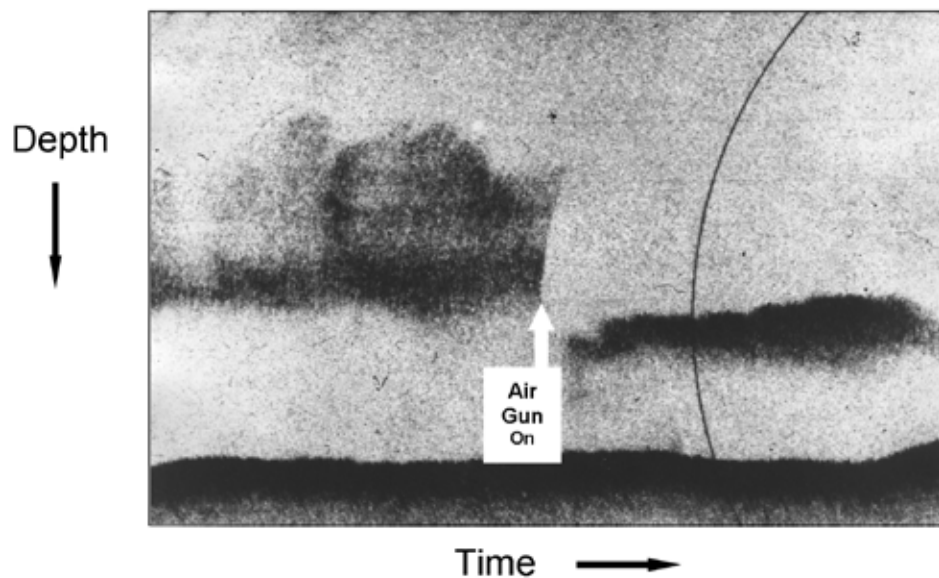
Figure 4: One of the earliest observations of fish reacting to a seismic air gun was made from a vessel anchored in Upper Loch Torridon on the west coast of Scotland. Aggregations of whiting *Merlangius merlangus* were observed with the ship's depth sounder. The fish dived and concentrated in response to repetitive firing of the air gun

It is possible to use sonar to track pelagic schools with high precision (Misund et al., 1998). Depth sounders can be mounted on moored (Ona and Godø, 1990) or drifting buoys (Godø et al., 1999; Wilson and Demer, 2001; Handegard et al., 2003) and used to examine changes in behaviour of fish in response to a passing vessel. Fernandes et al. (2000) mounted a depth sounder on an Autonomous Underwater Vehicle (AUV), capable of moving independently. This type of system can, for example, monitor the behaviour of fish in advance of a vessel and trawl, while a sounder mounted on the vessel can compare the

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subsequent positions of the fish. Sonar mounted on trawl, looking upwards, has been used to compare distributions beneath the vessel and above the net (Michalsen et al., 1999). Engas and Ona (1990) used a headline mounted scanning sonar operating at 330 kHz to identify the entry position of fish in a survey trawl.
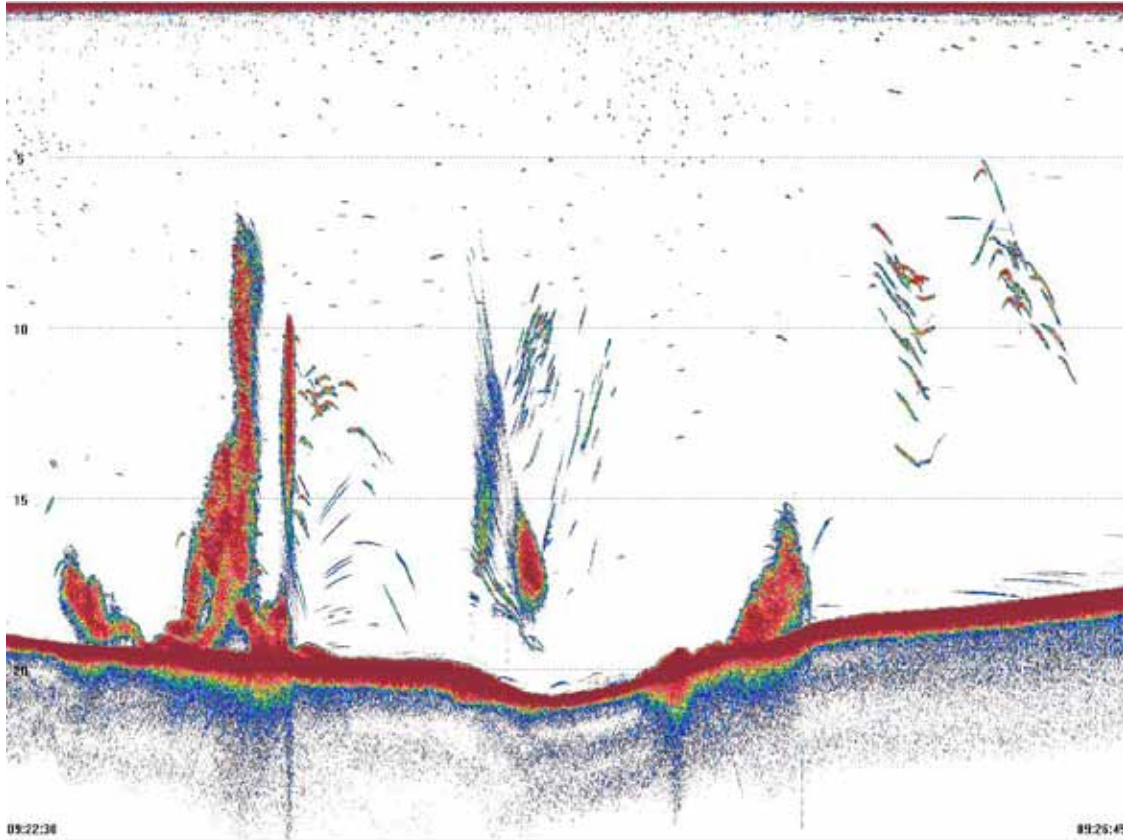
Figure 5: Images of fish from a scientific sonar (Simrad EK60). In this echogram predatory mackerel are attacking schools of sprat. The sprat school in the centre has dived, and the individual fish have released gas from their swim bladders. The gas bubbles can be seen rising to the surface. It is possible that the sprat schools were also reacting to the noise of the vessel carrying the sonar.

The development of narrow beam transducers with minimal side lobes has permitted the use of sonar within rivers and fish-ways to accurately count fish. Such systems can provide valuable information on the passage of fish through dams and hydroelectric systems. Sonar is also used extensively in open river systems to count returning adults for assessment of the overall run of fish. Split-beam transducers are especially useful in this context as they contain elements that are electrically divided into two orthogonal pairs. An acoustic wave front propagating towards the transducer arrives at different times at the pairs causing the phase angle of the electrical output signal from the pairs to differ. The angle of the target is determined from the electrical phase difference between transducer pairs. It is possible to use such sonars to track individual fish by aligning the transducer beam axis with the target using motors to move the transducer so that the tracked target remains on-axis (Hedgepeth et al., 2000). Deviation of the target from the beam axis produces a correction to point the axis towards the target.

Multi-beam sonar (sometimes called swath sonar) has been applied very successfully to study the behaviour of schooling pelagic fish (e.g. Freon et al., 1996; Mackinson et al., 1998; Misund et al., 1998; Gerlotto et al., 1999). Indeed, multi-beam sonars have been mounted on a towed vehicle to observe fish entering and escaping from a bottom trawl (Jones et al., 2001). With suitable data processing 3D images can be created.

The WASSP multi-beam sonar operates at two frequencies, 160 kHz and 80 kHz for different depths of operation. It can be interfaced with the ship's GPS, compass, roll, pitch and heading to provide seafloor profiles. There are a variety of ways of observing the collected data including a real-time 3D view, 2D view, normal echosounder, sonar and side-scan sonar views. The fish can be observed against the topographical background of the seabed (Figure 6).
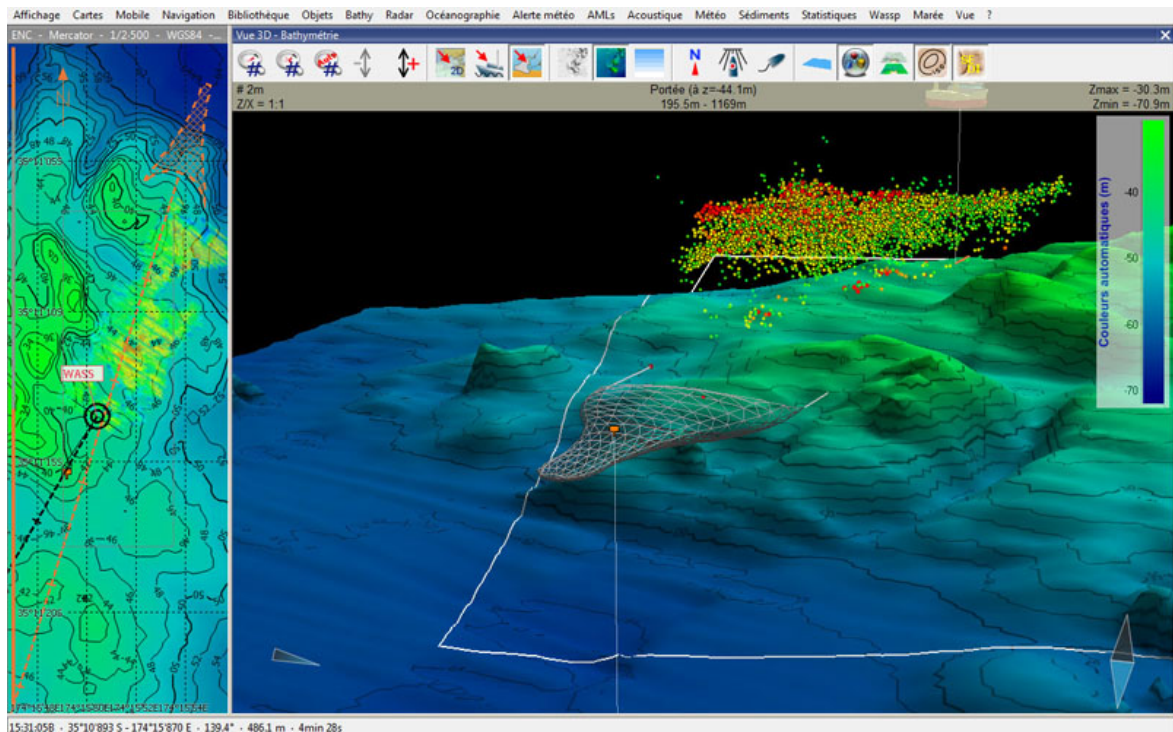
Figure 6. Image from WASSP multi-beam sonar showingfish above the seabed. Such sonars can provide a variety of image options. Image taken from the WASSP website.

Signals returning to a multi-element receiving transducer can be electronically processed to produce the effect of a very narrow beam, repetitively scanning a sector. The whole sector is scanned for returning echoes within the time taken for the transmitted pulse to travel its own length through the water. A picture of the sector is displayed on a screen. Such sonars usually operate at high frequencies (>300 kHz) and their range is therefore limited. An example is the sector scanning sonar described by Mitson and Cook (1971), which was used from a ship to follow the movements of fish fitted with transponding acoustic tags (see below). The same system was also used to determine the efficiency of a trawl at capturing fish (Harden Jones et al., 1977). Such systems operate over ranges of tens to hundreds of

metres. They can yield images of large individual fish, or locate precisely fish fitted with transponding tags.

The Simrad Mesotech MS2000 sonar provides quantitative data throughout the water column from 128 simultaneously synthesized beams over a swath of 180°. Maximum ping rate varies with range setting, but for ranges of over 100 m, rates in the order of 2-3 per second are attainable. The multi-beam sonar operates at 200 kHz, with an individual beam angle of 2.5° x 20°. A 3-D presentation can be obtained using multiple pings.
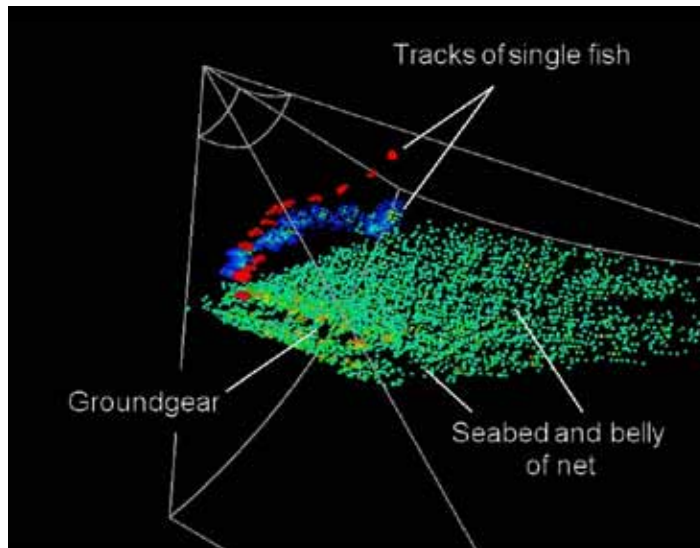
Figure 7. Processed output generated from EchoScope sonar mounted on the headline of a bottom trawl showing traces from two individual fish in a 3-D volume (approximate distance from ground gear to rearmost part of trawl belly is approximately 6 m). Image courtesy of Norman Graham.

The Echoscope sonar, operating at 375 kHz, is capable of delivering 12 acoustic images per second in real time. It generates images from over 16,000 focused beams (128 x 128 beam array) with a range resolution of 3 cm giving a true three-dimensional image. Operated from a surface vessel or mounted on an AUV/ROV, it is generally used for navigation, bathymetry, construction and inspection. It has also been used to observe the behaviour of fish within towed fishing gears (Graham et al., 2004), see Figure 7.

By operating at even higher frequencies, for example in the MHz range, individual fish can be observed in more detail. The "Dual-Frequency Identification Sonar" (DIDSON) is a high definition imaging sonar that obtains near-video quality images for the identification of objects underwater. Developed originally for naval use in harbour surveillance and underwater mine detection, the DIDSON bridges the gap between existing fisheries sonars and optical systems. The images within 12 m of the sonar are sufficiently clear for the swimming movements of large fish to be followed (Figures 8 & 9). In its high-frequency mode, the system scans over a 29° field-of-view.

The DIDSON sonar uses an acoustic lens to focus the sound (Belcher 2002). It has two available frequency modes: a low-frequency mode of 1.0 MHz and a high-frequency mode of 1.8 MHz. These two frequencies bring trade-offs in both maximum range and resolution. In high-frequency mode, the 0.3° beam widths ensure that within the 12-m range all but the

smallest targets (<63 mm at the furthest range) intercept multiple beams. For a 12-m range the DIDSON updates the image at seven frames per second. The result is not just an acoustic "still" image of the underwater environment, but something akin to an acoustic video camera. For fisheries applications within rivers, the high-frequency mode has been found the most useful because it provides high-resolution images that defined the outline, shape, and even fins of target fish. DIDSON-count data have achieved a high degree of precision in counting migrating salmon within a river system (Holmes et al 2006). Moursund et al (2003) have described the use of the DIDSON in a river environment close to a dam.
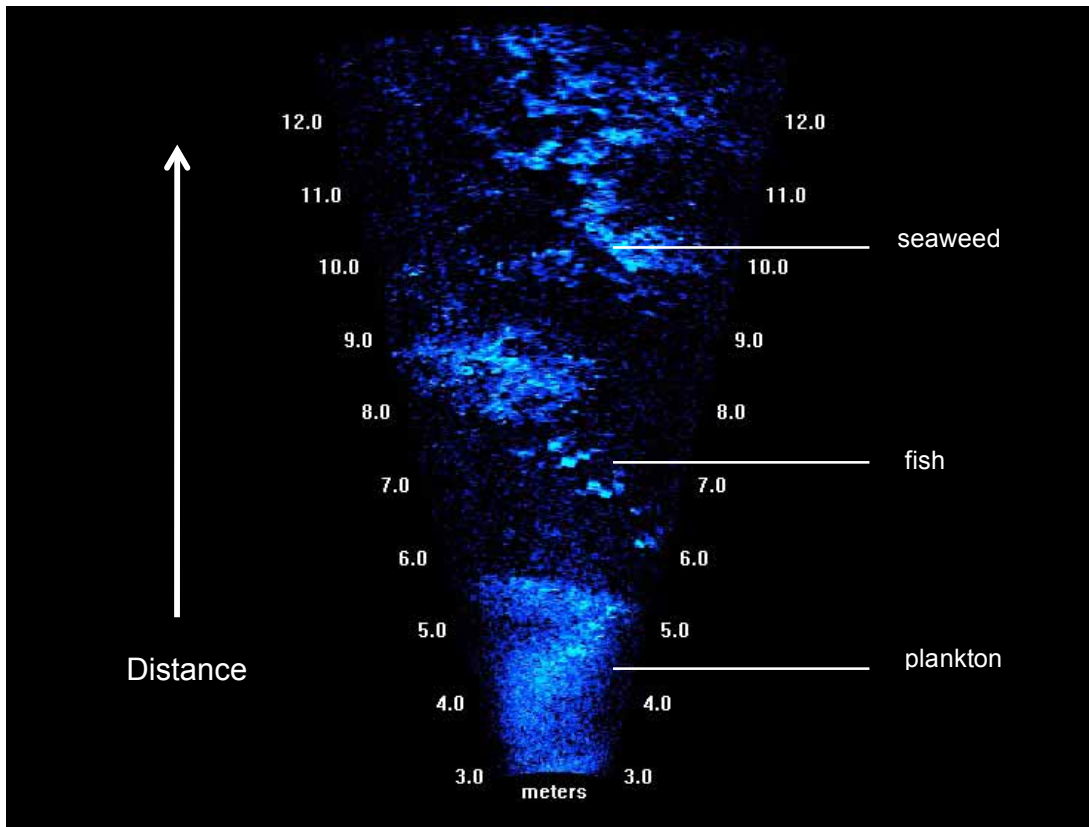
Figure 8: Deployment of a DIDSON sonar to observe fish behaviour in a narrow channel (Lough Hyne). Although the sonar has a limited range it is able to 'see' fish and can be used to track their movements.

An earlier LIMIS system was designed to be diver hand-held and battery-operated and the DIDSON maintains the low weight, small profile, and low power consumption characteristics of its predecessor. Physically, the sonar is small and nearly neutrally buoyant in water. The transducer array, acoustic lens, and the associated electronics are all contained in a single underwater housing. The DIDSON connects to a laptop computer for displaying images in real-time, and for recording the raw data.

Individual fish have been tracked within a mid-water trawl using a DIDSON (Handegard and Williams, 2008). The DIDSON provided an easily deployable platform for observing fish movement within the trawl, and when combined with an automated approach for tracking individual targets yielded quantitative data.
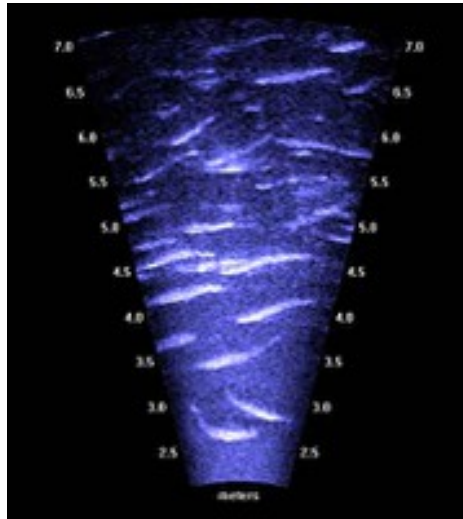
Figure 9: The detailed body movements of individual fish, in this case salmon, can be observed by the DIDSON.

The Blueview imaging sonar is similar to the DIDSON but operates at lower frequencies (450 and 900 kHz). It is capable of seeing and tracking individual fish over a sector with a rather longer range than the DIDSON but with lower resolution.

Perhaps the greatest limitation of the DIDSON and other similar sonars is the relatively narrow 'thickness' of the sonar beam. This is not a problem in a shallow river, where the fish may be confined to narrow depth ranges and remain within the beam. In open water, where fish may move vertically as well as horizontally they may move outside the beam. Because of the very high frequency used there may also be problems in discriminating fish in water containing zooplankton, air bubbles, and other sound scatterers. Seaweeds and eelgrass beds also reflect the sound but this can be used to advantage, allowing the movements of fish within plant material to be observed.

Fish abundance estimation

Scientific sonars are especially valuable for mapping fish distribution and for estimating fish abundance.

Two measurements are derived from the acoustic data to estimate abundance: the backscatter from individual targets, and the backscatter from a volume of water containing fish. The two important quantities in fisheries acoustic applications are the Target Strength (TS) obtained for resolvable echoes and the volume backscattering strength (Sv) for overlapping echoes.

When the fish are large and dispersed, it is possible to obtain echoes from individuals. In this case, echo counting can be used to derive a numerical density estimate as well as to measure the acoustic backscattering cross-sectional area of the individual fish. Abundance is estimated by multiplying the numerical density by the volume of water in the survey area.

The sonar system must be able to resolve a single target by bearing and by range to count fish effectively.

Most pelagic fish aggregate in schools, making echo counting difficult. In this case, echo integration is used to derive density estimates. Echo integration is essentially the summation of the echoes within a sampling volume (the volume backscatter). For most fish aggregations, the summation is linearly proportional to the numerical density of the organisms (Foote, 1983). When the packing density of the fish is high, non-linear effects can occur (Toresen, 1991; Furusawa et al., 1992; Alvarez and Ye, 1999), and other methods are required to estimate numerical density (e.g. Zhao and Ona, 2003). Volume backscatter can be vertically integrated and horizontally averaged to obtain area backscatter, which is proportional to the area density of the fish. Area backscatter values are used to derive population estimates in fisheries surveys. Echo integration is the most common technique currently used to estimate fish populations acoustically.

Acoustic fish assessment methods involve continuous sampling in the vertical and horizontal dimensions along the track of the sampling vessel, but other methods, such as fishing or the deployment of underwater cameras, are required to identify the source of the scattering. The largest sources of error in such surveys are incomplete coverage of the entire population, inaccuracy in apportioning backscatter to fish and other organisms, and variations in the target strengths of the fish. Recently Knudsen et al (2009) reported apparent differences in abundance of fish within a land-locked sea basin by day and by night, which they attributed to changes in the target strength of the fish. During the day the fish were attacked by predators and lost gas from their swim bladders, resulting in a fall in target strength generating low backscatter. Target strength was subsequently restored at night to a higher value, increasing the backscatter. Release of gas from the swim bladders could be seen during daytime on the sonar. There is a critical need to examine the effects of fish behaviour on the acoustic scattering characteristics or target strengths of individuals and aggregations of fish.

Species identification is often difficult and requires additional information. Acoustically this can be achieved by increasing the number of frequencies, as different species often reflect those frequencies to a differing degree. Sonar may operate with multiple, discreet frequencies or by transmitting broadband sound. Broadband transducers transmit a continuous, wideband signal over a wide frequency range. Broadband systems can provide greater spatial resolution (Chu and Stanton, 1998) than single-frequency systems and may be able to measure fish orientation directly (Stanton et al. 2003; Coombs and Barr 2004).

It is possible to have echo sounders collecting data at two or three frequencies during acoustic surveys. A common problem when surveying fish is to separate the backscatter from zooplankton from the backscatter by fish. A simple echo-integrator sums all the echo energy it receives including noise and signals from plankton, jellyfish and other scatterers. Because most zooplankton do not have a gas-bladder the combination of a lower frequency (e.g., 12, 18, or 38 kHz) with a higher frequency system (e.g., 120 or 200 kHz) can be used to separate the two types of scatterer (McKelvey 2000; Kloser et al. 2002).

Multi-beam systems, originally developed for bathymetric mapping have recently been applied to abundance estimation, enabling fish on either side of the vessel to be examined (e.g., Gerlotto and Paramo, 2002). However, although multi-beam sonar systems have a great potential to provide quantitative 3-D images of fish schools and may provide a much

more efficient way to estimate the abundance of the fish stocks accurately, there are few standardised quantitative data processing and visualisation techniques available as yet.

Problems in observing fish with sonar

One problem with assessing fish abundance by means of sonar, or indeed with observing fish behaviour, is that the sonar itself must often be mounted on a ship, which generates a noise field. Fish may react to the vessel by diving or moving to one side. Remotely Operated Vehicles (ROVs) and Autonomously Operated Vehicles (AUVs) have been used as a substitute for large research vessels as they may be quieter in operation (Fernandes et al., 2000).

It is a general tenet that any system for observing fish behaviour should not itself influence the behaviour of the fish. In acoustic abundance estimation, any avoidance of the sampling system by the fish will bias acoustic density estimation. Fisheries research institutions worldwide have invested in new 'silent' research vessels in accordance with recommendations from the International Council for the Exploration of the Sea (Mitson, 1995). However, contrary to expectations, the reactions evoked by these new vessels have been stronger and more prolonged than the ones initiated by conventional vessels (Ona et al., 2007). Sand et al., (1008) have suggested that the stimuli initiating vessel avoidance may include infrasonic particle accelerations. Near-field particle motions generated by a moving hull are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses in several species of fish.

Whether sonar is operated from a small boat, a large research vessel, or attached to the shore it is important to remember that any sound audible to fish which is generated by the mounting system, or even changes in the pattern of flow around the device, are potentially able to influence behaviour. In the worst cases the fish may no longer appear on the sonar. One of the advantages of using multi-beam or scanning sonars is that any movement of the fish in response to the vessel itself may be observed.

Some species of fishes, including shads and menhaden, are able to detect ultrasound (frequencies above 20 k Hz) and may react directly to sonar signals (Dunning et al. 1992; Nestler et al., 1992). Thresholds obtained by cardiac conditioning of the American shad *Alosa sapidissima* by Mann et al (1997) found sensitivity to high level sounds at these ultrasonic frequencies. Similarly, it has been shown that the menhaden *Brevoortia* is capable of detecting sound frequencies from 40 kHz to at least 80 kHz (Mann et al. 2001). In contrast, Pacific herring *Clupea pallasii* in a shallow tank with immersed sound projectors yielded Auditory Evoked Potentials at frequencies up to 5 kHz, but not to ultrasonic frequencies (Mann et al, 2005). Negative results were obtained from other species of Clupeinae; the bay anchovy *Anchoa mitchilli*, scaled sardine *Harengula jaguana*, and Spanish sardine *Sardinella aurita* only detected sounds at frequencies up to about 4 kHz (Mann et al, 2001). It seems that within the Clupeidae only members of the subfamily Alosinae, which include the shads and menhaden, detect ultrasound.

Fish may be able to detect high level pulses of ultrasound, like those produced by sonars, through a variety of mechanisms. A phenomenon known as radiation pressure means that any reflector of sound may receive a small pressure impulse as a result of rectification of the

impinging sound pulse. Fish tissues, and the water itself may behave non-linearly to very high-level sounds. Sonar signals, and even ultrasonic fish tags may be audible as low amplitude clicks to the fish. In most instances the effects are likely to be minimal.

Tracking fish fitted with tags

For many years fishery biologists have caught fish, noted their position, labelled them with a tag, and then returned them to the sea. When a fish is caught a second time, then the fisher notes its new position. There are essentially two fixed positions derived for the fish – at the two points of capture. That data in itself may provide information on the movement of the fish. However by making the tag a miniature transmitter, capable of conveying information on its own position, or even of telemetering information on the physiological state of the fish, then it may be possible to track the fish more or less continuously and in real time.

Tag attachment and other important considerations

Tags may be attached to the outside of the fish, in direct contact with the water, or placed within the body of the animal. Internally placed tags are still effectively in contact with the water by way of the aqueous tissues of the fish but some tissues, like the fatty liver or gas-filled swim bladder may attenuate the acoustic signal. The propagation of high frequencies (above 200 kHz) may be especially badly affected. However, internal tags have the advantage that there is no bulky object attached to the fish to impede its movement. A great many researchers have placed transmitters within the stomachs of fish. The device is made smooth so that it can be pushed down the oesophagus into the stomach where it may be retained for long periods. Salmon in their non-feeding river migrations may retain tags in their stomach for many months. Predatory species like the cod are accustomed to ingest large items, including gastropods and crabs in their shells, and the insertion of a tag of similar size does not appear to cause problems for the fish. Fish may retain them for days and even weeks. Cod will continue to feed with the tag inserted.

Tags may also be implanted within the abdominal cavity by surgery. The fish is anaesthetised and a small incision made in the abdominal wall. A chemically sterilised tag is then inserted and the wound closed with sutures or with surgical adhesive. Unfortunately in many fish the abdominal wall is thin and poorly supplied with blood and healing can be prolonged and incomplete. The advantage of this method of internal insertion is that the tag cannot be regurgitated. However, it is less successful with some species where infection of the insertion site may occur. There is also the disadvantage of postoperative stress. Surgical implantation has become a well-established method for attaching telemetry transmitters in studies of fish behaviour despite many reports of transmitter expulsion, fish mortality and adverse effects on fish physiology or behaviour. Jepsen et al. (2002) describe how choice of surgical procedure, fish size, morphology, behaviour and environmental conditions can affect the success of implanting telemetry transmitters.

Tags can be attached externally in a great variety of ways and in many positions, limited only by the ingenuity of the researcher and the anatomy of the fish. Tags are most commonly placed on the head or back, held in place by clips, sutures, pins, barbed hooks, straps, metal

or plastic loops or thread. In general, whichever technique of attachment or insertion is used it should involve a minimum of surgery and should not result in chafing or abrasion of the skin. The skin of many fish does not normally come into contact with hard surfaces.

An external tag may impede the motion of the fish either by direct interference with locomotion or by increased drag or weight. Entanglement with aquatic vegetation and fouling of the tag with biological organisms can also pose problems. Ross and McCormick (1981) concluded that the weights of external transmitters in water should be less than 1.5% of the body weight. However, some fish may adjust their buoyancy to compensate for additional weight.

One of the problems in tracking fish fitted with transmitting tags is that the fish must first be caught and handled before they can be released with their tags attached. Capture itself can be traumatic. Fish caught in towed fishing gears are often damaged from being dragged along with other fish in the back of the net. They may also be exhausted from their efforts to avoid capture. Fish caught in gills nets may be damaged by the net itself. Fish caught on hook and line may be damaged by the hook and may again be damaged by swimming to exhaustion. In bringing fish up from depth their swim bladders may expand, causing them to be too buoyant at the surface, so that they find it difficult to return to their original depth. In some cases the swim bladders may burst. Handling of the fish may cause damage to the skin and scales. Some of these problems can be resolved by designing special fishing gears, minimising handling and even by raising the fish only slowly to the surface so that its swim bladder can slowly adapt to depth change.

Anaesthetics are often used to sedate or immobilise the fish but many anaesthetics themselves have adverse effects upon the physiology of the animals treated. Hawkins et al (1974) reported periods of hyperactivity by fish immediately following release.

Some workers have kept fish in captivity for long periods (for several weeks) before their release and others have released fish distant from their original point of capture, on the assumption that this treatment will not affect their behaviour. However, fish are often acclimated to conditions at particular locations and keeping them in captivity for a period and then moving them to a new and unfamiliar location may have major effects upon their subsequent behaviour.

Fish fitted with radio tags

Radio tags emit electromagnetic energy at radio frequencies (100-200 MHz). Because radio waves are very severely attenuated by salt water such tags are of little value for tracking fish in the sea. They are, however, widely used on freshwater fish in rivers and lakes where they have some advantages over acoustic tags. In shallow water, or when the fish is swimming close to the surface, much of the transmitted energy passes through the water/air boundary and can be detected by receiving stations located on shore, or mounted on an aircraft. Individual fish can be followed along a river by means of a hand-held bi-directional antenna, or the time of passage past a fixed receiving station can be recorded. Detection range is often very good (up to 1.5 km) and although the exact location is often difficult to pinpoint fish can be followed for hundreds of kilometres. Radio tags have proved to be especially valuable for tracking migratory fish in rivers and lakes. They have also been used for fish

moving near the sea surface. The radio signals can be rendered unique by varying either their transmitting frequency or their repetition rates and by this means it is possible to distinguish between different tagged fish.   Digitally encoded radio tags transmit a unique numerical code that differentiates the tag from other tags, even those transmitting on the same frequency. This allows a researcher to track hundreds of fish on any one radio frequency.

Tags that contain both radio and acoustic transmitters have been attached to fish moving from the sea into freshwater. The acoustic transmitter enables the fish to be tracked in the sea and in estuaries, whereas the radio transmitter is more effective at tracking the fish when it enters fresh water.

Fish fitted with acoustic tags

In seawater, acoustic tags transmitting sound at ultrasonic frequencies offer scope for detection at a distance, and are also especially useful for telemetering information from fish. Urquhart and Hawkins (1983) have described the various types of acoustic tags and their design. The tags can be small or large and can operate at a range of frequencies. Higher frequencies travel less well through water than lower frequencies. For a range of several hundred metres a frequency below 200 kHz will usually be suitable. The choice of transducer size (small transducers usually transmit best at higher frequencies) is often a compromise between the wish to make the tag small to avoid loading the fish, and the wish to make it large to transmit greater distances.

There are a variety of types of acoustic tag, including continuous wave (CW) tags, pingers, and data storage tags.

Figure 10. An archival (data storage) tag attached to a cod. Image from Star-Oddi website

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Continuous Wave tags

CW tags produce a sinusoidal wave of ultrasonic energy. Because they transmit continuously their life is short. The tags can be located by obtaining a bearing with a single directional receiver, and then by moving the receiver to obtain a new bearing. Or a second receiver can be used to obtain a cross-bearing and locate the tag in 2 or 3 dimensions. The most common use of a CW tag is to telemeter physiological parameters like the electrocardiogram (ECG), body temperature, or other electrical changes like the electromyogram (Cooke et al., 2004). Potentials may be picked up by electrodes, amplified and used to modulate the frequency of the transmitted ultrasonic frequency. Or a small sensor can be used to detect temperature and may again modulate the frequency of the tag. A suitable receiver can demodulate the signals. CW tags have monitored the heart rates and the tail beat frequencies of free-swimming fish, (Kanwisher et al.,1974).

Telemetry of physiological parameters may also be obtaining using other types of tag (see later).

Pingers

Pingers produce a continuous train of short pulses; usually about a few ms long, repeated about once per second, but these parameters can be varied. Pingers have a longer life than CW tags. One or more directional receivers can locate them. However, in addition they can be located by an array of spaced receivers by detection of the time of arrival at each element. Sound travels at a fixed speed through water. The difference in time of arrival of a ping at any two receivers defines a hyperboloid of revolution on which the sound source must lie. With a minimum of three receivers deployed in a fixed array the position of the fish is defined by the intersection of three hyperbolae Figure 11). Hawkins et al (1974, 1983) described a hyperbolic tracking system operated in open water with four receivers placed on a relatively flat seabed. Fish had pingers operating at 76 kHz inserted into their stomachs. The receivers were placed several hundred meters apart, with cables carrying the received signals to a processor that determined the time of arrival of the leading edge of the sound pulse at each receiver. It then solved the hyperbolic equations to yield the position of the fish as the intersection of two straight lines in the plane of the hydrophones. A 3-D array, with one receiver in mid-water, is able to track fish in three dimensions. MacLennan and Hawkins (1977) have considered the errors in positioning a pinger with a hyperbolic tracking system.

The choice between a receiving system based on directional hydrophones or one based on time of arrival measurements essentially depends on the pattern of movement shown by the fish. With fish moving great distances and often only able to be detected at poor signal strengths a system of one or more mobile directional receivers may provide a satisfactory solution. For very precise tracking of fish within a home range several hundred metres across then a time delay system has many advantages.

With synchronous pingers, producing pulses at a very exact repetition rate synchronised to a clock, it is possible to track a fish by time measurements between only two hydrophones. Since the time of emission of the ping is known the range can be derived from a single

hydrophone, and with a pair of hydrophones the signal source is located by two range measurements. Holand and Mohus (1973) describe an elegant realisation of such a system.

Transponding acoustic tags contain a receiver, which is activated by a signal received from a sonar transmitter and then transmits a signal back. With such a tag the range of the fish (the distance from the sonar transmitter) can be determined directly, as well as the bearing.

Pingers may be designed with characteristics that enable individual fish to be identified. Tags fitted to different individual fish may operate at different frequencies, spaced several kilohertz apart. Or tags may emit a short train of pulses with characteristic inter-pulse spacing.

The systems used to track fish fitted with pingers can vary greatly in their design. Some receivers simply detect the presence of a fish in an area (see for example the study by Bacheler et al., 2009). Or the passage of fish through a 'fence' or line of receivers can be monitored (see for example Welch et al., 2009). For examining the detailed movements of a fish, where the position is required from second to second, then a hyperbolic tracking system comes into its own.
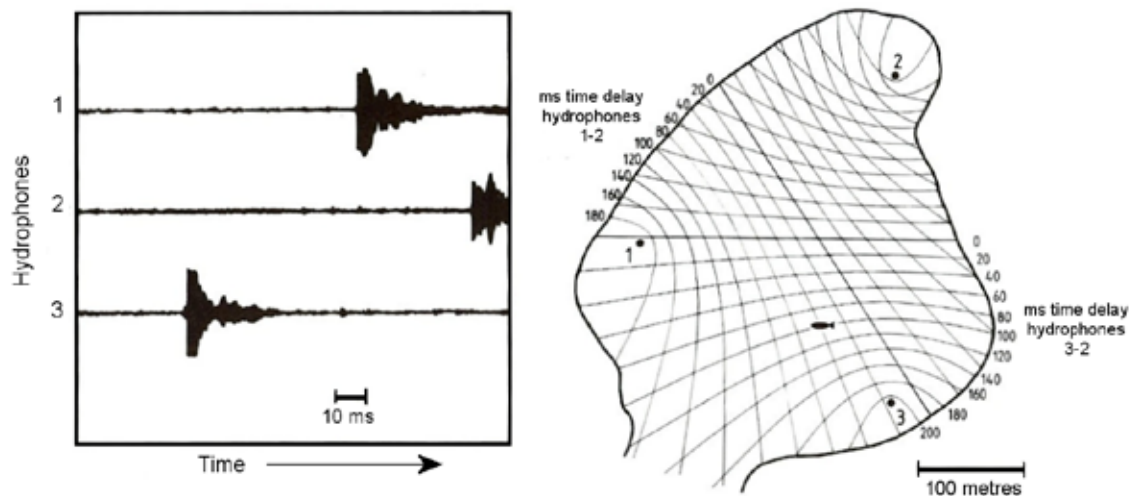
Figure 11: Hyperbolic or time delay tracking of a tagged fish. The times of arrival of the sound pulses from a pinger are measured at three widely spaced receiving hydrophones. Each hyperbola represents a difference in time of arrival at 2 of the hydrophones. The crossover between two hyperbolae indicates the position of the fish. In practice the time delays are measured electronically and the position of the fish calculated in rectangular coordinates. With an additional hydrophone at a different depth such a system can operate in three dimensions.

One of the problems in tracking fish tags, by whatever method, is the huge quantity of positional data that can accumulate over several days. Displaying these data in a form that can readily be assimilated is a major challenge.
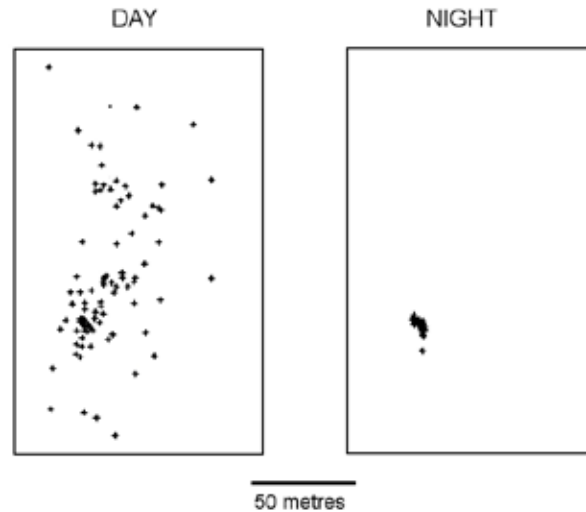
Figure 12: Successive positions of a tracked cod (at 10 min intervals) by day and by night for one 24 h period.

Data storage tags

Some tags are able to store data for long periods and the data are subsequently downloaded when the tag is retrieved from the fish. The tags carry sensors to record data at predetermined intervals. They have a large memory capacity and a long lifetime. Most archival tags contain batteries that allow the tag to record data for several years. Some of these tags archive environmental data including salinity, temperature, light level and depth. Others log data on the pitch, roll and compass bearing of the tag.   Specialised tags can listen for acoustic signals from sonar transmitters, or the calls made by the animal to which the tag is attached. Data storage tags are mainly used for analysing the migrations of fish, their distribution, feeding behaviour, and vertical and horizontal movements.

Most tags attached to fish are recovered when the fish is caught. However, there are also tags that detach themselves at a pre-programmed time, float to the surface and transmit collected data via Argos satellites. From the downloaded data it is often possible to reconstruct the detailed daily history of a fish's travels. The pressure reading reveals its precise water depth, and the light measurements can contain sufficient information to allow calculation of the fish's latitude and longitude, using an process known as light-based geo-location.

Fish fitted with satellite tags

Where fish are of suitable size, and swim near the surface, tags which communicate with GPS or Argos can be used to track movements, and to telemeter data from the fish. Priede and Miller (2009) describe the satellite track of a basking shark, *Cetorhinus maximus* and its movements in relation to a thermal front. The shark was shown to have been swimming, presumed to be filter-feeding zooplankton, in warm coastal water off the west coast of Scotland parallel to the line of a thermal front.

Telemetry

Telemetry may be used to transmit the signal from a receiver, or from an array of passive hydrophones to a ship or shore-based station. Sonobuoys use VHF radio waves. Most systems require line-of-site between the transmitter and receiver. Telemetry is also capable of delivering video signals from remote locations (Svellingen et al. 2002).

Tracking fish from the sounds they make

Over 800 species of fishes from more than 100 families are known to be vocal, though this is likely to be an underestimate (Kaatz 2002). More than 150 sound producing species of fish are found in the northwest Atlantic (Fish and Mowbray 1970). Amongst the vocal fishes are some of the most abundant and important commercial fish species, including the cod, haddock and pollack (Gadidae) and the drum fishes (Sciaenidae). Passive listening for fish has been used for over 50 years (see Fish et al. 1952 and Fish and Mowbray 1970 for a summary of early work) and is capable of being used to determine habitat preferences and to delineate and monitor spawning areas, as well as to study the behaviour of fishes (Hawkins, 1986; Rountree et al., 2006, Luczkovich et al., 2008)). Many species, such as the haddock (Hawkins and Amorim, 2000) and damselfish (Mann and Lobel, 1995) produce different sounds at various stages of courtship, enabling their behaviour to be inferred from the sounds recorded (Figure 13).
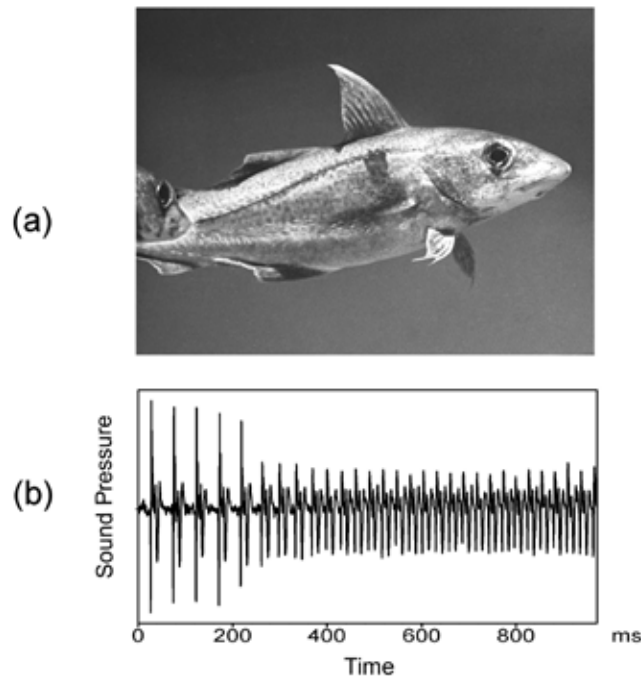

Figure 13: Many fish make sounds. In the case of the haddock the male fish produces a series of short low frequency pulses. The repetition rate of the pulses increases as courtship proceeds

Many fish sounds are made up of a series of short sharp low frequency pulses of sound. It is therefore possible to use directional receivers and hydrophone arrays to locate them, using similar techniques to those employed to track pingers. Drifting hydrophone arrays have been used for determining the locations of vocalizing whales in many different situations (e.g., Watkins and Schevill 1972; Clark 1980), but this technique has only recently been applied to fishes (Mann and Jarvis 2004).

Parsons et al. (2009) have tracked the movements of individual mulloway (*Argyrosomus japonicus*) within a spawning aggregation and have observed their behaviour throughout a diel spawning cycle. The sounds from vocal mulloway were collected from a four-hydrophone array. Arrival-time differences proved the most robust technique for locating the individual fish. Different individual fish could be identified from their characteristic tone-burst frequency and sound-pressure levels. Calibration signals could be located within a mean distance of 3.4 m. Three-dimensional locations, together with error estimates, were produced for 213 calls during an example four-minute period in which 495 calls were audible (Figure 14).

The study by Parsons et al., (2009) has shown that fine-scale localisation of calling individuals is possible within a spawning aggregation by means of a passive array of hydrophones. Passive acoustic listening can be used to provide behaviourally unbiased, *in situ* information on fish position, movement, co-specific interaction, and response to anthropogenic impacts. The technique has the great advantage that the fish do not need to be captured, or loaded with internal or external tags, and the monitoring method does not itself involve the generation of sounds or any other form of disturbance.
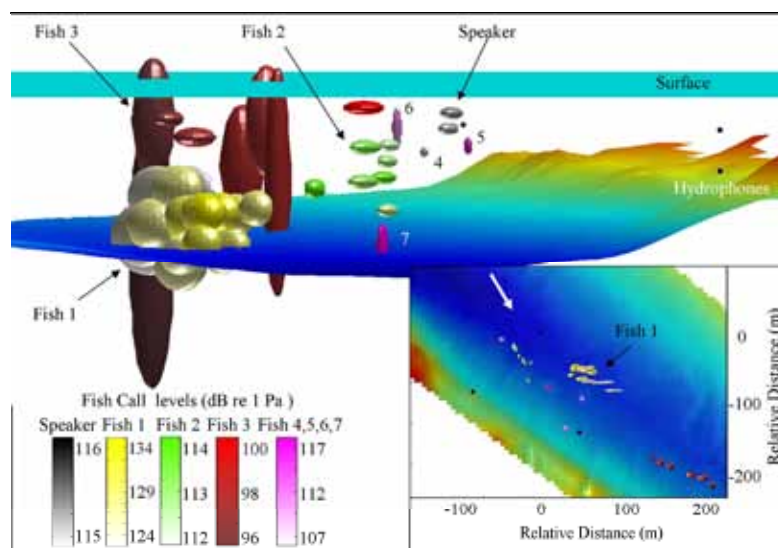
Figure 14: Locations of a loudspeaker and calling fish 1-3 positioned over the bathymetry of Mosman Bay (depth has been exaggerated by 10%). Single calls from Fish 4-7 are also shown to provide an impression of caller density. Dimensions of each ellipse are determined by localisation variance and error ranges. A plan view is shown (bottom right) with a white arrow illustrating direction of main view. Black spheres are the hydrophone positions. From Parsons et al., 2009.

Conclusions

A guiding principle in observing the behaviour of fish, which applies to all techniques, is that the fish should not be aware of or influenced by the method of observation. Where a camera requires light to operate successfully, or where sonar is mounted on a noisy vessel, there is always the possibility that the behaviour of the fish is influenced by the observing system. That possibility must be avoided.

Similarly, where a fish caught, handled and tagged with a transmitting tag, extreme care must be taken to ensure that the fish is not unduly loaded by the tag, or suffering trauma from the attachment or insertion of the tag or administration of an anaesthetic. It is also critical to ensure that fish are not damaged by capture, handling and transport.

Ideally, the behaviour of fish should be observed under conditions where they are well adapted to a particular location and show normal behaviour patterns. It is not a good idea to capture fish in one place and then transport them to another for release. Nor is it sensible to hold fish in captivity for extended periods before release, or to work with farmed fish if the main interest is in wild fish.

Where experiments are to be performed to investigate the responses of fish to sounds it is most appropriate to conduct these experiments in a quiet environment where fish are not excessively exposed to sound from anthropogenic sources. It is increasingly difficult to find such locations inshore or close to the coast.

Optical techniques have the great advantage of showing the behavioural responses of fish in detail. They are especially valuable for examining the behaviour of fishes that occupy home ranges or show restricted movements.

Sonar comes into its own for following the movements of wide-ranging mobile species. The latest sonars can locate fish with great precision and allow the detailed movements of fish to be observed. They can also be used at night and for observing pelagic fish. The type of sonar to be used must be tailored to the particular experiment.

Fish tagging can provide very detailed information on the behaviour of fish over long periods. The type of tag and the configuration of the tracking system must again be decided in the light of the topography and conditions surrounding the experiment.

The detection and tracking of fish from the sounds they make is not applicable to all species. However, this methos has the advantage that there is little or no interference with the behaviour of the fish. Moreover, the fish concerned are engaged themselves in acoustical activities – and we should be especially interested in the impact of anthropogenic sounds upon those species.

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A Role for Biomarkers in Assessing Noise Induced Stress:

A white paper for the Sound and Marine Life Workshop sponsored by OGP, ESRF and OEER.

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Abstract

If anthropogenic sources of sound are having effects on fish and shellfish at the population level, it is understood that they would not be readily measurable (other than perhaps in a small cove or similar) due to confounding factors such as natural variability, fishing pressure and animal migration. Thus the only feasible approach for assessing risk/no risk is through the use of biomarker studies at the individual level. Such studies can be carried out in the laboratory or through small scale field experiments. An overview is provided on some biomarker studies that have been carried out on fish and shellfish upon exposure to various sources of sound. Many such biomarker studies have been pivotal in assessing risk and providing advice. In our case this is in relation to seismic and interests by regulators as well as energy and fishing industries.

Upfront biomarker studies are not only critical for assessing risk/no risk, but given the difficulty of measuring damaging effects at the population level, *i.e.* via pathologies of such nature that they would result in measurable effects on populations, it would seem that biomarkers are also the only option for field monitoring should it be considered necessary to answer questions on whether effects might be occurring in the environment or not.

Introductory Discussion

Measuring effects on ecosystems or animal populations is difficult from a conceptual as well as practical viewpoint, therefore, by way of introduction, discussion is provided on a role for biomarkers in assessing risks to animal health. The discussion is taken from a short invited article dealing with the use of biomarkers in monitoring for the effects of contaminants (Payne, 2007). However, the concept of using biomarkers is generally applicable for assessing effects of a variety of other stressors. Also, biomarkers used in monitoring typically come from "up-front" laboratory studies carried out to screen for potential health effects. The introductory discussion is presented (in italics) before covering biomarker studies carried out with anthropogenic sounds.

There are constant reminders nowadays about the virtues of an ecological or ecosystem approach to assessing and managing the effects of human activities on the marine environment. Although words such as ecological or ecosystem approach may have been born in a scientific cradle, one often gets the impression that they are used more and more as a percept not unlike the comfort of a warm karma cleanser or indeed chicken soup for the soul of fisheries or environmental management.

An ecological approach would not seem to be so simple and linear and are we stuck too much in a deterministic frame of mind where phenomena can be explained in terms of deterministic laws with accurate and "final" predictions for a given set of conditions?
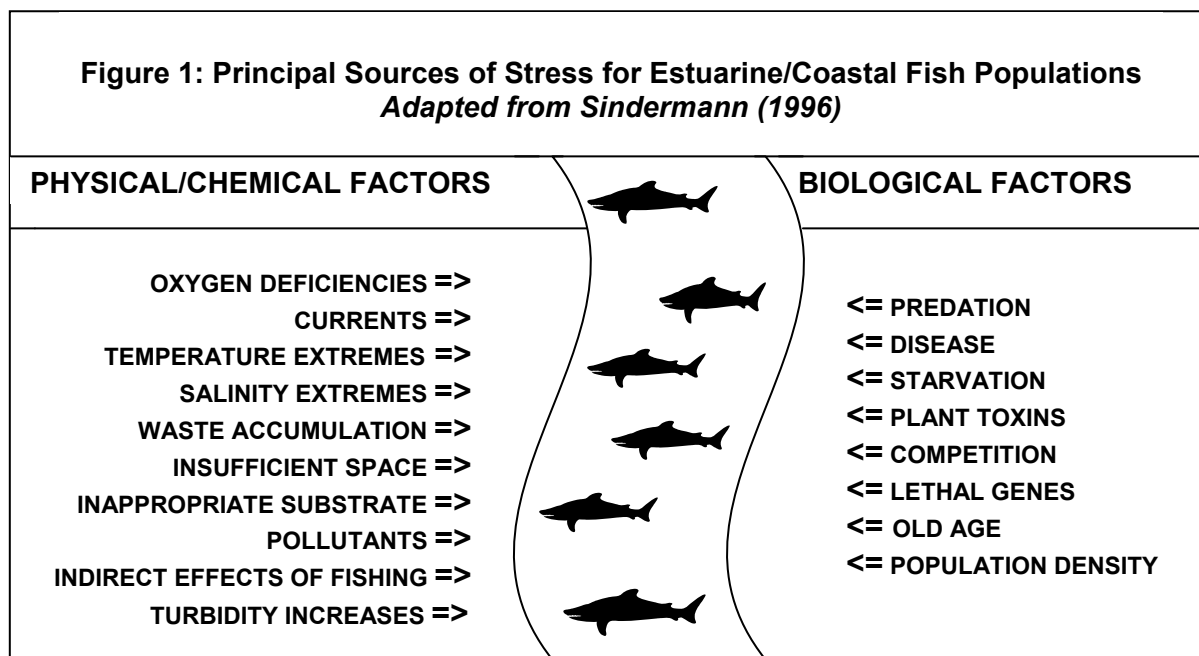
Didn't physicists throw this deterministic concept in the dustbin decades ago through realization that a given set of initial conditions can lead to several alternative and unpredictable final states, even in relation to happenings in a sphere of gas. And we all can accept that happenings in an ecosystem or indeed a fish population are of equal or greater complexity in comparison with a sphere of gas.

Old style deterministic laws would seem to be of little value for understanding ecology, but there are also major road bumps in trying to apply "in-deterministic" laws (i.e. stochastic or probabilistic) to predict happenings in animal populations. There is especially the pesky problem of quantification and ground-truthing. Indeed, it has been noted that until observations of truly staggering dimensions can be expended in the testing of indeterminate laws, their scientific analysis will remain ambiguous (Stent, 1978).

Yet it is paradoxical that when recommendations are being made for instance about the importance of determining how multiple stressors may be identified, assessed and quantified through studies on the structure and function of ecosystems, we generally all nod in agreement.

Conundrum of Linking Contaminants Even to Population Level Effects

Agencies such as the International Commission for the Exploration of the Sea (ICES), recommend the development of ecological indicators in conjunction with pressure indicators in order to provide guidance on the application of an ecological approach to management of human activities. As used here, pressure refers to any force on a population such as eutrophication, overfishing, hazardous chemicals, seismic, etc. Usage of the term pressure indicator is not unlike historical use of the term stressor. For instance, fishing, contaminants, etc. can be viewed as potential stressors or pressure indicators for fish stocks. The goal is to be quantitative and predictable and although the ecological indicator concept is useful, the quantitative partitioning of responsibility on the importance of different pressure indicators in influencing populations would seem to be a somewhat formidable task. Sindermann (1996) lists a large variety of stressors or pressure indicators that could be important in influencing fish populations (Figure 1). How can we work out the metrics to provide a predictive model for instance on what the status of a fish stock would be a couple of years down the road or resolve a contaminant (or anthropogenic sound) stressor from all other potential stressors?

Figure 1: Principal Sources of Stress for Estuarine/Coastal Fish Populations
Adapted from Sindermann (1996)

PHYSICAL/CHEMICAL FACTORS

OXYGEN DEFICIENCIES =>
CURRENTS =>
TEMPERATURE EXTREMES =>
SALINITY EXTREMES =>
WASTE ACCUMULATION =>
INSUFFICIENT SPACE =>
INAPPROPRIATE SUBSTRATE =>
POLLUTANTS =>
INDIRECT EFFECTS OF FISHING =>
TURBIDITY INCREASES =>

BIOLOGICAL FACTORS

<= PREDATION
<= DISEASE
<= STARVATION
<= PLANT TOXINS
<= COMPETITION
<= LETHAL GENES
<= OLD AGE
<= POPULATION DENSITY

Following on with the question of the effects of contaminants on fish, as for reminders about the importance of an ecological or ecosystem approach to assessing effects in the environment, decisions are increasingly being made about the importance of separating and quantifying pollution impacts from other variables at the level of individual populations of fish which may be either the same or different species in a particular area.

Furthermore, statements continue to be made along the line: "biological monitoring programs that cannot separate pollution-induced changes from natural causes should be terminated and those regulatory requirements which require such programs changed" (Segar and Stamman 1986).

Excepting small circumscribed populations such as in small ponds or streams, both theory and practice suggest that only major or drastic changes in populations could ever be linked in a quantitative manner to contaminant pressure (or in our case seismic pressure). A simple lesson in this regard comes from fisheries science. Even in the case of fishing exploitation rates which are set in the 15-20 percent range for many commercial species, stock surveys are still required on a year to year basis because of the difficulty of accurately modeling and forecasting change in stock status. Substituting contaminant exploitation rate for fishing exploitation rate sheds light on the dimension of the problem of resolving whether populations are being affected or not by pollution. The same would hold through for anthropogenic sounds.

Biomarker Assistance

Given the realization that cause and effect relationships between chemical contamination and changes at the population or community level can be difficult or virtually impossible to establish for practical as well as theoretical reasons, more attention has been given in recent years to the use of sub-lethal effect indicators or biomarkers for providing guidance on whether and to what extent chemicals may be having subtle yet important effects on fish health. This includes use of various biochemical and physiological indices as well as a recognised "gold standard" in human and veterinary medicine, namely histopathology. By way of historical interest, although the word biomarker has only been used for awhile, the concept has been around for a long time. For instance, in the seventh century BC, Sushustua noted that the urine of diabetics attracted ants because of its sweetness, thereby discovering the "ant test". Also, what is now called proteinuria and associated with kidney disease was actually discovered in the fourth century BC by Hippocrates.

Upfront biomarker studies carried out in the laboratory or similar controlled conditions are of critical value in assessing elements of risks/no risks. Biomarkers are also especially valuable for surveillance monitoring, diagnosing unanticipated health effects, and providing information on their geographical reach. ICES and other agencies have been a major driving force for use of indicators in biological monitoring and they are being used extensively in various countries with at least a few hundred field studies available in association with contaminants in freshwater and marine systems.

It is also important to note biomarkers can be a powerful tool for providing assistance in "disproving" as well as "proving" whether contaminants may be having effects on fish health. For instance, perceptions/concerns about population level effects around oil development sites would have little scientific credibility in the absence of evidence for individual level effects (Mathieu et al. 2005; 2011).

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Biomarkers have been accused of having some "ring around the collar" problems since they can't predict - indeed quantify effects on populations. As noted some years ago, it is difficult to accept a conceptual basis for such an expectation (Payne et al 1987). However, a weight of evidence approach can provide information of considerable value for determining whether and to what degree contaminants may or may not be affecting fish health in an area. It is extremely important in this regard that all bioindicators not be treated equally. A variety of histopathological lesions in the liver of fish should not be accorded the same "adverse" health status as a small change in an enzyme activity (yet a sensitive enzyme response can still be quite valuable for delineating the geographical reach of potential effects).

In summary, in spite of pronouncements on the importance of an ecological or ecosystem approach to environmental issues, even a straightforward request such as the quantification of the effects of contaminants on a fish population can be inexorably difficult. Although no panacea for determining population reductions, biomarkers can be a useful tool for providing guidance on whether and to what extent health effects are occurring in a population.

Upfront initial screening for biomarker effects in the laboratory or under similar controlled conditions, also provide the critical information on what health effects might be expected to occur or not in the environment.

Biomarkers Studies with Anthropogenic Sounds

A brief overview is provided along with tables on biomarker studies that have been carried out on fish and shellfish upon exposure to various sources of sound, including from explosives, airguns, pile driving, and low frequency sonar. Also included are biomarker studies related to aquaculture and boat noise. Different sources of information have been used including from journals, technical publications, and contractor reports. This is in keeping with the principle that public interest is most often best served with many voices. Although sound pressure levels associated with explosives can be rather extreme, there is some commonality, on pressure levels produced by airguns, pile driving and sonar, as well as vessels to some extent. Metrics associated with some major sources of sound are provided in Table 1.

Table 1   Some Reported Metrics Associated with Various Underwater Sound Sources

Source	Bandwidth (Hz)	Dominant Frequency (Hz)	Signal Duration (ms or s)	Source Level (dB re 1 µPa-m)	Prevalence
Explosives	2 – 1000 Hz	6 – 21	~ 1 – 10 ms	272 – 287 peak	Localized, infrequent
Air guns	10 – 100,000	10 – 120	30 – 60 ms	200 – 262 p-p	Approx. 90 crews worldwide
Pile Driving	20 – 20,000	100 – 500	30 – 70 ms	243 – 257 p-p	Localized, infrequent
Shipping Large vessels	6 – 30,000	> 200	Continuous	150 – 190 RMS	Ubiquitous
Low Frequency Active Sonar	100 – 500		0.6 - 1 s	235 RMS	No more than 4 crews
Mid Frequency Sonar	2800 – 8200	3500	0.5 – 2 s	223 – 235 p	Several hundred in use

Adapted from OSPAR (2009)

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The purpose here is not to enter into detailed discussion about the risks associated with various sources of anthropogenic sounds but to provide some appreciation on the use of biomarkers to date. Having said this, examples are provided where biomarker studies have provided major assistance for assessing risk. Valuable insight into the potential effects of seismic can also come from studies with pure tones/white noise (*e.g.* Popper and Clarke, 1976; Hastings *et al.*, 1996; Smith *et al.*, 2004; 2006), but these are not discussed here.

Explosives

Tables are not provided on the effects of explosives but a number of studies have been carried out, extending back a number of decades. Here, however, as common in the past for toxicology, the biomarker most commonly used was mortality.

Explosives produce very high pressure levels (and faster rise times) compared to airguns, and fish mortality has often been observed at close range (e.g. Aplin, 1947; Yelverton *et al.*, 1975; Nedwell *et al.*, 2004; Govoni *et al.*, 2008).

However, it is of interest that studies have indicated some crustaceans to be relatively insensitive to explosives, even at very close range (*e.g.* Gowanloch and McDougal, 1946; Kemp, 1956; Linton *et al.*, 1985).

Given the marked energy difference between explosives and airguns, the results of studies with explosives can provide perspective on comparative risks.

Airguns

The lack of significant effects on lobster and snow crab exposed to airguns have been useful for providing advice to managers dealing with seismic surveys in waters around Newfoundland and Labrador. This has included select biomarker studies on animal biochemistry (Table 2), organ histopathology (Table 3), physiology (Table 4) and animal movement (Christian *et al.* 2003; 2004; DFO, 2004; Payne *et al.* 2007; Courtenay *et al.*, 2009; Oceans Ltd., 2010; 2011).

It is noted that there is no evidence of immediate or delayed (up to 8 months post exposure) mortality, even at very close proximity (within 2 meters) in crustaceans and various other groups of invertebrates (Koshleva, 1992; Matishov, 1992; Webb and Kempf, 1998; McCauley *et al.*, 2000; Parry *et al.*, 2002; GIA, 2002; Christian *et al.* 2003; 2004; DFO, 2004; Payne *et al.* 2007; Oceans Ltd. 2010; 2011).

One parameter of special interest was animal scaring which is an important concern for the fishing industry. Studies in this area included bringing representatives from the fishing and petroleum industries and local managers into the laboratory for first hand observations. Thus valuable biomarker information on the lack of animal scaring was provided which could be further validated in the field for assurance, if considered necessary by management or petroleum and fishing interests.

However, it is important to note that although the pilot studies carried out in the laboratory on lobster (mainly) demonstrated little effect, small changes were noted in various serum parameters and animal feeding for some time (along with some changes

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in hepatopancreas histology which may have been linked to feeding) (Payne *et al.*, 2007). Thus, the early warning biomarker responses observed in the pilot studies with lobster can lead to the question of potential for other important biomarker effects "down the road" such as for instance on animal moulting.

Regarding the potential for seismic surveys to affect fish, the biomarker studies on gross pathology (Table 5) and organ histopathology (Table 6), including on fish ears, carried out in conjunction with seismic surveys in Sydney Bight (CEF Consultants, 2006) and the Mackenzie River (Popper *et al.*, 2005; Song *et al.*, 2008), have been valuable for assessing potential risks to fish.

Also of value have been more recent observations noting the lack of effects on fish physiology (namely hearing) in association with a seismic survey in Australian waters (Hastings and Miksis-Olds, 2010) (Table 7).

There appears to be limited studies on the effects of airguns on fish biochemistry (Table 8). However, it is of interest to note that a pilot study carried out by DFO, found effects on feeding in codfish exposed to airgun noise in the laboratory (Payne, 2006; Andrews *et al.*, 2007). Interestingly, as noted above, a feeding effect was also noted in lobster.

Tables 9 and 10 include various biomarker studies (e.g. growth, development and pathology) carried out on eggs and larvae of invertebrates and fish exposed to airguns. Some effects have been noted in organisms exposed at close range – or high energy levels (where measured).

Regarding seismic surveys in Newfoundland waters, special concern was expressed about the eggs of commercially important monkfish, whose eggs float at the surface. Studies carried out in the laboratory found no effects on monkfish larval mortality or on developing capelin eggs when exposed at the water surface (~10cm) (Payne *et al.*, 2009). The results were of value for management and fisheries interests.

Pile driving

Biomarkers studies carried out in conjunction with pile driving are of interest since sound levels are in the same range or higher than those produced by airgun arrays. Also, animals in the nearby vicinity of pile driving can be subjected to thousands of high level exposures for days, unlike transient high level exposures from a passing seismic ship. Tables 11 and 12 provide observations on some biomarker studies, namely gross pathology and histopathology, carried out in association with pile driving. Most studies indicate little effect even at close range.

Low Frequency Sonar

Biomarker studies carried out in association with low frequency sonar are also of interest since sound pressure levels (and frequency to some extent) can be in the same range as those from airguns. Biomarker studies on fish gross pathology (Table 13), histopathology (Table 14) and Physiology (Table 15) indicate little, if any, potential for sonar surveys to damage fish and shellfish.

Boats

Boat noise is the major anthropogenic source of sound in the ocean with large ships producing sound pressure levels which can be in the "lower" range of those produced by airgun arrays. Some biomarker studies have been carried out on the effect of boat noise on fish (Tables 16 and 17). Startle responses associated with boat noise including small recreational craft can result in transient elevation in blood cortisol (Wysocki *et al.*, 2006; Spiga *et al.*, 2010) and in heart rate (or stroke volume) (Graham and Coke, 2008). Boat noise has also been associated with other physiological biomarker responses in fish including temporary hearing loss and sound masking (Scholik and Yann, 2002; Vasconcelos *et al.*, 2007). Such biomarker studies dealing with the major source of sound in the ocean are of value for providing perspective.

Aquaculture

Sounds associated with aquaculture (Table 18) are also of interest to some extent. A number of biomarker responses including growth rate, hearing sensitivity and serum constituents were not affected in fish chronically exposed to aquaculture sounds (Wysocki *et al.*, 2007; Davidson *et al.*, 2009).

However, Lagardere (1982) and Regnault and Lagardere (1983) reported that exposure of brown shrimp to in-tank noise levels about 30dB higher than levels encountered in their natural habitat resulted in effects on growth and metabolic rate.

Overview on Biomarker Studies with Anthropogenic Sounds

Studies on biomarkers that have been carried out in association with sound pressure levels ranging from the rather extreme associated with explosives to the rather low associated with small boat noise indicate that biomarkers can provide a valuable role in assessing risk.

Indeed it can be argued that given the results of biomarker studies carried out on fish and shellfish upon exposure to high sound pressure levels from airguns, explosives, pile driving and low frequency sonar, if a weight of evidence approach were considered, it would be difficult to make a case for transient high level exposures from a passing seismic survey ship to produce adverse health effects on nearby animals. Having said this, it can equally be argued that we are not yet in a position to suggest sound exposure guidelines for fish and shellfish for airgun based seismic operations.

There are no boundary limits or number of studies that can be suggested for the large varieties of fish and shellfish species. However, detailed dose-response biomarker studies on representative fish and shellfish species would be helpful for providing more informed opinion for industry and management interests. Furthermore, such studies would be valuable if only for assurance.

Field studies are logistically difficult and can be prohibitively expensive but important range finding data can be obtained in a very cost effective manner through laboratory and small scale field experiments. For instance if development of snowcrab eggs is not shown to be affected in such experiments with sound levels much greater (*e.g.* 100-fold or higher) than those considered to be realistic during a seismic survey, the question can

be asked about the need (from a scientific viewpoint) for rather expensive open sea field trials. Also, many important biomarker endpoints cannot be studied with any degree of scientific validity in field studies. For instance, the results of preliminary studies with lobster (Payne *et al.*, 2007) indicate that biomarker responses may be delayed and/or persist to varying degrees after animal exposure. Similar observations have been made with respect to histopathology of fish ears (McCauley *et al.*, 2003). This indicates the importance of periodic assessment of various parameters which would not be logistically feasible after a field survey type experiment where animals would have to be retained on the sea-bottom for weeks or months. Also, any repeated lifting of animals from the sea-bottom for sampling could introduce serious artifacts for many physiological parameters. Furthermore, biomarkers like feeding, which can affect growth and reproduction could not be assessed at all. Starvation of animals through holding in cages would also greatly compromise histopathological criteria. However, this is not to say that opportunistic "monitoring" studies carried out during authentic field surveys would not be of value.

Whether using laboratory or small scale field experiments, the ideal would be to carry out dose-response studies for biomarkers of interest. However, such dose-response studies can still come with major logistical and cost considerations (consider for example any biomarker studies related to lobster moulting or cod reproduction).

One approach is to begin with a few rather extreme responses and work backwards if required. For instance, the lack of effects on egg development in berried snow crab examined ~ 6 months after exposure to a large number of airgun emissions, at very high pressure levels (and putatively high particle velocity levels given the close exposure range), provided an important signpost for assessing the potential for seismic surveys to affect egg development (DFO, unpublished). Egg development in snowcrab is fairly easy to assess through its passage from an early yellow stage color to a brown color several months later. Animals bearing yellow eggs were exposed. All animals passed from a yellow egg stage to a brown egg stage, with no difference being observed between exposed and control animals as assessed through analysis of color photographs by 6 observers. Surface spectral studies provided the same results. As such, this biomarker study was valuable for providing advice to management on an important question for a major commercial species in Atlantic Canada.

The Special Issue of Cumulative Effects

The largest knowledge gap with respect to seismic surveys is probably not the question of the effects of a limited number of high level episodic exposures on any nearby animals for a few minutes or so, but the question of chronic lower level exposures which can occur over a large geographical area for a number of weeks and potentially lead to chronic "over" stimulation of neuroendocrine systems. There is presently no information in this area and the issue should be investigated to some extent with laboratory and small scale field studies; and again, if only for assurance. The issue can be addressed through use of authentic recorded sounds and speaker systems in which biomarker studies would be carried out on a few representative species subjected to sounds for varying periods. Small scale "bench top" experiments, such as those which have been used to investigate the effects of various tones on "small" organisms, also have considerable potential to provide valuable information in this area.

However, there is also a difficult perspective issue in that the chronic levels of sound found some distance from seismic ships may not be unlike those to be expected over

broad scale areas from vessels, especially in "busy" traffic lanes. Thus, as for concerns about fish movement, comparative "risks" associated with seismic or ship noise present a pesky perspective question.

Acknowledgments

Table 2   Effects of Airguns on Invertebrate Biochemistry

Organism	Exposure Level (dB re 1 µ Pa)	Observations	Reference
Snow crab *(Chionoecetes opilio)*	(a) 201-227 dB or 183-187 1µPa²Hz (b) 197-237 dB or max 175 1µPa²Hz	- No significant differences in haemolymph solute, serum proteins and enzymes or haemocyte counts between control and exposed crabs sampled immediately and 2 weeks after exposure.	Christian *et al.* 2003, 2004
Golden carpet shell *(Paphia aurea)*	<147 dB	- Significant difference in hydrocortisone, glucose and lactate in hepatopancreas and muscle between testing and control sites.	La Bella *et al.* 1996
Lobster *(Homarus americanus)*	(a) ~ 202 pp or 144 to 169 dB Pa²/Hz (b) ~ 227 pp or 175 to 187 dB Pa²/Hz	- Decrease in serum enzymes AST and CK. - Decrease in serum protein and calcium.	Payne *et al.* 2007
Lobster *(Homarus americanus)*	204 to 211 p-p; 174 to 178 RMS; Particle velocity of 137 to 142 dB re 1µPa²/sec	- No significant differences in serum concentration of calcium.	Oceans Ltd. 2010
Lobster *(Homarus americanus)*	5 successive days of exposure to 20 shots of air gun/per day with decreasing pressure from 500 to 100 psi 148 to 172 RMS	- No significant differences in serum concentration of protein, glucose and triglycerides between control and exposed.	Oceans Ltd. 2011

Table 3   Effects of Airguns on Invertebrate Histopathology

Organism	Exposure Level (dB re 1 µ Pa)	Observations	Reference
Snow crab *(Chionoecetes opilio)*	(a) 201-227 dB or 183-187 1µPa²Hz (b) 197-237 dB or max 175 1µPa²Hz	- No histological effects on hepatopancreas, heart and statocysts immediately after exposure.	Christian *et al.* 2003, 2004
Snow crab *(Chionoecetes opilio)*	170 to 192 pp at distances < 1.5 km or 156 to 177 dB Pa²/Hz C ~ 125 to 132 pp 112 to 118 dB Pa²/Hz	- Slight histological differences in hepatopancreas and gonads that might be linked to environmental differences between the test and control sites.	DFO 2004 Courtenay *et al.* 2009
3 shrimp species *Litopenaeus schmitti Farfantepenaeus subtilis Xyphopenaeus kroierii*	na	- No histological effects associated with air gun discharges on gills and gonads. - Decrease in lipid concentration in R-cells observed in the hepatopancreas of shrimps exposed up to 20m.	GIA 2002 Andriguetto Filho *et al.* 2005
2 species of red lobster *Panulirus laevicauda Panulirus argus*	na	- No histological effects associated with air gun discharges on gills and gonads - Decrease in lipid concentration in R-cells observed in the hepatopancreas of lobsters exposed up to 200m.	GIA 2002
Lobster (female) *(Homarus americanus)*	204 to 211 p-p or 174 to 178 RMS Particle velocity of 137 to 142 dB re 1µPa²/sec	- No delayed (7 months) histopathological changes in ovary and hepatopancreas.	Oceans Ltd. 2010
Lobster (female) *(Homarus americanus)*	5 successive days of exposure to 20 shots of air gun/per day with decreasing pressure from 500 to 100 psi 148 to 172 RMS	- No delayed (6 months) histopathological changes in ovary and hepatopancreas	Oceans Ltd. 2011
Lobster *(Homarus americanus)*	(a) ~ 202 pp or 144 to 169 dB Pa²/Hz (b) ~ 227 pp or 175 to 187 dB Pa²/Hz	- No histopathological changes in gonads - Elevated deposits of carbohydrates in hepatopancreas of exposed lobsters.	Payne *et al.* 2007

Table 4   Effects of Airguns on Invertebrate Physiology

Organism	Exposure Level (dB re 1 µ Pa)	Observations	Reference
Lobster *(Homarus americanus)*	204 to 211 p-p; 174 to 178 RMS; Particle velocity of 137 to 142 dB re 1µPa²/sec	- No immediate effects on mechano-balancing systems (righting ability test).	Oceans Ltd. 2010
Lobster *(Homarus americanus)*	(a) ~ 202 pp or 144 to 169 dB Pa²/Hz (b) ~ 227 pp or 175 to 187 dB Pa²/Hz	- No effects on mechano-balancing systems (righting ability test). - Increase in food consumption.	Payne *et al.* 2007

Table 5   Effects of Air Guns on Fish Mortality and gross Pathology

Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Various marine species Cod, salmon, cunner and smolt	~ 202	- No mortality or gross pathology immediately or within 2-month post exposure.	Andrews *et al.* 2007 DFO unpublished
Cod (*Gadus morhua*)	204 p-p at cages	- No increased mortalityor gross pathology immediately and after 5 days.	CEF consultants 2006
Demersal fish, blue whiting and some pelagic fish	200 to 210	- No mortality observed upon exposure.	Dalen and Knutsen 1987
Coregonids including (*Coregonus autrumnalis*)	234 at 0.6 m 219 at 3.4 m	- No mortality of caged fish or wild fish in the River within 16 km. - Some cases of swim bladder damage inr fish at 0.6 and 1.5 m from the gun.	Falk and Lawrence 1973
Red snapper (*Lutjanus synagris*), mojara (*Haemulon aurolineatum*)	na	- No mortality at any distances.	GIA 2002 Boeger *et al.* 2006
Sandeel (*Ammodytes marinus*)	221 at 54 m (water depth)	- No differences in mortality between control and experimental groups.	Hassel *et al.* 2003
Northern anchovy (*Engraulis mordax*)	215 to 234	- No mortality reported. - Higher prevalence of swim bladder damage at the highest exposure.	Holliday *et al.* 1987
Various freshwater species Chub, longnose sucker, northern pike, pearl dace	224 at 2 m, 193 (178 RMS) at 85 m, and 169 (159 RMS) at 446 m	- No mortality attributable to the seismic program within a 48h holding time. - Some fish at very close range were temporarily stunned but recovered within 30 min.	IMG-Golder Corp 2002
Cod (*Gadus morhua*)	226 at 0.5m, 220 at 1 m and 214 at 2 m	- No mortality at any distances. - Internal damage such as bleeding as well as eye injuries were observed only at 0.5 m.	Koshleva 1992
Twelve species	p-p 146 to 195 RMS	- No immediate mortality. No delayed mortality (up to 58 days) for 1 species.	McCauley *et al.* 2000
Broad whitefish (*Coregonus nasus*), lake chub (*Couesius plumbeus*), Northern pike (*Esox pucius*)	Average mean peak of 207, Mean RMS of 197, Mean SEL 177 (re 1 μPa^2.s)	- No mortality of fish from the 3 species held for 24 h after exposure. - No gross pathology observed on swim bladder, eyes, gills or internal organs.	Popper *et al.* 2005
Sea bass (*Dicentrarchus labrax*)	210 at 180 m 204 at 800 m 199 at 2500 m	- No mortality up to 72 h post exposure. - No modification of spinal chord or alteration of fin rays.	Santulli *et al.* 1999
Rainbow trout (*Salmo gairdneri*), salmon smolt (*Salmo salar*)	142 p-p at the cages (4km) 186 p-p at 150 m from guns	- No mortality during or immediately after exposure.	Thomsen 2002
Juvenile saith and cod Adult pollock and mackerel	218 o-p at 5 m, 210 o-p at 16 m and 195 o-p at 109 m	- No indication of mortality. - No observation of external damage.	Wardle *et al.* 2001
Coho salmon (*Onchorhynchus kisutch*)	208 to 241	- Mortality of 1 to 10 fish at 1m and no mortality at other distances within 72 h after exposure. - No gross pathology attributable to air gun.	Weinhold and Weaver 1972

Table 6   Effects of Air Guns on Fish Histopathology

Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Cod (*Gadus morhua*)	Fish caged in the vicinity of an authentic seismic survey SEL 204 p-p at cages	- No morphological changes in non-auditory tissues (intestine, liver, heart, gills) in 16 fish. - No abnormalities seen in the inner ear of 11 fish by scanning electron microscopy.	CEF consultants 2006
Red snapper (*Lutjanus synagris*) Mojara (*Haemulon aurolineatum*)	na 0, 10, 20, and 200 m	- No changes in gills, liver, kidney and gonads attributable to exposure.	GIA 2002 Boeger *et al.* 2006
Various freshwater species Chub, longnose sucker, northern pike, pearl dace	224 at 2 m, 193 (178 RMS) at 85 m, and 169 (159 RMS) at 446 m	- No histopathological abnormalities attributable to air gun exposure.	IMG-Golder Corp 2002
Cod (*Gadus morhua*)	226 at 0.5 m, 220 at 1 m and 214 at 2 m	- Injury to blood cells such as bubble formation observed in cell nuclei at 0.5 m.	Koshleva 1992
Pink snapper (*Chrysophrys auratus*)	146 to 195 RMS < 212 p-p at 5 m	- Some damage to the hair cells of the saccula observed as early as 18 hours post-exposure. - Damage more extensive 58 days post exposure.	McCauley *et al.* 2003
Broad whitefish (*Coregonus nasus*), lake chub (*Couesius plumbeus*), Northern pike (*Esox pucius*)	SEL 176-180 per shot	- No damage observed in the sensory cells of the inner ear, despite the fact that 2 of the species had shown a temporary threshold shift.	Song *et al.* 2008

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Table 7   Effects of Air Guns on Fish Physiology

Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Cod (*Gadus morhua*)	~ 202	- Increase in food consumption.	Andrews *et al.* 2007
Tropical species *Chromis viridis, Lutjanus kasmira, Myripristis murdjan and Sargocentron spiniferum*	Fish in the vicinity of an authentic seismic survey Up to 190 dB re 1 μPa^2.s	- No threshold shift in any species.	Hastings and Miksis-Olds 2010
Broad whitefish *Coregonus nasus,* lake chub *Couesius plumbeus,* Northern pike *Esox pucius*	Average mean peak of 207 Mean RMS of 197 Mean SEL 177 (re 1 μPa^2.s)	- Temporary hearing threshold shifts in chub and pike species with recovery within 24h of exposure. - No shift in whitefish. Concerning pike, a shift was observed only in adults and not in juveniles.	Popper *et al.* 2005

Table 8   Effects of Air Guns on Fish Biochemistry

Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Pink snapper *(Chrysophrys auratus)*	146 to 195 RMS < 212 p-p at 5 m	- No changes in blood cortisol and glucose levels and in blood smear cell counts for air gun exposure of 146-195 dB RMS	McCauley *et al.* 2000
Sea bass *(Dicentrarchus labrax)*	210 dB at 180 m 204 dB at 800 m 199 dB at 2500 m	- Variations of cortisol, glucose, lactate, AMP, ADP and cAMP in different tissues indicating a typical primary and secondary stress response after air gun detonations. Parameters returned to normal within 72h.	Santulli *et al.* 1999

Table 9   Effects of Airguns on Invertebrate Eggs, Larvae and Plankton

Life stage/ Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Fertilised eggs of snow crab (*Chionoecetes opilio*)	216 at 2 m	- Indication of higher mortality and slower development in exposed fertilized eggs when sampled 12 weeks after exposure.	Christian *et al.* 2004
Embryos of snow crab (*Chionoecetes opilio*)	174 (exposed) 118 (control)	- No effect on the survival of embryos carried by females and on the locomotion of larvae after hatch.	DFO 2004
Macro zooplankton (larvae of decapods and copepods)	na	No evidence of air gun impact on swimming ability.	GIA 2002
Plankton		No distribution changes.	Lokkeborg *et al.* 2010
Various stages of larvae Dungeness crab (*Cancer majister*)	Up to 231 at 1 m	- No significant effects in immediate and long-term survival, development and behaviour.	Pearson *et al.* 1994

Table 10   Effects of Airguns on Fish Eggs and Larvae

Life stage/ Organism	Exposure Level (dB re 1 μ Pa)	Observations	Reference
Eggs and yolk sac larvae of various commercial species including cod, saithe, herring and turbot	220 to 242 0.75 to 6 m	- Effects varied, with the highest mortality rates and pathology in the 1.6 m range and low or no mortality rates and infrequent pathology in the 5 m range. - Pathological effects in turbot larvae included strong vacuolation of the brain, nerve tissues and eyes as well as ablation of sensory cilia of neuromasts at 0.75 m.	Booman *et al.* 1996
Eggs, larvae and fry of cod (*Gadus morhua*)	220 to 231 1 to 10 m	- No mortality and no differences in feeding success for any stages studied at any distance. - No behaviour changes in all stages, except for the older fry which exhibited brief balance problems after exposure at 1 m, but recovered in a few minutes.	Dalen and Knutsen 1987
Eggs, yolk sac (YS) and early swim bladder (SB) larvae of Northern anchovy	223 to 235 p 1.5 to 3 m	- Egg survival decreased slightly (9%) at lower peak level and energy but no differences at higher levels. - 4-day YS larvae survival decreased (~35%). - No survival differences for SB stages.	Holliday *et al.* 1987

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(Engraulis mordax)		- Growth rate reduced for 2 and 4-day YS and 22-day SB. - No indication of histological damages in eggs and SB, but ~ 6% decrease in general condition in YS.	
Eggs and larvae of plaice *(Pleuronectes platessa)*	214 and 220 1 and 2 m	- High mortality (unspecified) at 1 m and no mortality at 2 m.	Kosheleva 1992
Eggs of red mullet, Anchovy, blue runner, crucian carp and other commercial fish	Estimated exposure level 210 to 236 0.5, 5 and 10 m	- Survival (combined species) one day post exposure: 75.4% at 0.5 m, 87.7% at 5 m, 90.2% at 10 m compared to 92.3% in controls. - Pathological effects (embryo curling, membrane perturbation and yolk displacement) observed in small percentage in anchovy and blue runner eggs at 5 m and crucian carp at 0.5 m. No effects noted in mullet eggs. - It is reasonable to assume a cause effect relationship at 5 m since effects were recorded at this distance for 2 species but absent at 10m.	Kostyuchenko 1973
5-day larvae of cod *(Gadus morhua)*	Estimated 214-220 1, 2, 3 and 4 m	- No histological changes detected in gills, liver, kidney, and intestine. - Rupturing of nerve and epithelial layers in the retinal tissues was found in larvae exposed at 1m.	Matishov 1992
Larvae of monkfish *(Lophius americanus)* Fertilized eggs of capelin *(Mallotus villosus)*	199 to 205 p-p 1.5 to 2.5 m	- No differences between controls and exposed for hatched larvae of monkfish or capelin eggs in relation to survival (24h-72h post exposure).	Payne *et al.* 2009

Table 11   Effects of Pile Driving on Fish Mortality and Gross Pathology

Organism	Exposure Level (dB re 1 µ Pa) Distance from source	Observed Response	Reference
Shiner perch *(Cymatogaster aggregate)* Chinook salmon Northern anchovy	Not measured ~ 10 m	- No difference in mortality between controls and exposed.	Abbot 2004 Marty 2004
Black fish *(Orthodon microlepidotus)*	Not measured 45 to 850 m	- No mortality and no behavioral effects (as observations for 5 hours post exposure). - Suggestion of no damages below 183 dB p (but no measured sound levels at the cages) and more damage to fish closer to the source.	Abbot and Bing-Sawyer 2002
Various wild species including salmon, anchovy and shiner perch *(Cymatogaster aggregate)* held in cages	160 to 196 RMS 100 to 200 m	- Mortality of several different species in the field at a distance within a range of 50m: with zone of direct mortality about 10-12 m from source and zone of delayed mortality assumed to extend out at least to 150 to 1,000 m.	Caltrans 2001
Steelhead *(Oncorhynchus mykiss)* Shiner surfperch *(Cymatogaster aggregate)*	158 to 182 dB re 1 µPa^2 s^{-1} at distances of 23 to 314 m from the pile	- No statistically significant mortality following exposure or 48h post exposure. Gross pathology similar in controls and exposed.	Caltrans 2004
Cod *(Gadus morhua)* Sole	144-156 p, cod: 140-161 p Particle motion between 6.51x10^{-3} and 8.62x10^{-4} m/s^2 p	- No mortality	Mueller-Blenke *et al.* 2010
Brown trout *(Salmo trutta)*	193 pp at 1 m pp 134 p at 400m	- No mortality - Gross pathology (eye hemorrhage and rupture of swim bladder) was only monitored for fish at 400 m and no injuries were reported.	Nedwell *et al.* 2003
Brown trout *(Salmo trutta)*	Source level 193 pp at 1 m	-No mortality or evidence of trauma (inner ear microscopy, gross pathology including swim bladder rupture, eye haemorhage or embolism).	Nedwell *et al.* 2006
Steelhead *(Oncorhynchus mykiss)*	SPL 163-188 p SEL 178-194 35 to 150m	No mortality and no significant differences in gross pathology.	Oestman and Earle 2010
Coho salmon *(Oncorhynchus kisutch)*	SEL 179 µPa^2-s or 207 over the 4.3h exposure period	-No mortality and no gross pathology in fish sampled at 10 and 19 days post exposure.	Ruggerone *et al.* 2008

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Table 12   Effects of Pile Driving on Fish Histopathology

Organism	Exposure Level (dB re 1 µ Pa) Distance from source	Observed Response	Reference
Brown trout *(Salmo trutta)*	Source level 193 pp at 1 m	- No evidence of microscopical trauma in the inner ear.	Nedwell *et al.* 2006
Steelhead *(Oncorhynchus mykiss)*	SPL 163-188 p SEL 178-194 35 to 150m	- No significant differences in histopathology (head, gill, liver, swim bladder, kidney, spinal chord and vertebrae) between controls and exposed.	Oestman and Earle 2010

Table 13   Effects of Low Frequency Sonar on Fish Mortality and Gross Pathology

Organism	Exposure Level (dB re 1 µ Pa)	Observed Response	Reference
Herring *(Clupea harengus)*, cod *(Gadus morhua)*, saithe *(Pollachius virens)*, spotted wolfish *(Anarhichas minor)*	150 to 190 At 3 m	- No direct mortality among the fish larvae or juveniles exposed, except for 2 experiments (of a total of 42) repeated on juvenile herring where significant mortality (20 to 30%) was observed for a 189 dB SPL. - No differences in delayed mortality or growth related parameters (up to 4 weeks).	Jorgensen *et al.* 2005
Rainbow trout *(Oncorhynchus mykiss)* Channel catfish *(Ictalurus punctatus)* Sunfish *(Lepomis sp.)*	Received peak signal: 193 RMS for 170-230 Hz frequencies and 210 RMS for 2.8-3.8 kHz frequencies	- No immediate mortality related to exposure. - No gross pathology	Kane *et al.* 2010
Rainbow trout *(Oncorhynchus mykiss)* Channel catfish *(Ictalurus punctatus)*	Max received RMS 193 dB μPa^2 for either 324 or 648 s	- No mortality	Popper *et al.* 2007 Halvorsen *et al.* 2006

Table 14   Effects of Low Frequency Sonar on Fish Histopathology

Organism	Exposure Level (dB re 1 µ Pa)	Observed Response	Reference
Larvae and juveniles			
Herring *(Clupea harengus)*, cod *(Gadus morhua)*, sSaithe *(Pollachius virens)*, spotted wollfish *(Anarhichas minor)*	150 to 190 at 3 m for 1.5, 4.0 and 6.5 kHz frequencies	- No obvious differences in histology of various non-auditory tissues - No effects on inner ear tissues of young herring larvae using SEM.	Jorgensen *et al.* 2005
Adult			
Rainbow trout *(Oncorhynchus mykiss)* Channel catfish *(Ictalurus punctatus)* Sunfish *(Lepomis sp.)*	Received peak signal: 193 RMS for 170-230 Hz frequencies and 210 RMS for 2.8-3.8 kHz frequencies	- No effects on inner ear tissues using SEM. - No histological effects in various tissues and organs (gill, skin, eye, liver, spleen and kidney).	Kane *et al.* 2010
Rainbow trout *(Oncorhynchus mykiss)* Channel catfish *(Ictalurus punctatus)*	Max received RMS 193 dB μPa^2 for either 324 or 648 s	- No ultra structural differences on the sensory hair cells of the inner ear. - No histopathological effects on non-auditory tissues including brain, swim bladder, heart, liver, gonads and blood.	Popper *et al.* 2007 Halvorsen *et al.* 2006

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Table 15   Effects of Low Frequency Sonar on Fish Physiology

Organism	Exposure Level (dB re 1 µ Pa)	Observed Response	Reference
Rainbow trout (*Oncorhynchus mykiss),* channel catfish (*Ictalurus punctatus)* and sunfish (*Lepomis sp.)*	Received peak signal: 193 RMS for 170-230 Hz 210 RMS for 2.8-3.8 kHz	- No differences in haematocrit.	Kane *et al.* 2010
Rainbow trout (*Oncorhynchus mykiss)* Channel catfish (*Ictalurus punctatus)*	Max received RMS 193 dB µPa^2 for either 324 or 648 s	- A 10-20 dB auditory threshold shift at 400 Hz immediately after exposure. -Recovery after 24 h for catfish and 48 h for trout.	Popper *et al.* 2007 Halvorsen *et al.* 2006

Table 16   Effects of Boat Noise on Fish Physiology

Organism	Source Characteristic Exposure Level (dB re 1 µ Pa)	Observations	Reference
Fathead minnow (*Pimephales promelas*)	Horse boat engine noise 142 during 2 hours	- Temporary hearing loss.	Scholik and Yann 2002
Toadfish (*Halobatrachus didactylus*)	Ferry boat noise SPL 130.8 at 20 m	- Temporary hearing loss.	Vasconcelos *et al.* 2007
Largemouth bass (*Micropterus salmoides*)	Various recreational boating activities (canoe, paddling, trolling, outboard motor noise)	- Heart rate increase. - Stroke volume decrease.	Graham and Cooke 2008

Table 17   Effects of Boat Noise on Fish Biochemistry

Organism	Source Characteristic Exposure Level (dB re 1 µ Pa)	Observations	Reference
Carp (*Cyprinus carpio*) Gudgeon (*Gobio gobio*) European perch (*Perca fluviatilis*)	Boat noise of 153 equivalent continuous SPL over 30 min	- Increase of cortisol levels.	Wysocki *et al.* 2006
European sea bass *Dicentrarchus labrax* Gillhead sea bream	0.1 to 1 kz linear sweep 150 RMS	- Elevated serum glucose and lactate. - Increase in haematocrit levels.	Buscaino *et al.* 2010
Red drum (*Sciaenops ocellatus*) and spotted seatrout (*Cynoscion nebulosus*).	175 to 180	- Transient increase in cortisol.	Spiga *et al.* 2010

Table 18   Effects of Aquaculture Noise on Fish and Invertebrates

Organism	Exposure Level (dB re 1 µ Pa)	Observations	Reference
Rainbow trout (*Oncorhynchus mykiss)*	115 to 150 RMS On 8 months	- No effect on survival and growth. - No effect on hearing. - No effects on blood glucose, sodium and chloride. - No effect on disease resistance.	Wysocki *et al.* 2007
Rainbow trout (*Oncorhynchus mykiss)*	149 RMS for 5 months	- No long-term effect on growth rates and survival.	Davidson *et al.* 2009
Brown shrimp (*Crangron crangron)*	About 30 dB higher than levels encountered in the natural environment	- Significant reductions in growth and reproduction rates. - Increased mortality. - Higher metabolic rates (expressed as ammonia excretion rate and oxygen consumption.	Lagardere 1982 Regnault and Lagardere 1983

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Use of Fisheries Statistics
in the study of
Behavioural Responses of Marine Fish and
Invertebrates
to
Exploration and Production
Seismic Energy

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INTRODUCTION

The OGP Joint Industry Programme on "E&P Sound and Marine Life", in cooperation with the Canadian Environmental Studies Research Funds (ERSF) and the Offshore Energy Environmental Research Association (OEER) is planning a March 2011 workshop on the effects of exploration and production (E & P) energy on marine fish and invertebrate behaviour. The workshop would address behavioural issues (not physical damage) around marine sound sources, primarily seismic survey. This will be a technical workshop aimed at defining the nature and methodology of the scientific studies needed to determine what, if any, effects seismic sound sources have on fish behaviour. The outcomes of the workshop could then be used to develop field studies within a defensible scientific design framework.

The specific objectives of the March workshop are:

- To examine current and future technologies required to assess the impact on fish behaviour of E&P-generated sound that could lead to significant population effects or effects on fish catch
- To derive specifications for experimental design that include hypotheses to be tested, methods to be deployed and statistical analyses that will be required both before and after any field work
- To develop research strategies to address key questions of concern to sponsors and further to determine the limitations and pitfalls associated with field experiments

In support of these objectives, the current report was commissioned to review the use of fishery statistics and catch reports in the study of the effects of sound energy on the behaviour of fish and invertebrate populations in open marine environment. It considers the use of fishery statistics in understanding how the behavioural response to sound affects population biology rather than how it impacts fisheries. It does not consider the lethal effects of sound energy. While specific examples are used in the report, it provides generic guidance, highlighting the most appropriate use of fisheries statistics including their advantages and disadvantages.

NATURE OF FISHERIES STATISTICS

It is useful to describe the term 'fisheries statistics' as this can mean different things to different people. Fisheries statistics includes all data collected during the operation of a fishing vessel. This includes information collected both at sea and at off-loading at port.

At sea information is typically collected through the use of logbooks which record the vessel characteristics, type of gear used (e.g. trawl, hook and line, trap), the species composition and quantity by fishing set location and time, thus providing information on the catch per unit of fishing effort (CPUE). Programs to monitor at sea activities and thus verify the logbooks range from electronic monitoring (Stanley and Olsen, 2009) to observers. Some form of at-sea monitoring is required to capture information on discarded fish.

Dockside monitoring programs (DMP) record the total landings from a fishery by species and quantity, linking these data to the appropriate logbook information. Since the advent of property rights systems in the 1990s, DMP has typically been 100% of the landings, compared to at-sea monitoring which, except for a few jurisdictions (e.g. Canadian Pacific Coast fisheries), have typically been undertaken at lower (e.g. 10 – 30%) levels of coverage.

Research survey activities (e.g. collection of samples using trawl) could be considered as a type of fisheries data. The differences between a research trawl survey and one using contracted fishing vessels operating under a specific gear and sampling protocol are minor. Where considered appropriate, these data are also considered.

POTENTIAL EFFECTS OF E & P SEISMIC ENERGY

Some Biology

It is useful to briefly review the biology underlying the behavioural effects of sound on fish and invertebrates. Hawkins (1993) highlights the importance of sound production and detection to a fish's biology. Sound is produced and detected as a means of communication in a highly opaque environment and given the physical properties of water, this can occur over quite large distances. It is used in aggression displays, flight response from a potential predator, in spawning and so on. Sound is typically produced either stridulatorily (rubbing parts of body together) or hydrodynamically (water turbelance produced through motion). Fish with swimbladders (the ray-finned species) have particularly sophisticated means of sound production using this organ. Brawn (1961a; 1961b; 1961c) and Hawkins and Amorim (2000) describe the role of sound production in the spawning in cod and haddock respectively. Rowe and Hutchings (2006) hypothesize that sound production in cod is related to competition among males for access to females and may help synchronize gamete release. Similar observations have been made on numerous other fish species.

Regarding sound detection, a fish's ear is the key organ but for those species with a swimbladder, it is especially important. The latter acts as an 'amplifier' to received sound and thus species with this organ are highly sensitive to sound. Even within the teleosts, sound detection can vary greatly, with species such as cod and catfish much more sensitive to sound than salmon or dab (Hawkins, 1993). Sensitivity audiograms have been developed for a wide range of fish species with distinctions made as to sensitivity to detection versus reaction. For a fish to detect a sound, the stimulus must exceed the ambient noise level (about 80 - 90 dB re 1 uPa Hz.1 in the open sea) by about 20 dB (Hawkins, 1993). However, the level at which fish respond to a sound stimulus (the reaction threshold) may lie significantly above the detection threshold. For instance, the reaction threshold for vessel noise has been shown to be approximately 20 dB above the detection threshold (Engas et al., 1996)

Regarding invertebrates, as with fish, a range of behaviours are associated with sound production and detection (Moriyasu et al., 2004). While comparatively little is known on invertebrate sound detection, many species have mechanosensors that resemble the vertebrate ear. Crustaceans have vibration receptors in both the statocysts and walking legs. On the other hand, Moriyasu et al. (2004) point out that there is a general

but unproven belief that bladderless fish and invertebrates are less susceptible to seismic E & P energy. In support of this, Payne et al (2008) point out that unlike fish, no literature has been found documenting major startle or movement responses upon exposure of crustaceans to sound. They also observed no startle responses in aquarium experiments with lobsters and shrimp exposed to peak-to-peak SPLs of approximately 200 dB re 1μPa.

Thus, it appears that invertebrates are overall less sensitive to sound than fish.

Types of Behavioural Interaction

The previous section provides context for understanding what fish and invertebrate behaviours may be impacted by sound and how these may relate to the species' population biology. When designing studies on the effect of sound on fish and invertebrates, it is important to state the hypothesis of interaction being tested (e.g. impact on local movement, migration, spawning, etc). DFO (2003a) categorizes the behavioural issues associated with seismic sound:

- Finfish juveniles and adults
    - Diversion from "normal" migration or feeding location
    - Interference with courtship, spawning etc.
    - Interference with schooling
    - Interference with predator avoidance patterns
    - Disruption of other normal behaviours (e.g. avoidance of a particular area)
- Finfish eggs & larvae
    - Diversion from "normal" transport, diurnal migration or feeding location
    - Interference with predator avoidance patterns
    - Disruption of other normal behaviours (e.g. avoidance of a particular area)
- Invertbrates
    - Diversion from "normal" transport, diurnal or season migration routes, or feeding location
    - Interference with predator avoidance patterns
    - Interference with courtship, spawning etc.
    - Interference with schooling
    - Disruption of other normal behaviours (e.g. avoidance of a particular area)
    - Stunning

Many of these behaviours will be relatively short-term (less than 5 days) phenomena, for instance, disruption of feeding movements in the horizontal and vertical plane. Many studies have focused on these relatively small scale movement of fish as these may have implications for the economics of a fishery but not for population biology. On the other hand, sound stimuli which affect feeding migrations and / or spawning success have long-term (5 days +) implications for a population. In addition, one needs to consider whether or not the accumulation of short – term impacts (e.g. feeding disruption) may have long-term, population consequences. Payne et al (2007) for instance observed a change in lobster feeding associated with seismic energy. Sustained

disruption of feeding could change an individual's growth which would have population – level implications.

STUDIES ON USE OF FISHERIES STATISTICS IN FISH BEHAVIOUR

Since the 1960s, a wide variety of studies using fisheries data have been conducted on fish and invertebrate behaviour. The majority of these have been focused on the effects of seismic energy rather than considering other sound sources. A synopsis of these studies is provided (table 1). General observations are then made on the utility and design of studies which use fisheries statistics in the study of fish behaviour.

A number of studies have examined the effects of sound on fish and invertebrate behaviour using non-fisheries methods (e.g. acoustic surveys, tagging, cage experiments, field enclosures). While some of these are mentioned here, only those using fisheries statistics are reported in table 1.

Studies on Fish Species

Chapman and Hawkins (1969) undertook one of the first studies on fish behaviour and sound. They examined the behavioural response of saithe (*Pollachius pollachius*) to ship and trawl sound. They were one of the first to estimate a sensitivity audiogram for a fish species (saithe).

Pearson et al (1992), in their study of rockfish off the coast of California, used field enclosures to estimate the startle and alarm thresholds (180 and 163 dB) of these species to seismic airguns. They observed a variety of behavioural responses with the dominant one being movement of the rockfish to the bottom in response to the sound stimulus.

Skalski et al. (1992) were one of the first to use fisheries statistics to study the behavioural effects of seismic energy on California rockfish (Sebastes spp.). Their experimental design consisted of a point sound source (airgun with 223 dB re. 1 uPa on a vessel) with individual fish aggregations as the experimental unit. The latter were sonified with two emission levels (mock emission + 186 dB produced at base of rockfish aggregation) and the effect on hook and line CPUE (the main objective of the study) examined. The number of trials (20) was established based on the CPUE coefficient of variation (CV) observed in preliminary fishing. An Analysis of Covariance was used to adjust CPUE for depth and aggregation height and area effects. CPUE decreased 52.4% which they felt was due to a change in gear catchability associated with an alarm behavioural response. They note that this was a short term effect and queried on the cumulative effects of repeated surveys in the area.

Lokkeborg and Soldal (1993) examined the CPUE of longliners fishing cod (Gadus morhua) as recorded in logbooks in an area which had been sonified by a seismic survey. They also examined cod bycatch CPUE in shrimp and saithe trawls. Mean CPUE was compared before and 24 hours after the seismic survey. Cod longline CPUE was observed to decline 55-80% with these reductions occurring to at least 9 km from the seismic area while cod bycatch in the shrimp trawls declined by 80%. Reductions in CPUE were observed in both gear, suggesting that that cod were moving away from the seismic survey area, rather than just diving to the bottom.

Engas et al. (1996), in their study of the seismic effects on Barents Sea cod and haddock longline and trawl CPUE, took a more systematic approach in their experimental design. The sound source was a towed airgun array using a standard 3D protocol. An array of longline and trawl stations was fished before, during and after the seismic survey. This array also sampled at specified distances (0, 1-3, 7-9 and 16-18 nmi) from the seismic survey area. Trawl and longline fishing protocol was standardized. A linear model was used to examine trawl and longline CPUE as a function of distance and time. They also undertook acoustic mapping of cod and haddock to observe movement in cod and haddock biomass. They observed cod and haddock trawl CPUE and haddock longline CPUE to decline 70% and cod longline CPUE to decline 45%. These reductions occurred over a long distance (18 nmi) and lasted at least five days. From the acoustic mapping, fish appeared to move out of the seismic area due to an avoidance behaviour. Importantly, large fish appeared to move further than small fish, implying a process that was not picked up in the CPUE data.

In their study of the behaviour of a number of gadoids on an inshore reef off Scotland, Wardle et al (2001) used a seismic sleeve gun to sonify areas of the reef and observed fish behaviour through a combination of tracking of acoustically tagged fish and underwater cameras. They observed no affects of the seismic sound.

Hassel et al (2004) carried out a field experiment of sandeel behavior and survival during a seismic survey in the southern part of the North Sea. The seismic source was of a 28 airgun array. Three sandeel cages were placed at a depth of 55 m in the center of the shooting area with the control fish being caged about 35km from the experimental site. Fish activity was monitored with cameras placed in the cages and by a remotely-operated vehicle. The distribution and/or abundance of sandeels were also monitored through acoustic surveys and grab surveys of sediments. Importantly for this report, they also visually (not a statistical analysis) examined daily landed sandeel catches for different geographical fishing areas close to the shooting area before, during and after seismic shooting. Overall, a startle or flight response was observed in association with shooting. Both acoustic surveys and grab samples of sediments indicated no apparent changes in sandeel abundance between control eel experiment sites and declines in landings after the seismic shooting were deemed only short-term.

While the study of Slotte et al. (2004) did not use fisheries statistics, it does highlight the utility of acoustic mapping which was used to see the impact of seismic noise on the post spring spawning migration of herring, blue whiting and mesopelagic fish. There was no convincing evidence of a short term scaring effect in the horizontal scale. While blue whiting and mesopelagic fish moved deeper, fish density seemed to be higher at about 20 nautical miles from the centre of the shooting area, which coincided with the typical approximate reaction distance to seismic shooting observed in species like cod and haddock (Engas et al, 1996). From their observations, the herring migration would appear to have proceeded normally after the seismic shooting.

Lokkeborg et al (2010) undertook one of the most comprehensive studies to date on the effects of seismic sound on a range of gadoid species off Norway. The sound source was a seismic 3D survey. Longline and gillnet fishing, under a standardized protocol, was undertaken before (12 days), during (38 days) and after (25 days) the seismic survey. As well, the area was acoustically mapped. The overall approach was similar to that of Engas et al. (1996). Greenland halibut and redfish gillnet CPUE

increased while halibut CPUE in longlines decreased and then increased 25 days after the seismic survey. Haddock CPUE in longlines also declined. Overall, they report that the behavioural changes were less than generally less than observed in previous studies.

Worcester (2006) reviewed the literature to date of laboratory and in situ studies on the behavioural, physical and biochemical responses of fish to sound, focusing primarily on impacts of airgun sources. Based on the limited number of studies available, she considered that there is a high probability that some fish within the general vicinity (i.e. hundreds of meters) of a seismic survey would exhibit a startle response, changes in swimming speed or direction, and changes in vertical distribution, with recovery likely within minutes to hours after exposure. There is a lower but still reasonable probability that seismic surveys will influence the horizontal distribution and catchability of some fish under certain conditions, such as during migration of pelagic fish. If horizontal dispersion does occur, impacts are more likely to be observed over greater distances (kilometers) and for a longer duration (days). The potential for seismic surveys to disrupt communication and other sound-dependant activities of fish is essentially unknown, as is the long-term ecological significance of the impacts described above. She goes on to state that biological factors that may influence the response of fish to airgun impulses include whether they are engaged in migration, spawning or feeding, and the extent of their typical range, i.e., do they tend to move around or stay in one location. For example, Wardle et al. (2001) indicated that pollock did not move away from their home reef upon exposure to seismic noise, while the study by Slotte et al. (2004) suggested that horizontal distribution of herring and whiting may have been related to the fact that they were migrating. While the results by Engas et al. (1996) have been disputed (e.g. Gausland, 2003), this study provides the strongest evidence for horizontal dispersion of cod and haddock from a large area (74 km^2). The temporal scale of these effects were not clearly established, as monitoring was only conducted for five days after exposure and fish densities within the survey area did not returned to pre-exposure levels during this time. Given these results, the possibility of movement of fish away from a seismic survey area should not be discounted. Should this occur during spawning or other ecologically significant life-history events, population level effects may occur. Finally, Payne et al (2008), in their update, note that the variety of behavioural responses elicited by sound highlights the importance of considering all sources of noise, not just seismic, in any study.

Studies on Invertebrate Species

The literature on the effects of sound on the behaviour of invertebrate species is generally less voluminous and more recent than that on fish. Very few of these involved fisheries statistics. Some of the earlier work is summarized in Christian et al. (2003).

In their study reported by Moriyasu et al. (2004), Steffe and Murphy (1992) monitored changes in Australian prawn trawl CPUE before, during and after a seismic survey. This appears to have been an opportunistic study rather than set out as an experimental design, although this would have to be confirmed through access to the original report. There were no detectable impacts on Australian prawn behaviour.

In another study also reported in Moriyasu et al. (2004), LaBella et al. (1996) studied the effect of a seismic survey on trawl, gillnet and clam dredge CPUE of a

number of invertebrate species in the Adriatic Sea. The location of each gear (8 trawl stations, 14 clam dredge sets and 2 gillnet stations) was established in relation to the seismic and CPUE compared using an analysis of variance before and after the survey. The exact details of the experimental design would have to be confirmed through access to the original report. The only difference was in Sea Snail (Bolinus brandaris) gillnet CPUE.

Jeffs et al. (2003), in their study of New Zealand coastal crab species, which sonified larval stages in experimental traps, showed that larval crabs may use sound as a settlement cue.

Christian et al (2003) studied the impact of seismic sound on snow crab (*Chionecetes opilio*) trap CPUE. The sound source was an array of airguns at one location in Conception Bay, Newfoundland, the output of which was recorded at a site within the study area. Controlled experimental commercial snow crab fishing was conducted at the study site before and after experimental seismic shooting using a specified crab trap protocol. For each experimental set, 40 traps were deployed. Analysis of the trap CPUE (by crab size) was limited to examination of trends in estimates means. Treatments considered were pre- and post-seismic stimuli, soak time and distance from sound source. In addition, behavioural reactions to seismic were observed using acoustic tags and video cameras. There was no detectable response to the seismic sound in either the trap CPUE or in behaviour. As well, there were no large scale movements of crab out of the study area.

Courtney et al. (2009) reported that a bottom trawl survey carried out after the seismic survey (June 2004) provided no evidence of reduced abundance or changed geographic distribution of multiparous female snow crab compared with a bottom trawl survey conducted before the seismic survey (September 2003). However, there is considerable variation associated with the abundance estimates, and they considered that the data obtained from bottom trawl surveys could provide the spatial resolution to provide a definitive conclusion.

Moriyasu et al. (2004), in their literature review of 35 articles, noted that only two sound sources had been studied, both seismic and of the four devoted to the study of behaviour, three showed some impact on behaviour and one none. They also reported some anecdotal observations by fishermen which suggested that snow crab CPUE declined close to a seismic survey but not at distance and no changes in shrimp trawl CPUE off Norway. Overall, they concluded that there was no robust scientific evidence to draw any conclusion (positive or negative) in relation to the impact of seismic energy on invertebrate behaviour.

Payne et al. (2008) reviewed the literature appearing during 2003 – 2008 and noted that a few studies were now available indicating absence of effects at the population level. They note however, that if seismic surveys are having effects on fish or shellfish at the population level, they would not be readily measurable due to confounding factors such as natural variability, fishing pressure and animal migration. They felt that across a range of species, there was little evidence of a behavioural response of invertebrates to seismic energy.

Summary

A wide variety of approaches has been used in the study of the fish and invertebrate behavioural response to sound. Virtually all studies were motivated by a desire to understand the effects of seismic energy specifically, with the exception of the study of Chapman and Hawkins (1969) which considered the effect of ship and trawl noise. Given the number of studies, it is not possible to ascribe any one approach to a particular agency or nation. However, it is possible to discern a general progression from studies which were exploratory in nature, making opportunistic use of available fisheries statistics, to those which have a specified experiment design to test a stated hypothesis. During this progression, other sources of information and technology (other than fisheries statistics) come increasingly into the studies. These include the use of acoustic (not seismic) surveys to map the distribution of fish before, during and after seismic shooting, deployment of electronic tags to track the movements of individual fish and invertebrates, underwater video cameras to record detailed behaviours (e.g. startle or avoidance response) and stomach / biochemical analyses to understand the impacts on feeding.

The next section draws upon the above experience to outline the elements of the study design of fish and invertebrate behaviour in response to seismic energy. For each, it discusses issues to be considered and makes recommendations.

Table 1. Summary of design and conclusions of studies investigating sound effects on fish behaviour using fisheries statistics

Study	Area	Species	Fishing Gear	Sound Source	Experimental Design	Conclusions
Skalski et al (1992)	California	Rockfishes (Sebastes spp.)	Hook & Line	Airgun (223 dB re. 1 uPa) on vessel	• Individual fish aggregations sonified; 180 dB at bottom + control • Aggregation fished after aggregation sonified; blinded • 20 trials	• 52.4% decline in rockfish CPUE • Significant decline in catch of 3 of 5 most abundance species • Due to change in catchability associated with alarm behavioural response
Lokkeborg & Soldal (1993)	Northern Norway	Cod (Gadus morhua)	Longline	Seismic survey using 4 sleeve gun array	• Opportunistic • Geophysical survey of 3 tracklines • Fishery logbooks from area of survey	• 55 – 80% reduction in CPUE
Lokkeborg & Soldal (1993)	Northern Norway	Cod (Gadus morhua) bycatch in shrimp & Saithe trawls	Shrimp & Saithe Trawls	Seismic surveys (3) using variety of configurations	• Opportunistic • Geophysical survey of 3 tracklines • Fishery logbooks from area of survey	• 80% reduction in CPUE • Catch reduction at distances of at least 9 km • Catches returned to pre-shooting levels with 12 -24 h
Engas et al (1996)	Barents Sea	Cod (Gadus morhua) & Haddock (Melanogrammus	Longline & trawl	Seismic 3D survey	• Acoustic mapping of seismic survey area • 3 x 4 time and	• Acoustic density reduced 45% during seismic survey & 64% after

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Reference	Location	Species	Gear	Signal	Results
		aeglefinus)			70% reduction in trawl cod & haddock CPUE during & after survey 70% reduction in haddock longline CPUE 45% reduction in cod longline CPUE - Effect over 18 nm and lasted at least five days - Fish moved out of area distance from seismic area combinations for each gear (trawl & longline) • Standard fishing protocol
Hassel et al (2004)	North Sea	Sand eel	N/A	Seismic survey	- No obvious effect - Short – term decline in landings after shooting • 3 cages sonified & behavioural response observed • Acoustic survey • Daily landings
Lokkeborg et al (2010)	Norway	Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes marinus*), saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*)	Longline and Gillnet	Seismic 3D survey protocol	- Gillnet CPUE of halibut & redfish increased - Longline CPUE of habibut decreased & then increased 25 days later - Saithe left area - Longline CPUE of haddock declined - No obvious changes in feeding (stomach analysis) - Less change than • Acoustic mapping of seismic survey area & determination of species biomass based on backscatter • Fishing protocol

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					Methods	Results
Steffe & Murphy (1992)	Australia	Prawn (Penaeus plebejus)	Shrimp trawl	Seismic survey	• Opportunistic • Monitoring of CPUE of selected fishermen before, during & after seismic survey	previous studies perhaps due to larger size of seismic area • No detectable impact
LaBella et al. (1996)	Adriatic	Wide range of species	Trawl, gillnet, clam dredge	Seismic survey	• Experimental design • Monitoring of CPUE of selected fishermen before & after seismic survey	• Only difference was in Sea Snail (Bolinus brandaris) gillnet CPUE
Christian et al (2003)	Conception Bay, NFLD	Snow Crab (Chionecetes opilio)	Crab traps	Airgun array	• Crab trap CPUE before and after sound stimuli • Sound x soak time x distance treatments • 6 crabs tagged with acoustic transmitter & tracked • Video monitoring	• No detectable response • No large scale movement out of area

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RECOMMENDATIONS ON USE OF FISHERIES STATISTICS

Study Purpose

When contemplating the use of fisheries statistics to study fish and invertebrate behaviour in response to sound, it is important to clearly state the purpose or objective of the study. The objective of many of the studies to date has been to determine the effect of seismic energy on fishery catch rates, perhaps to estimate the amount of monetary compensation of affected fishermen (e.g. Skalski et al. 1992). The spatial and temporal extent of these studies tends to be local (compared to the area of the population) and short-term. For these objectives, the use of fisheries statistics is very useful and indeed indispensable. Given that CPUE changes observed in these studies are due to the effect of seismic energy on fish and invertebrate behaviour, the use of fisheries statistics at this spatial and temporal scale are also useful to understanding the underlying biological processes.

When the objective of a study is to determine the effect of seismic energy on population biology, the scale of the problem changes. Here, the focus of the effect is on the larger population over the long-term. An example of this is the effect of a seismic survey on a feeding migration. Another, less direct effect would be the cumulative impact of seismic energy of fish and invertebrate feeding and thus growth. Notwithstanding the difficulties of this class of studies (see Payne et al, 2008), to study these problems, one needs to consider a population modeling approach which puts seismic effects into the broader context of other sources of disturbance (e.g. fishery and shipping noise). Interestingly, in this context, fisheries statistics has a long history of use and indeed has been essential component of the modeling.

Issues with both classes of problems are discussed below, highlighting issues with each, organized by the elements of a study or experimental design.

Local and short-term Studies

Study Area

As noted above, the spatial extent of these studies is smaller, sometimes substantially, than that of the population. However, it is often not clear from the studies reviewed above how the size of the study area was determined. In most cases, details on the sound emission at source are provided but in only a limited number of cases (e.g. Engas et al., 1996) was the sound at the target (i.e. the sonified fish and invertebrates) monitored. Sound can travel long distances in water and thus the size of the study area should reflect this potential for effect. A way to establish the size of the study area is to use sound detection and behavioural response thresholds from audiograms available for the species in question in combination with an estimate of transmission loss using x log R where x is 25 or 35 for open or shallow water and R is the range over which the sound is propagated (see Pearson et al., 1992) for an application).

While this provides an estimate of the sound energy at the target, it is important to consider sound monitoring to confirm these estimates and thus the size of the study area.

Sound Source

All the studies reviewed above described the characteristic of the seismic energy source in detail. This includes

- Number of airguns and their size
- Pressure (KPa) and volume (cm^3) of emission
- Sound level at source (e.g. 223 dB re. 1uPA)
- Temporal schedule of shooting
- If a survey, spatial extent of survey in relation to study area

Engas et al. (1996) provides an example of these specifications.

Model

Statement of the model is a key element of the experimental design. When fisheries statistics are used in local and short-term studies, the response or dependent variable is catch per unit effort (CPUE) described as a function of a number of treatments or independent variables:

$$CPUE = B_0 + B_1 + B_2 + B_1*B_2...B_n + e$$

Where B_0 is the intercept and B_1 to B_n are treatments such as time in relation to sound stimuli (e.g. before, during and after), distance from sound stimuli (e.g. 0 – 10 nm, 10 – 20 nm, 20 – 30 nm), time of day (day, night) and so on. The underlying assumption is that as fish move in response to the sound stimuli, their local abundance or biomass, and thus CPUE, changes. The form of the equation is very case specific with many examples in the studies reviewed above (e.g. Engas et al., 1996).

The literature on catch rate standardization is huge. Xiao et al. (2004) provides a recent review of the literature which is dominated by General Linear Models (GLM), Generalized Additive Models (GAMs), Generalized Linear Mixed Models (GLMMs) and so on with many software applications (e.g. R) available. Issues to consider relevant to the study of the effect of seismic sound on fish and invertebrate behaviour are

- Use of mock or zero emissions as a control (e.g. Skalaski et al., 1992)
- Incorporation of treatments levels before, during and after sound emission
- Consideration of confounding factors such as fish size, school size, the nature of prey on which fish might be feeding at the time (e.g. capelin which are sensitive to sound and may move away from the area versus shrimp which are indicated not to be sensitive to sound), whether the fish were "migrating", and whether other ship traffic might be traversing the area at the time
- Model error structure; most models assume lognormal errors but many others (e.g. Poisson, Delta) are possible

Suffice it to say that considerable forethought must be given to the experimental model

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Sample Unit

As noted above, CPUE is the dependent variable, typically expressed catch in weight (kg) per unit time. Given that the objective is to determine how local biomass and thus CPUE changes with sound stimuli, it is critical to remove variation due to gear configuration and operation from the study. This calls for a standardization of gear protocol. Some of the studies reviewed above provide specifications on the gear configuration and operation. This is not possible when commercial CPUE data are used opportunistically. In this case, there is a real possibility of the confounding of CPUE changes and gear protocol.

Some issues to consider in relation to the sampling unit:

- It is essential to have a study fleet with a specified protocol or, in the extreme, the equivalent of a research vessel operating under a standardized protocol
- Fixed gear can be easier to use; however, they require the fish to move due to the desire to feed (traps, hook and line), which is turn requires the use of bait, or to move in some other directed fashion (e.g. migration), for instance with gillnets; if the sound stimuli affects feeding, this has implications for the use of fixed gear, and trawling should also be used; a range of gear types should be used to cover this possibility
- Fish of different sizes may behave differently in relation to a sound stimulus (e.g. Moriyasu et al., 2004). This possibility was not examined in many of the studies reviewed. It is a confounding effect which introduces significant error into the model. When studying CPUE changes, this should be considered by fish and invertebrate age/size

Sampling Design

The intensity and spatial arrangement of the sampling need careful consideration. Regarding the intensity of the sampling, this is obviously constrained by a study's budget but some sense of an experiment's power (capacity to determine a statistical difference), which is a function of the sampling intensity, can be obtained through conduct of preliminary sampling to determine the coefficient of variation (CV) of the CPUE. This is then used to estimate how many sampling units or trials are needed (e.g. Skalski et al, 1992).

The spatial arrangement of these sampling units is typically either as a fixed grip or dependent on a stratification scheme. Given the spatial extent of these studies, fixed station designs are likely more appropriate unless there is compelling reasons for the use of strata.

Some issues to consider:

- Ensure that the sampling grid comprehensively covers the study area
- If there is reason to believe that there are sub-areas of the study area (e.g. reef) to which fish or invertebrates my preferentially move, consider establishing strata for these areas

Population scale and long-term Studies

Study Area

      If the focus of a study is a behavioural process with population level consequences (e.g. migration), then the scale of the problem needs to shift to this level. This requires considering knowledge on the biology of the species to establish the study area. It may be that the whole stock is the study area.

Sound Source

      When studying the effects of seismic energy at the population level, it is useful to consider all seismic sources, not just one activity. For instance, if there are five seismic surveys potentially affecting a particular fish stock, then it would be important to document the total amount of sound produced. If these surveys have been conducted over a number of years, then a time series of seismic energy is required. This in turn requires the development of metrics of the characteristics and intensity of this sound per unit area. It is beyond the scope of this report to describe how exactly this could be done but one could envision estimating the sound energy received by each km^2 of the habitat of a species using a transmission loss model and accumulating these data over a specified time period (e.g. month). This may require the collection of empirical observations on received sound as sound propagation models have show discrepancies (Lawson, 2009). Further, it would be useful to have information on the sound energy impinging on these areas from both ambient and other (e.g. shipping) sources. This would allow considering the potential seismic effects in the context of others.

      DFO (2003b) provides a time series of annual 2D and 3D seismic energy received by the Scotian Shelf (figure 1). It shows that regular pulses of 2D energy during 1960 – 2002 with a significant increase in 3D energy during 1995 – 2002. Frank and Lee (pers. Comm.) reported, to their knowledge, that this time series has not been updated. To examine potential population – level effects of seismic energy, time series such as these are required.
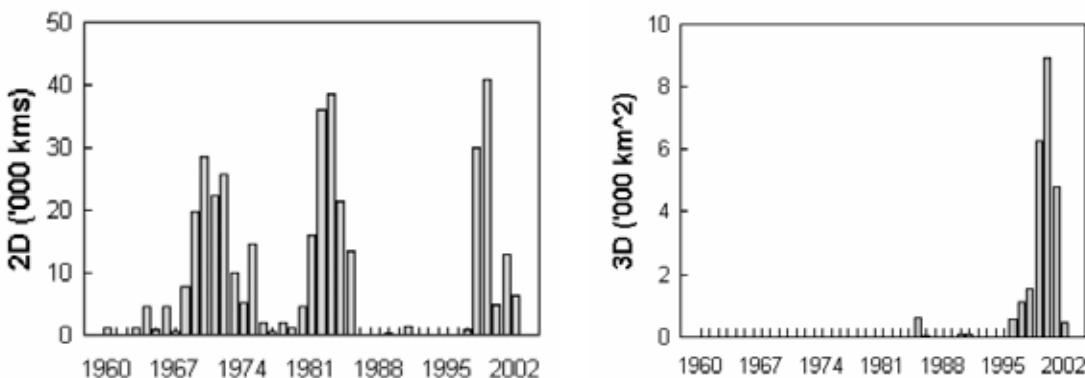

Figure 1. Area (km2) of 2D (a) and 3D (b) seismic tracks on Scotian Shelf during 1960 – 2002 (from DFO, 2003b)

Model

There are numerous models of fish and invertebrate behaviour available for use in study of the effects of seismic energy. Behind all these is the notion of describing normal behaviour to which disturbed behaviour and its consequences can be examined. In their review, Theile and Ferno (2004) highlight some of the more prominent models in the field, these being Individual-Based Models which have a relatively long history of use (e.g. DeAngelis and Gross, 1992). The Population Consequences of Acoustic Disturbance (PCAD) model considered by NRC (2005) in its treatment of marine mammal – noise interactions is an evolution of this modeling environment. However, as Thiele and Ferno (2004) state, information on the scale required to use these models is relatively scare and there is a need for modelers and biologists to collaborate to make use of these models.

The class of models of more immediate use in the study of the population – level effects of seismic energy on fish and invertebrates is that of stock assessment. It is the models in this class that make most use of fisheries statistics, both total catch and CPUE. The most heavily used models in this class are Virtual Population Analysis (VPA) and Statistical Catch at Age (SCAA) (see Quinn and Deriso, 1999 for a good review of the two approaches). These models, until quite recently, have not typically included spatial processes due to the requirement to have movement coefficients between adjacent boxes in the model. However, there have been substantial developments in these models in recent years, which are reviewed in Goethel et al. (2011). The latter proposes a generalized tag-integrated meta-population model, which is fully discussed in the paper and which is an evolution of the Box-Transfer models discussed in the review and a spatial variant of an SCAA model. This model allows the estimation of movement rates amongst spatial areas of a stock. It uses time series of catch, CPUE and abundance index information to describe population dynamics over time (typically annual). Goethel et al. (2011) highlight the importance of tagging information in these models. Historically, movement rates between spatial areas were input into these models (see Horbowy et al., 2005 for spatial VPA of Baltic Sea herring). While it is possible to undertake spatial modeling without information on movement (see Miller et al (2008) model of Eastern Bering Sea pollack without tagging data), tagging data is needed to incorporate migration and movement rates which can vary between years. The recent advances in tagging technology (e.g. Hewitt et al, 2010; Pine et al, 2003; Walsh and Morgan, 2004) and indeed those highlighted by the Ocean Tracking Network (OTN) open the door to the use of a generalized tag-integrated meta-population model or like framework, to study population – level effects of seismic energy. These can be implemented using software such as ADMB (http://admb-project.org)

Sampling Unit (Data)

When CPUE data are used in local, short-term studies, considerable attention is given to the problem of standardization. In a population modeling environment, this standardization can occur either outside the model or within it (Maunder and Langley, 2004). Similar considerations as noted in the previous section apply here as well although the treatments would be different.

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As noted above, when studying seismic energy – fish/invertebrate behaviour interaction at the population level, other data sets such as tagging, surveys, etc become important to consider.

Sampling Design

Most of the issues noted above for local, short-term studies do not apply here.

Advantages and Disadvantages

An advantage of using fisheries data in local, short-term studies is that they can provide insight on fish and invertebrate behaviour for relatively low cost. This assumes that the issues noted above on study design are addressed.

A disadvantage of these studies is perhaps whether or not the results of these studies inform the broader implications of seismic energy on a fish or invertebrate species. A review of the studies to date tends to suggest that the effects of seismic energy are localized and short-term but there has been little work to confirm this.

Thus, an advantage of undertaking the study of the effects of seismic energy on the fish and invertebrate population consequences of behavioural modification is that it explicitly tries to see if there is an issue. By undertaking this study, it would also put seismic energy effects in the broader context of other related possible effects. It could also highlight research required to fill data and knowledge gaps.

A disadvantage of undertaking studies at the population level is that there is a significant risk that cumulative seismic effects will be not readily measurable compared to other impacts, as indicated by Payne et al (2008). However, another way of looking at this possible result is that, well, cumulative seismic effects are not measurable compared to other impacts.

Perhaps a bigger disadvantage with undertaking these studies is the time required to compile and organize the required data. Much of the fisheries and survey data is available in a form that space could be added as a variable. What is lacking is information from tagging studies needed to provide movement rates. As noted above, however, the technology has significantly advanced and it is timely to consider how these data could be used in spatial population models.

CONCLUDING REMARKS

This report summarizes studies using fisheries statistics on the effects of seismic energy on fish and invertebrate biology. It makes observations on the design and implementation of potential future studies both at the local and population scale. It is hoped that these will stimulate discussion at the March 2011 workshop.

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Video Techniques to Study the Behavioral Reaction of Fish to Sound

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Summary

Video will provide the most detailed view of the immediate behavioral reaction of identified fish species to sound sources in comparison to other currently available techniques. However, video has many limitations, especially in the ocean. A comprehensive study of fish behavioral responses to sound should be founded on carefully framed questions and selection of suitable technology to answer those questions. Undoubtedly, more than one technology will be needed to answer a question.

The most appropriate video techniques will depend on the habitat of the species being studied. For example, gadids such as cod and pollock are not site-attached. Thus, their distribution is not very predictable in comparison to the typical field of view of video. For these species, towed camera systems can augment echosounder survey systems to study the distribution of fish (e.g. Williams et al. 2010), but they will not be as useful to understand immediate reactions on unrestrained fishes. Other species, such as groupers in the Gulf of Mexico that are associated with underwater structure, generally have a much smaller home range, and thus would be easier to study using video techniques. Individuals can be recorded on video for extended periods and behavior such as swimming and courtship activity can be readily captured (e.g. Montie et al. *in press*).

Recommendations

To minimize behavioral artifacts associated with the use of video, the following guidelines are recommended for using video to capture immediate behavioral responses of fish to sounds:

1. Fixed, recording video systems are preferred to those operated by divers or ROV's, because moving objects in the water can affect behavior and divers and ROVs typically have an associated surface vessel, which could also influence fish behavior.

2. Many video recording systems should be employed. Because it will generally not be possible to predict when fish will be in the field of view, many fixed video cameras will be required to increase the probability of capturing behavioral responses to sound exposure.

3. Illumination should either be only natural or red light (after verification that fish do not respond to artificial illumination). Under natural illumination low light video cameras will only be useful during the day, in areas with relatively clear water, and to depths of around 100 m. Artificial illumination could cause changes in fish behavior. Light that fish may not detect (red and infrared) will have limited transmission distance (~1-10 m), but might allow observations at night and at great depths.

Advantages of Video

Video provides unparalleled data on behavioral responses if the fish is in the field of view.

Video can be used to identify many species within a single view.

Most video cameras and recorders also have stereo audio channels, so that sound can be recorded at typical audio sample rates (e.g. 44.1 kHz), and thus provide a record of sound exposure that is synchronized with the behavioral reaction recorded on video. These audio channels will need to be calibrated, and may use non-linear compression techniques. Thus, additional audio recorders using non-lossy compression may need to be deployed to obtain accurate sound measurements.

Platforms

Video is flexible and able to be deployed from a number of platforms including fixed recorders in underwater housings, drop cameras, towed cameras, and cameras on remotely operated vehicles (ROVs). Most use of video for fish studies, involve using cameras with or without bait to augment traditional surveys, whether they be echosounder or visual diver surveys.

Limitations of Video

Light Transmission

The greatest limitations of video to studying fish behavior are related to limited light transmission in the ocean. Most studies using video are in clear water, such as on coral reefs. Visible light is strongly absorbed in seawater, especially at the longer red wavelengths (Figure 1). Thus, many ROV and diver-operated video systems use a white light source to augment natural light. However, artificial white light sources can affect fish behavior and may also attract zooplankton, which may attract fish (e.g. Ryer et al. 2009). Some studies have used red light for illumination, to which most marine fish are not sensitive (Figure 2). However, because red light is strongly absorbed it can only be used over a short range (few meters).
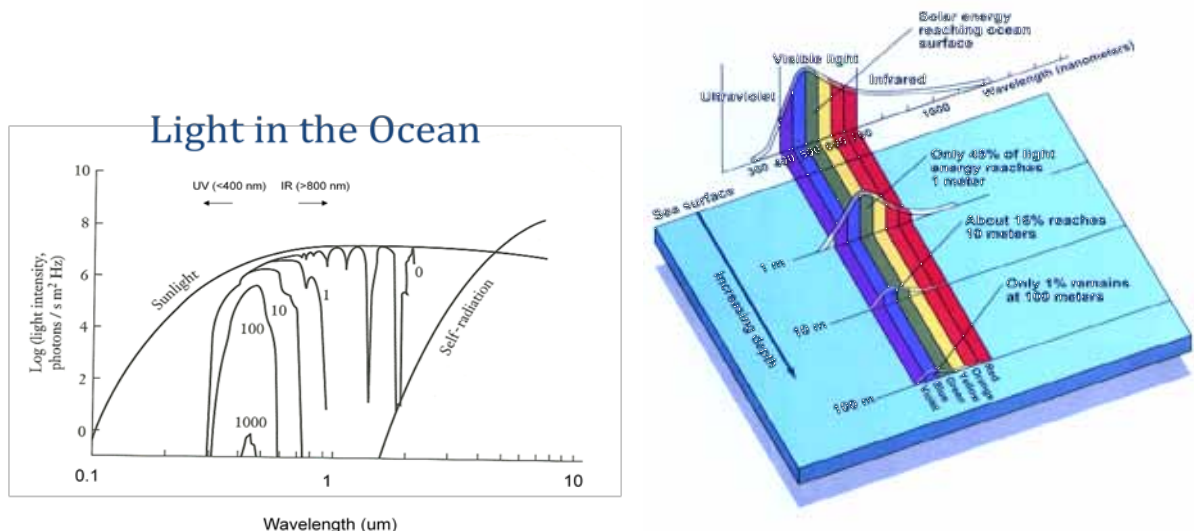
Figure 1. Light intensity as a function of wavelength and depth in the ocean. Visible light is absorbed most strongly in the red wavelengths in seawater (~50% is absorbed in 1 m). Infrared light, which is often used in low light security cameras in air, has very limited illumination distance in seawater. Sources: Dusenbery (1992) and oceansonline.com.
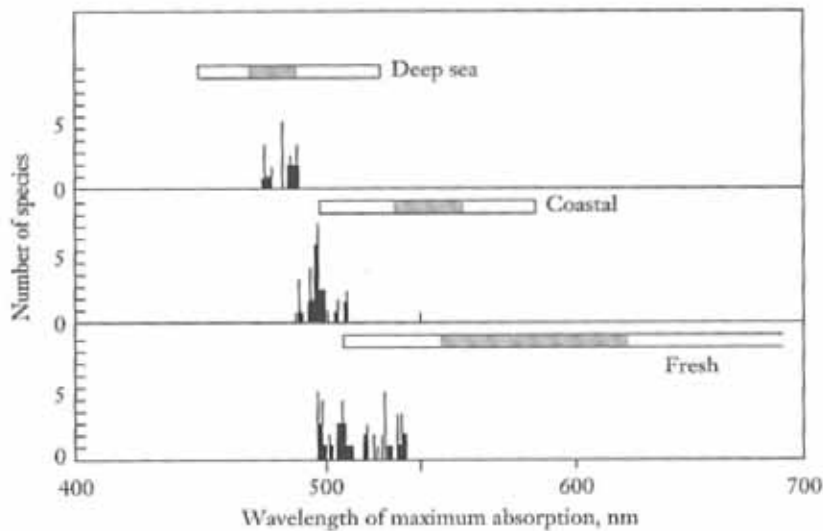

Figure 2. Summary of visual systems of deep-sea, coastal marine, and freshwater fishes.   Red light is about 650 nm. From Dusenbery, 1992.

Field of View

One challenge with remote video is that the field of view may be limited, and the same individual fish may not stay in the video frame prior to and during a sound exposure. This may be less of a challenge

3

with territorial, site-attached fish, but many fishes in locations where E&P sound sources are likely to be present, will not be site-attached. Even with site-attached fish, video can be challenging. To provide an example, we made 25 deployments of video cameras (each capable of recording 24 hours) with black-and-white wide angle lenses (70 degree) focused on red grouper in an attempt to record sound production associated with spawning. While we did record 116 sounds, 56 occurred at night and 35 were recorded when the fish were off camera. We never observed spawning, although there are instances of male and female fish swimming up in the water column (and out of the field of view).

In-air video systems sometimes utilize fish-eye cameras or multiple video cameras to obtain a 360 degree field of view, with software post-processing to transform the image to flat coordinates. Studies of fish using these types of imaging systems have not been made to my knowledge.

Power

The power requirements and bandwidth of recordings makes most deployments of standalone remote recording units relatively short (< 1 day).

Platforms

One issue with platforms is that fish may react to their presence. Moving platforms, such as ROVs, are most intrusive and may on their own cause a behavioral reaction. Fixed cameras, even though they are not moving, add structure that was not present prior to their placement. These effects can be minimized by placing the cameras as long as possible prior to a sound exposure.

Placing fixed cameras is best done by SCUBA divers, because they can visually observe the scene and decide on the best placement. However, diving on compressed air has a limited depth range (about 50 m). Tri-mix diving, while more complicated, extends the range to ~100 m. In some situations, diving can be complicated by extremely cold weather or rough seas. ROV's could be used to place cameras in deep water when it is not practical to use tri-mix divers. However, it can be difficult to run an ROV in deep water without a vessel with dynamic positioning. A third alternative might be development of an over-the-side video system with acoustic releases for recovery. Success of such a system would likely require greater redundancy than diver placed cameras. For depths deeper than 100 m, video using natural illumination will have limited utility due to low light levels.

Data Analysis

The analysis of video data has advantages and disadvantages over other types of data. The advantages are that detailed behavioral responses to sound exposure can be examined for identified fish species. The main disadvantage is that behavioral analysis from video recordings is labor intensive.

Automated video data analysis is an area of active research. But, no system appears to be able to automatically recognize fish species from video. There are techniques to reduce the amount of data that need to be manually analyzed by automatically detecting changes in the background scene (e.g. limit analysis to scenes where motion is detected).

Automated video analysis systems for caged animals and fish are available, where the setup can provide high contrast video (e.g. Ethovision from Noldus) and enable automated tracking and statistical analysis of these tracks. There are a few examples using caged fish in behavioral reaction studies using video (Popper et al., 2007; Kastelein et al. 2008). One critique of these types of studies is that the behavior of the fish may be affected by caging. However, this is generally the only way that fish can be exposed to a controlled sound field. Caged fish are a reasonable approach for initial studies of reflex behaviors, such as C-start escape behavior. However, a lack of reaction in caged fish does not mean that the same behavior would be observed in uncaged fish.

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Relevant Websites

Note this is not a comprehensive review of underwater video websites, but is intended to provide information on what is typically commercially available.

Drop cameras, wired cameras

These camera systems are hard-wired to a monitor and video recording system, and thus generally require a boat to be present to make observations.

www.seaviewer.com

www.splashcam.com

www.seaview.com

jwfishers.com

ROVs with integrated video

Small ROVs typically have a color and/or black and white camera onboard with a tether (either copper or fiber optic) back to a control box with real-time video.

sharkmarine.com

seabotix.com

videoray.com

jwfishers.com

Underwater Cameras (for ROVs)

deepsea.com   (Deep Sea Power and Light)

www.rosys.com

Camcorders with Underwater Housing

Many of these companies will mount a custom bulkhead connector in the video housing for attachment of an external hydrophone. Not all camcorders have an external microphone input jack. Camcorders are generally color, and are not very sensitive in low light. Camcorders record either onto flash cards or hard drive (e.g. Sony up to 240GB hard drive). Typical minimum illumination is 1-3 lux. Camcorders would be useful in high light situations (clear, shallow water).

www.gateshousings.com

ikelite.com

oceanimagesinc.com

Low Light Black and White Cameras

These cameras are commonly found in applications related to security (may be used with IR illumination—but IR does not travel underwater). We have used these cameras without additional illumination at 100 m. Low light cameras require a DVR system such as ChaseCam (below).

> SONY HAD black and white; Sensitivity**:** 0.0003 lux; 70 degree viewing angle
>
> http://www.spycameras.com/item,hrc-20hex,b-w-00003-lux-high-res-board-lens-camera.html

Video Recorders (such as DVRs that allow connection of external cameras)

> Record onto flash cards or hard drives using an external camera.
>
> ~24 hours record duration with a compressed video format with a 32 GB flash card.
>
> It is possible that battery powered, multi-channel DVRs which are typically used for security camera systems could be used to record video from many cameras to obtain nearly 360 degree field of view.
>
> www.chasecam.com