National Physical Laboratory

NPL Report AC 13

# Summary report of NPL workshop on underwater acoustic vector sensing 2014

Edited by Tanja Pangerc and Pete Theobald

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National Measurement System

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# Summary report of NPL workshop on underwater acoustic vector sensing 2014

Edited by Tanja Pangerc and Pete Theobald
National Physical Laboratory

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**Background on project and funding**

This document provides a summary of the underwater acoustic vector sensing/particle motion workshop, organised by the National Physical Laboratory (NPL), UK, which took place at NPL on 27 November 2014, and was funded through the National Measurement System, Acoustics and Ionising Radiation Programme. This document aims to summarise the main discussion outputs, in addition to providing an outline of possible recommendations towards achieving a more holistic representation of particle motion in aquatic environments, and is not intended to be a verbatim report of the workshop discussions. The report summary is intended to be used as the basis for identifying a road map for 'particle motion'.

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Approved on behalf of NPLML by Giuseppe Schettino, Divisional Knowledge Leader

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# 1 INTRODUCTION

The measurement of underwater sound generally refers to the measurement of sound pressure in the water, primarily because the hydrophone, used to measure sound, is a pressure sensitive device. Marine mammals are sensitive to sound pressure in the water much the same way as land mammals are sensitive to sound pressure in air. However, it has long been understood that fish respond to particle motion in water, and there is increasing understanding that at least some marine invertebrates are also sensitive to particle motion.

Many aquatic habitats are exposed to anthropogenic activities, which often produce radiated acoustic energy, generally into the water, and sometimes into the seabed. Examples span a range of activities including commercial fishing, boating, naval operations, shipping, offshore construction, energy generation, explosive discharge, marine surveying and resource exploitation.

The potential for offshore activities to impact aquatic life is recognised in the European Commission's (EC) Marine Strategy Framework Directive (MSFD) within Descriptor 11 for achieving Good Environmental Status (GES) with respect to underwater noise and other forms of energy. Under the MSFD, Member States are required to take steps to achieve or maintain Good Environmental Status for each of the descriptors by 2020. A technical subgroup has proposed advice and options for the implementation of MSFD Descriptor 11 through two indicators for underwater noise, relating to loud impulsive sounds, and ambient noise levels, respectively. In addition, national regulations can require environmental impact assessment (EIA), and monitoring of underwater noise for offshore developments. In general, existing regulation requires consideration of the sound pressure. The requirement to consider sound particle motion and seabed vibration is less clear, with no specific regulatory requirement to assess or monitor sound particle motion currently in existence.

Any effort to reliably describe the response of particle motion sensitive organisms to underwater sound, understand the impact of anthropogenic noise on marine species, and quantify the levels of sound associated with a particular effect, requires a reliable characterisation of the sound particle motion in the water column and vibration of the seabed.

For the purposes of this report, the term vector sensing refers to the measurement of acoustic vector quantities (*e.g.* sound particle displacement, sound particle velocity, sound particle acceleration, or sound intensity), and the instrumentation designed for the measurement of such quantities. The term particle motion is used to refer to the instantaneous motion (*e.g.* velocity, displacement or acceleration) of a material element due to the action of vibration or sound waves, specifically in the water column, along the interface between the seabed and the water, or within the seabed.

## 2 WORKSHOP AIMS AND CONTEXT

The overarching aim of the workshop was to facilitate a discussion between biology and acoustics experts with the intention to: i) outline the principal information/ knowledge gaps, and requirements relating to particle motion in aquatic environments, and ii) identify ways forward to address these knowledge/data gaps.

The workshop was structured to achieve this through a number of key questions, which were addressed during a series of presentations, a panel discussion, three parallel group discussions, and a plenary session. The discussion was generally guided by the following key questions:

- Do we need to quantify particle motion, and why?

- What are the main obstacles preventing us from quantifying particle motion? How can we make progress to remove these obstacles?

- What are the priorities for examining the sound detection abilities of fishes and invertebrates? How can we achieve a better understanding of the mechanics and physiology of particle motion detectors in fishes and invertebrates? How do we translate this to an understanding of impact?

- Under what circumstances is measurement of particle motion required? What are the measurement challenges? What steps are required to take this forward?

The workshop provided an opportunity for a dedicated, cross-disciplinary, expert group discussion, focused on the needs and requirements for reliable quantification of underwater particle motion (sound particle motion in the water column and particle motion of the seabed), in the context of anthropogenic underwater noise.

## 3 PRESENTATIONS

Four foundation talks, and an additional short talk, were presented to inform discussion during the workshop.

The workshop presentation session outline, in chronological order, was as follows:

- Tony Hawkins on ‘Biological drivers for particle motion measurement’
- Michael Ainslie on ‘Sound, particle motion and sound intensity’
- Dick Hazelwood on ‘Part I. Circular water particle motion and ground roll – how should we assess this? Part II. Testing the bio-sensitivity – a potential solution?’
- Markus Linné on ‘The FOI particle motion sensor - a technical viewpoint’
- John Dalen on ‘Sound exposure and its level’.

Copies of these presentations are provided in Annex A. The slides have been reproduced with the permission of the presenters.

# 4 PANEL DISCUSSION - 'DO WE NEED TO QUANTIFY PARTICLE MOTION, AND WHY?'

The requirement to quantify particle motion in the marine environment was acknowledged in a consensus view by workshop participants.

Various applications that rely on the measurement of vector parameters were identified, notably directivity measurements employed by the oil and gas industry, and in naval surveillance, where vector sensing is common practice. The primary area where particle motion measurement is required, but currently not realised, was recognised to broadly correspond to the research into environmental effects from particle motion on fish and aquatic invertebrates. The foundation presentation on '*Biological drivers for particle motion measurement*' by Tony Hawkins outlined the origins of this concern, highlighting that the research into fish sensitivity to particle motion dates back to the late 1960s and 1970s.

Further need for particle motion to be quantified was highlighted in the regulatory context, and with respect to the management of human activities that affect ecosystems and fisheries (for example, fisheries for invertebrates like the Norway lobster *Nephrops norvegicus*, and fishes like the mackerel *Scomber scombrus*), with concerns for economic and ecosystem-scale impacts.

The discussion focussed on two main points:

I) The expected spatial scale of the effect in relation to fish and aquatic invertebrates, and requirements of the European Commission's Marine Strategy Framework Directive (MSFD); and

II) The desired balance between modelling and measurement to fulfil the requirement to quantify particle motion.

Descriptor 11 of the MSFD for Good Environmental Status (GES) does not explicitly prescribe that particle motion, as one of the parameters to describe underwater noise, needs to be monitored.

In a 2010 Commission Decision, the European Commission produced a set of detailed criteria and indicators to help Member States determine what each descriptor means in practice and measure progress. Two indicators, one for impulsive sound sources and one for ambient noise were put forward by the Commission, based on the advice of a technical subgroup (TG11). Particle motion was suggested as a parameter of relevance during the early stage of discussions of TG11. However, that group did not consider particle motion of sufficient importance to include it as an indicator (see Tasker *et al*., 2010[1]). The Commission Decision on indicators to describe GES will be revised regularly, and this will likely happen in 2015/2016. In addition, while the Directive itself is not intended to be revised in the near future, there is a 6-year cycle in which EU Member States should revise assessments and environmental targets. In the ongoing revision process, the present set of indicators will be evaluated, and experts from EU Member States are being consulted on the usability of the present set of indicators and the need for further indicators. The new EU technical subgroup TG Noise is assisting in this revision process, and has produced a rationale to determine whether new indicators are needed. The present status of noise monitoring in European marine waters is that there is still no structural monitoring in place, and the vision of the European Commission (and of most EU Member States) is that starting monitoring programmes, making use of the first two indicators, should have priority over introducing additional indicators. It is therefore unlikely that there will be large scale monitoring making use of a particle motion indicator within the scope of the MSFD within a few years. That does not exclude the possibility that particle motion can be monitored, *e.g.*, for impact assessments of licensed activities such as piling and seismic surveys, however, this would then be guided based on other legislation. If

1 Tasker M.L., Amundin M., André M., Hawkins A., Lang W., Merck T., Scholik-Schlomer A., Teilmann, J., Thomsen F., Werner S., and M. Zakharia (2010) *Marine Strategy Framework Directive – Task Group 11 Underwater noise and other forms of energy*, EUR 24341 EN – Joint Research Centre, Luxembourg, p. 55.

information collected in such assessments shows that a particle motion indicator would have sufficient added value, particle motion can be taken up as an additional indicator in the next MSFD cycle.[2]

Much of the discussion of the panel focussed on the spatial scales where particle motion is expected to have an impact on sensitive marine life (distance, area), and the circumstances where the free-field plane-wave relationship between sound pressure and particle motion breaks down. The latter formed the second part of the panel discussion (see below).

It was noted that the work by Hawkins *et al.* (2014)[3] had reported mackerel response to acoustic stimuli, a species believed to respond to particle motion rather than sound pressure, and that the sound levels at which the response was observed would be expected to occur at considerable distances (many kilometres) from the specific sound source (impact pile driving operation).

Further discussion highlighted a number of key data gaps, where limited or no information exists:

- Information on ambient noise particle motion values, and levels for particle motion associated with specific sound sources, both along the seabed, and in the water column;
- Knowledge and understanding regarding expected reactions from marine life to particle motion, and the levels at which such response would occur (*i.e.* detection thresholds and sensitivity); and
- Understanding of the expected spatial dimensions of impact from particle motion.

With respect to environmental impact assessments (EIA)/consenting, and general regulatory advice, the requirement for informed decisions regarding the nature of impact was highlighted. This was substantiated by a further acknowledgement that no well-defined structure or system currently exists for assessing the impact of noise/human offshore activities on fish, as is the case for marine mammals and birds.

In summary, it was agreed that there is a requirement for i) focussed studies that will provide an indication of the expected amplitudes associated with particle motion in aquatic environments, and ii) concerted efforts towards characterising any impacts, and associated implications from exposure to particle motion.

The remainder of the panel discussion focused on propagation modelling, and the requirement to perform measurements. It was highlighted that quantifying sound particle motion in the water using numerical modelling solutions would be a reasonable approach in much the same way as this approach is suitable for applications where sound pressure needs to be quantified. In the foundation presentation on '*Sound, particle motion and sound intensity'* Michael Ainslie showed that the existing propagation modelling approaches, generally used to describe the sound pressure component of the sound field, can be used as the basis to extract values for particle motion in the water column from calculation of pressure gradient, assuming that sufficient resolution is used in the calculation. The prospect of modelling particle motion raised a number of points of discussion, with the key points captured in the following conclusions:

- Extraction of sound particle motion from acoustic propagation models is not widespread and not routinely provided as outputs by existing models;
- Modelled results require validation with measurements of particle motion; and
- Ocean propagation models are often 'simple' in their representation of the seabed (*i.e.* often do not support shear forces), and more detailed models might be required. This highlighted a further requirement for fully characterised seabed properties to support the modelling.

2 This paragraph contains supplementary information, in addition to that discussed at the workshop.
3 Hawkins A. D., Roberts L., and S. Cheesman (2014) *Responses of free-living coastal pelagic fish to impulsive sounds*, Journal of the Acoustical Society of America, 135, 3101-3116.

In terms of measurements, there was general agreement that the characteristics of seabed vibration are not widely known or understood, and hence measurements would be desirable, and it was further acknowledged that specialised equipment would be required. In relation to impact assessments, it was noted that measurements ought to be considered only if the risk assessments indicate large scale impacts (*i.e.* several km).

The discussion relating to the measurement of particle motion in the water column was mostly focused on the understanding of the relationship between sound pressure and sound particle motion within the water column, and whether particle motion always needed to be measured 'directly', *i.e.* under which circumstances would plane wave approximation be insufficient. It was further suggested that although the simple plane-wave relationship between sound pressure and particle motion breaks down in the interference regions (near field, and close to boundaries), the discrepancy might sometimes be less significant than it appears. In regions of destructive interference (nulls in the interference pattern), the cancellation for vector quantities tends to be less complete than for a scalar quantity such as pressure, leading to a greater relative difference between the particle velocity value and that predicted from a plane-wave relationship.

The following possible reasons were proposed as the main causes for the measurement of sound particle motion being a restricted activity, rather than a routine measurement; a) measurement historically not deemed important, b) general equipment unavailability, c) data analysis and interpretation not readily available or understood.

It was further postulated that measurements cannot be realised everywhere, and may not always be required, and it was suggested that using validated prediction tools might be an appropriate alternative. This may particularly be the case when considering wider scale effects, for MSFD for example. It was also pointed out that the seismic industry routinely acquires particle motion data, however, the equipment is elaborate, and the measurement associated with a considerable cost.

Overall, there was a clear desire to improve the confidence in modelling tools, and obtain validation data, and it was suggested that particle motion data held by the oil and gas industry might provide some opportunities for validation and quantification of particle motion under those conditions.

In general, the mutual reliance of biology and acoustics was recognised, with the requirement for better overlap in expertise. At present, the understanding from biology is needed to inform the requirements for measurement and modelling, which in turn is required to support research programmes focused on improving the understanding of hearing abilities, sensitivities and potential impacts to particle motion sensitive receptors.

**Key conclusions from panel discussion:**

- There is limited data on ambient noise values for particle motion, and levels within the sound fields associated with specific sound sources, both, along the seabed and in the water column.
- There is limited knowledge and understanding regarding expected reactions from marine life to particle motion, and the levels at which such response would occur (*i.e.* hearing thresholds and sensitivity).
- There is little understanding of the expected spatial dimensions of any impact from particle motion.
- There are no well-defined criteria for assessing noise impacts on fish, similar to those available for marine mammals and birds[4].

4 Editors' note: recent expert panel review (see Popper *et al*., 2014) considered existing information too limited to derive a set of sound exposure criteria for fishes akin to the Southall *et al.* (2007) framework for marine mammals, although where deemed appropriate Popper *et al.* provided guidance on likely threshold levels, or otherwise indicated the relative risk of an effect occurring.

- Numerical modelling of particle motion has been demonstrated, but is not commonly performed.
- Further work is required to take into account the effects of seabed (also applies to the sound pressure field).
- Predictive tools/models require validation (existing data might be acquired from the oil and gas industry to facilitate cost-effective validation).
- A requirement exists for increased involvement of acousticians in projects involving effects of sound on fish, in order to advise on the conditions and applications when the plane wave approximation cannot reliably be used to quantify particle motion from sound pressure measurements.

## 5 FOCUSED GROUP FEEDBACK AND DISCUSSION

Each break-out group was presented with a specific set of questions as follows;

A. *What are the main obstacles preventing us from quantifying particle motion? How can we make progress to remove these obstacles?*

The key points from group A in response to the above questions were that:

- Modelling methods and measurement instruments are available, although the main obstacle to their use is the requirement of specialist knowledge, and in some cases, the cost associated with them;
- Lack of funds and time has hindered the development of tools in this area which are required to bring down the cost;
- There is limited access to survey data which could be used in propagation models and for their validation;
- There has been a lack of collaboration between acoustic and biology expertise, which requires partnering in research projects and programmes;
- There is a need for greater understanding of the requirements, which should be overcome with greater collaboration, training *etc.*;
- There is limited measurement and modelling experience with regard to particle motion, requiring research and experience to enable standards to be developed;
- Lack of instrument calibration specification means that traceable measurements cannot be made.

B. *What are the priorities for examining the sound detection abilities of fishes and invertebrates? How can we achieve a better understanding of the mechanics and physiology of particle motion detectors in fishes and invertebrates? How do we translate this to an understanding of impact?*

The key points from group B in response to the above questions were that:

- There is an essential requirement for the reliable quantification of particle motion, particularly near the seabed and near the surface, where most of the biomass expected to be sensitive to particle motion resides;
- There is a need to prioritise effort/research on the sensitivity and detection abilities of fish and marine invertebrates. The selection of representative species may provide a possible solution; with potential selection criteria for particle motion sensitive species being: i) environmental protection status of the species; ii) commercial importance; iii) ecological significance (*e.g.* stage in the food web and 'ecosystem services' of the species); iv) reliance on sound by the species (*e.g.* vocal species, species known to rely on sound);
- There is a need to understand the nature of the effect of/response to particle motion and the associated level;
- There is a need to understand the scale of effect (*e.g. how might any observed effects have impacts upon animal populations and ecosystems; what are the spatial scales of certain impacts (e.g. distance from the sound source)*);
- Effort should be directed towards examining larger scale impacts, and studies are required for a variety of sound sources to inform the potential for impact.

C. *Under what circumstances is measurement of particle motion required? What are the measurement challenges? What steps are required to take this forward?*

The key points from group C in response to the above questions were that:

- In many cases sound particle motion in the water column can be derived from the measurement of sound pressure, and that even in shallow water for example, approximations might be reasonable;

- Relative impedance modelling (see presentation 2) may be used to show areas where there is a deviation from a plane wave approximation of particle motion; the deviations occurring as a result of pressure cancellation (*i.e.* a reduction in pressure levels, rather than an increase in particle motion) are due to pressure being a scalar quantity that experiences cancelling much more readily than particle motion, as a vector quantity;
- The circumstances primarily requiring measurement of particle motion are in the near-field and in shallow water (including tanks);
- Understanding the coupling of sensors to either the water column or seabed is a particular challenge;
- Understanding/measurement of seabed vibration, and its re-radiation into the water particularly in relation to pile-driving is essential;
- An understanding is required of the frequency range, noise floor and sensitivity requirements of the instrumentation, which may be further informed by the biological drivers. The frequency range between a few hertz to a few hundred hertz is understood to be the most likely range where particle motion measurement is necessary;
- There will be a requirement for measurement standards for particle motion, and for standards for the calibration of the measurement instruments;
- There exists significant expertise within the oil & gas/seismic industry, which should be exploited.

Potential options for funding were identified as i) the European Union, in particular the Horizon 2020 framework, ii) national research funding bodies, and iii) the Offshore Renewable Energy (ORE) Catapult (UK). A potential collaborative route forward, through the ORE Catapult, was proposed by Steve Simpson, building on existing work led by Exeter University (Rick Bruintjes).

## 6 SUMMARY

The existing information on particle motion in aquatic environments is mainly limited to particular specialist applications, such as geophysical surveying and naval surveillance. There is a requirement to increase the knowledge base and progress our understanding into the effects of noise on aquatic organisms.

There is a specific concern relating to potential impacts of particle motion on fishes and marine invertebrates, many of which are of considerable ecological, and/or commercial importance.

A number of research requirements and priority actions have been identified that will help establish a roadmap to quantify particle motion in the marine environment:

- There is a requirement for coordinated effort to quantify (through measurement and modelling) particle motion in the aquatic environment, which should include sound particle motion in the water column, and particle motion at the seabed.
- There is a requirement to increase confidence in modelling outputs through validation of models used for particle motion prediction (existing underwater acoustic propagation models from which particle velocity can be extracted). A possible solution might entail using existing measurement data of particle motion (*e.g.* from the oil and gas industry (although these typically have a limited frequency range between 3 Hz and 200 Hz)). The relationship between sound particle motion and sound pressure needs testing in shallow water environments.
- There is a requirement for better accessibility to practical particle motion measurement instruments, readily available data acquisition systems, and analysis tools. Development of cost-effective, readily usable sensors is considered a fundamental issue inhibiting data collection.
- There is a requirement for structured monitoring programmes in different environments, and for those sound sources where particle motion may be of particular significance.
- Improved understanding is required of the detection and sensitivities of fish and aquatic invertebrates, the levels at which effects occur, and the scales at which impact occurs. This might be best achieved using representative particle motion sensitive species selected using a criteria design assessing their: i) environmental protection status; ii) commercial importance; iii) ecological significance; iv) reliance on sound.
- There remains a requirement to grow the knowledge base to guide future research, and also to inform management, regulation and policy decisions.
- Guidance is required on measurement methodology, deployment, data analysis and reporting, and standard procedures for particle motion measurement.
- Calibration and associated standards for calibration of instrumentation are required to provide traceable measurements.
- Training, knowledge transfer and collaboration are important between the technical specialists, particularly acousticians and biologists, and also practitioners in the seismic industry, and between research scientists and management, regulation and policy decisions makers.

## 7 REVISION OPPORTUNITIES

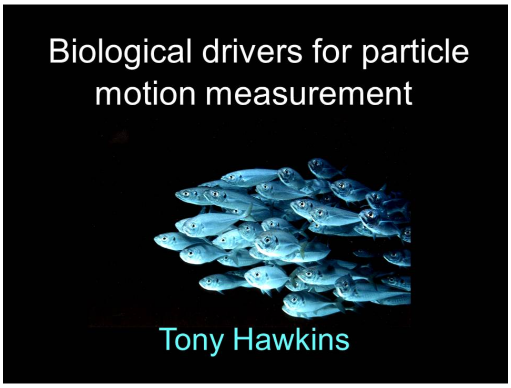
The workshop was set up to identify knowledge gaps across the relevant disciplines and highlight particular challenges to inform actions, and point to possible research steps to address these knowledge gaps and challenges. In light of this, it is intended to hold a follow up meeting within 18 to 24 months, which would be organised jointly by NPL and TNO.

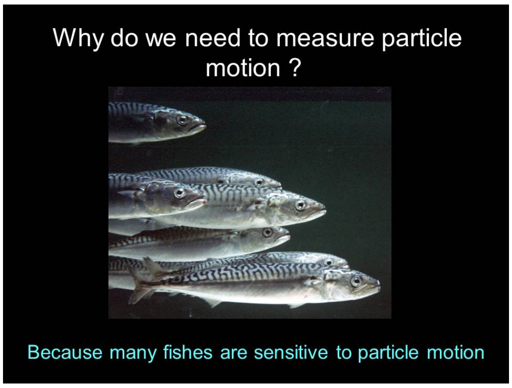
## 8 ACKNOWLEDGEMENTS

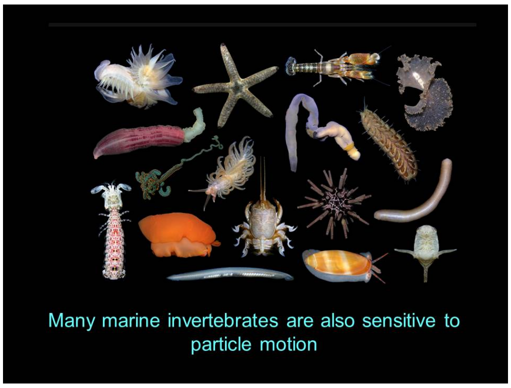
NPL would like to thank all the workshop attendees for their participation and valuable contribution. NPL would particularly like to acknowledge the help and assistance of Tony Hawkins and Michael Ainslie in planning and organising the workshop; Tony Hawkins, Michael Ainslie, Dick Hazelwood, Markus Linné and John Dalen for their time and effort in preparing and presenting their talks; Stephen Robinson and René Dekeling for chairing during the workshop, and Paul Lepper, Paul White and Frank Thomsen for leading the breakout groups, and the feeding back during the plenary session. NPL would also like to thank everyone who provided comments during the drafting of this report.

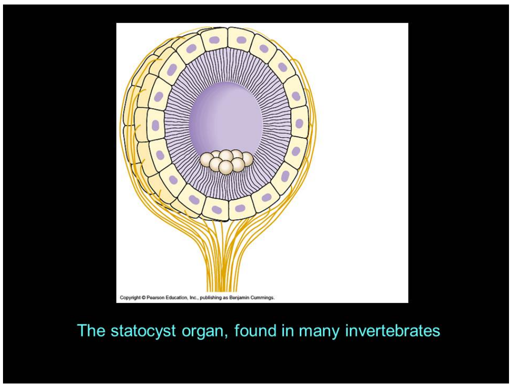
# 9 Annex A – Images of PowerPoint presentations

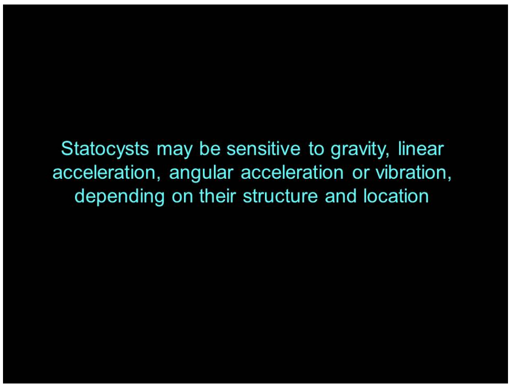
## Presentation 1: Tony Hawkins - Biological drivers for particle motion measurement

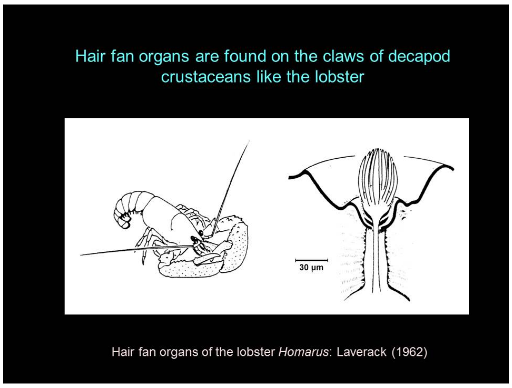


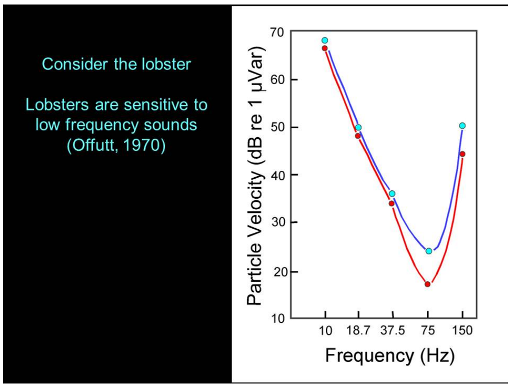



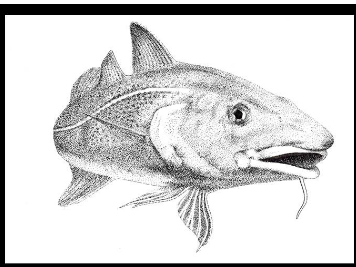



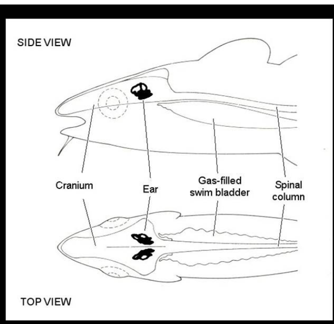



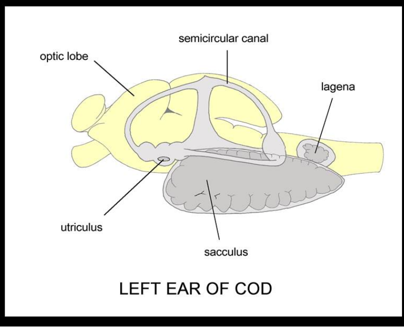



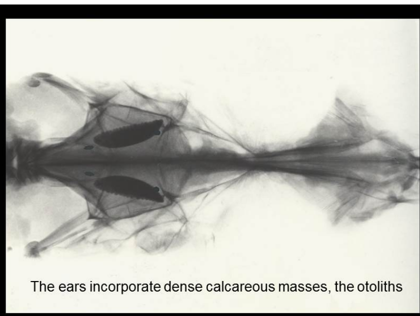
Fish have ears, but they are not visible externally



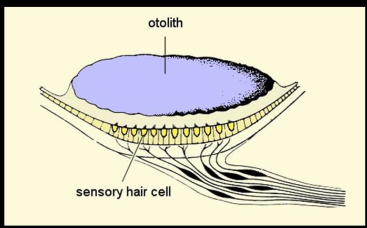

The cod ear

## Structure of cod ear

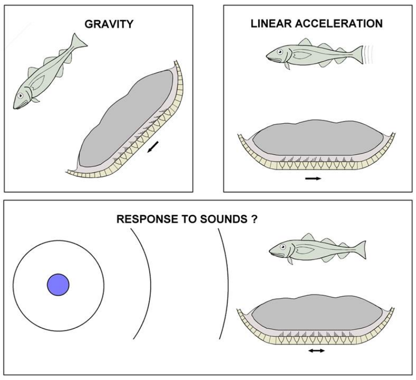


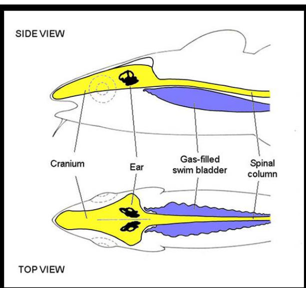




X-ray of cod head




Each otolith sits on a bed of sensory hair cells




It has been suggested that the otolith organs are sensitive to particle motion but those fish with gas-filled spaces close to or connected with the ear are sensitive to sound pressure

## How well can fish hear ?

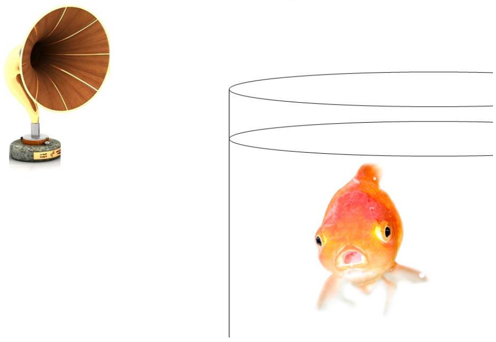
Von Frisch (1936) trained fish to respond to sounds

However, van Bergeijk (1964, 1967) queried whether the magnitude of the particle motion was ever sufficient to stimulate the otolith organs

He suggested that only only fishes with swimbladders coupled to the ear could detect sounds – responding to sound pressure

How can we present sounds to fish under good acoustic conditions and examine the effects of both sound pressure and particle motion?

Let's do some hearing experiments !



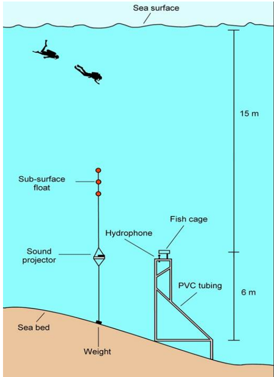
## Experiments in the sea

Three groups rejected experiments under poor acoustic conditions and went on to examine the hearing of fish in the sea, where particle motion can be estimated:

Enger & Andersen (1967) in Norway

Schuijf (1972), from Utrecht, working in Norway

Chapman & Hawkins (1973) in Scotland

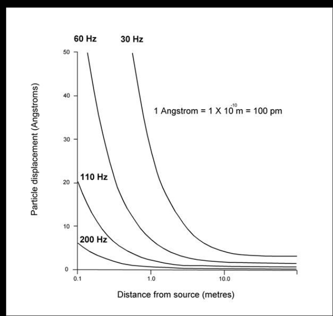



Chapman and Hawkins used measurements of sound pressure to estimate the particle motion

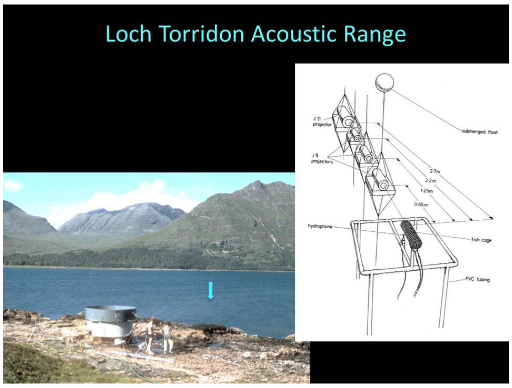
Under free-field conditions, distant from the source, the relationship between *sound pressure* and *particle velocity* is described by the plane wave equation

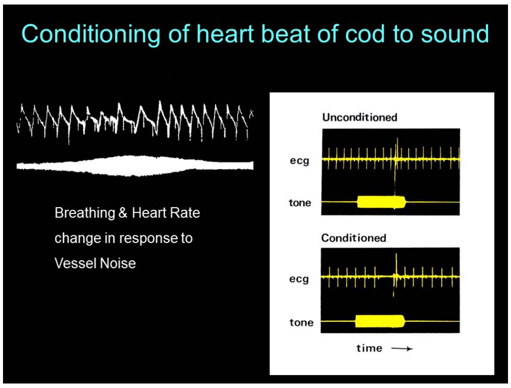
Close to a source the particle motion is described by the spherical wave equation

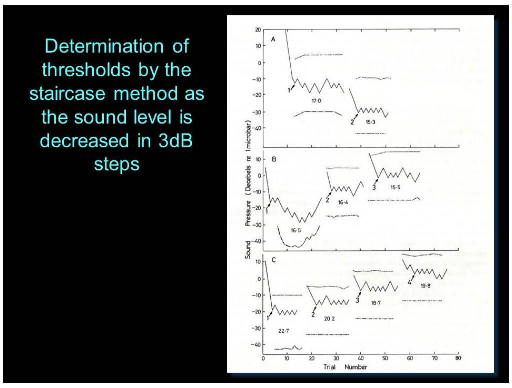
## The near-field effect

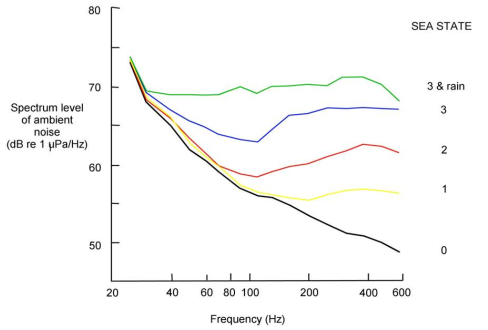



Displacements for a sound pressure of 100 dB re 1 µPa

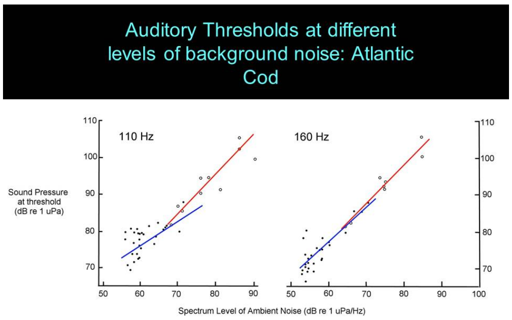



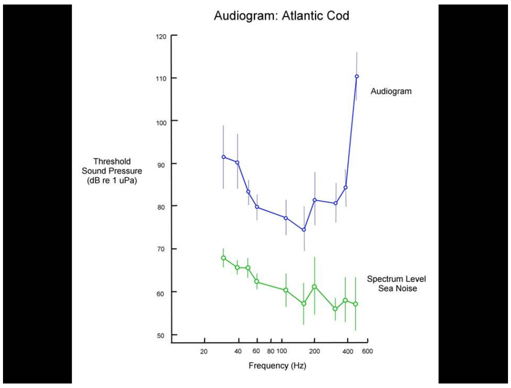



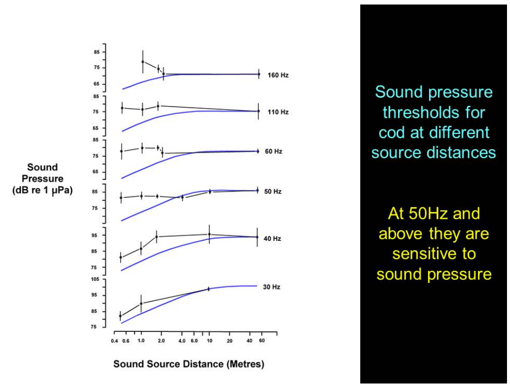




Ambient noise spectra at Loch Torridon at 15 m depth



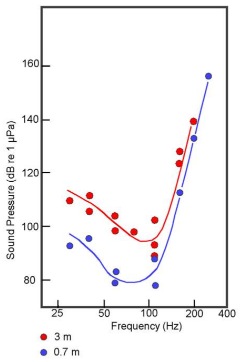

Relationship between Auditory Thresholds and Spectrum Level of Noise for Atlantic Cod *Gadus morhua*



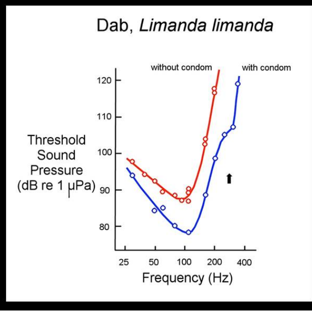



Sound pressure thresholds for the dab *Limanda limanda* at 0.7 metres and 3.0 metres from the sound source

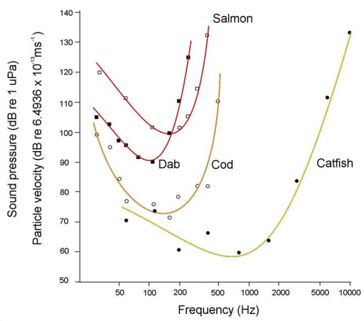
The dab is sensitive to particle motion



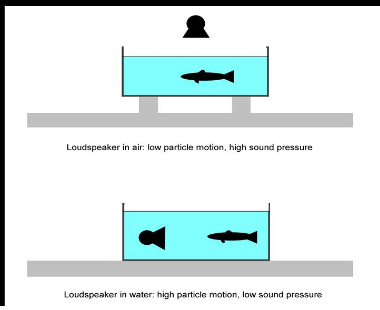

Chapman & Sand (1974): Effects of an inflated condom on hearing in the dab

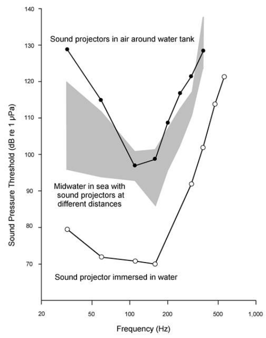



Fish audiograms obtained under good acoustic conditions

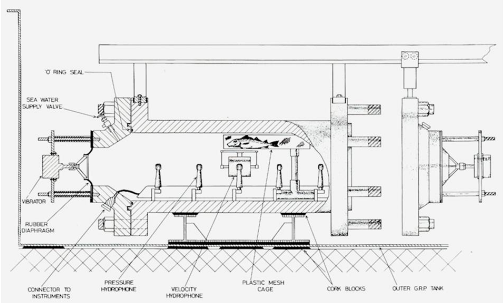



Can similar experiments be done in tanks?



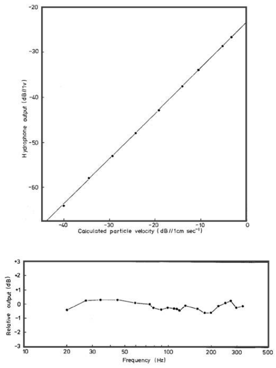




Sound pressure thresholds for salmon under different acoustic conditions

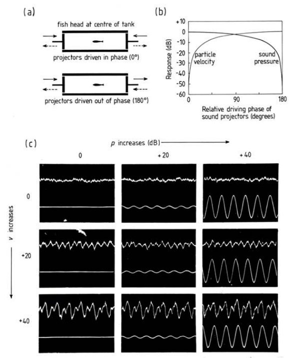


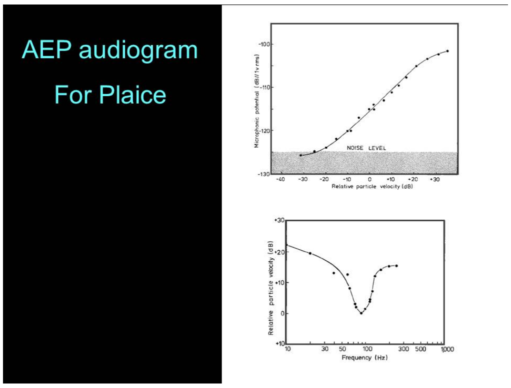

Special acoustic tanks can be built, (Hawkins & McLennan. 1976)

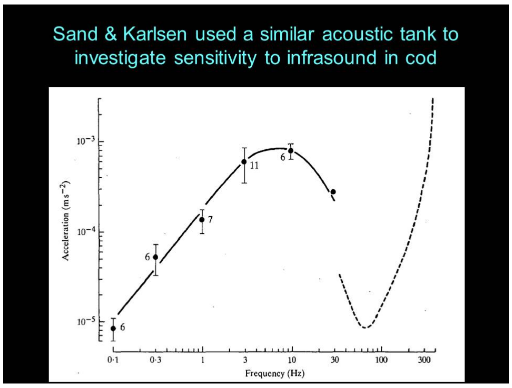
Calibration of Velocity Hydrophone

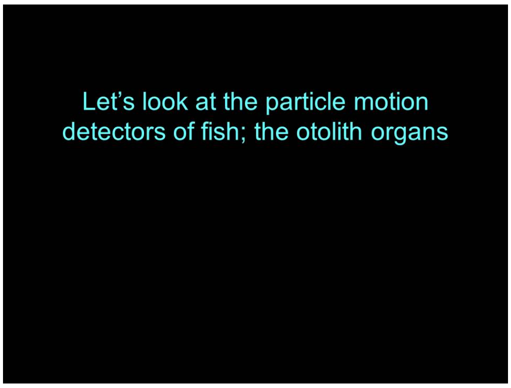


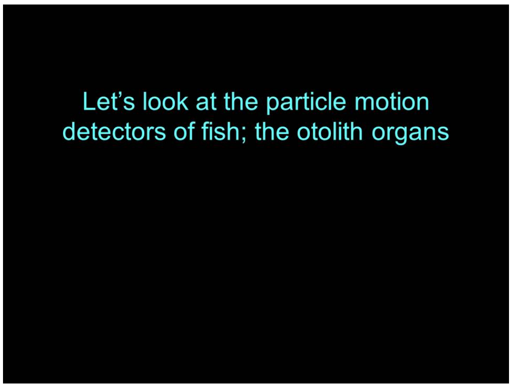

Response to Particle Motion in Plaice

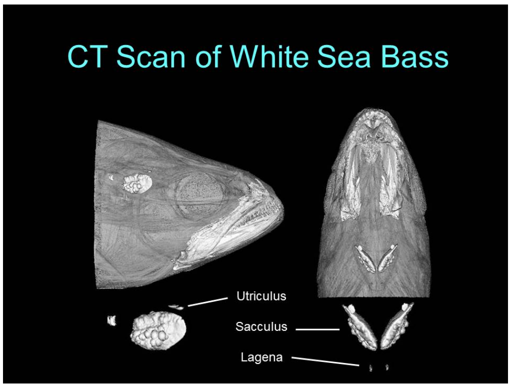


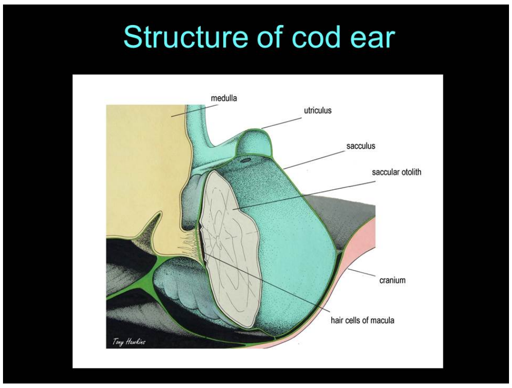

AEP audiogram
For Plaice
NOISE LEVEL
Relative particle velocity (dB)
Frequency (Hz)

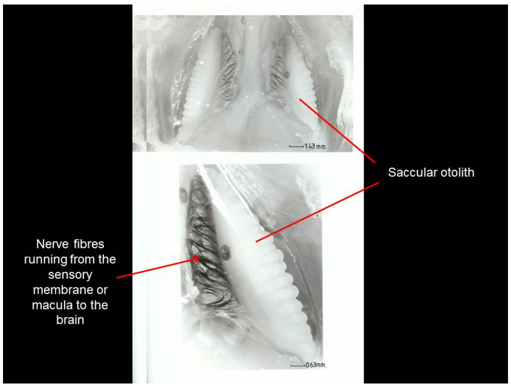

Sand & Karlsen used a similar acoustic tank to investigate sensitivity to infrasound in cod
Acceleration (m s$^{-2}$)
Frequency (Hz)

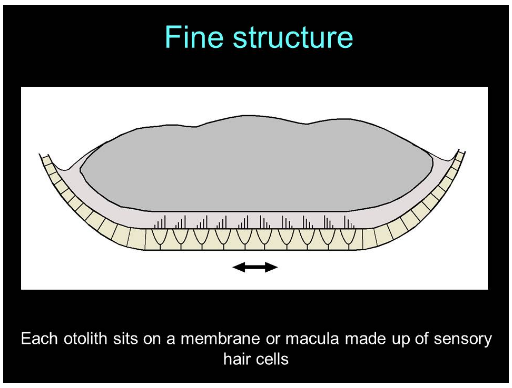

Let's look at the particle motion detectors of fish; the otolith organs

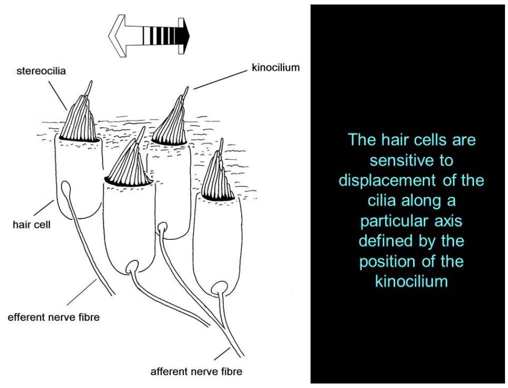

Let's look at the particle motion detectors of fish; the otolith organs

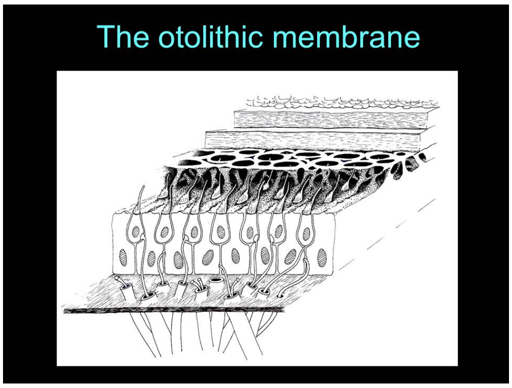

CT Scan of White Sea Bass
Utriculus
Sacculus
Lagena

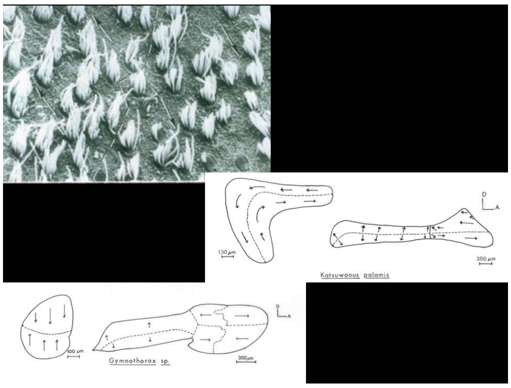

Structure of cod ear
medulla
utriculus
sacculus
saccular otolith
cranium
hair cells of macula

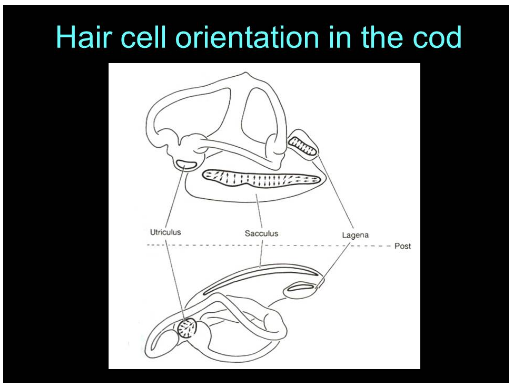

Saccular otolith
Nerve fibres running from the sensory membrane or macula to the brain

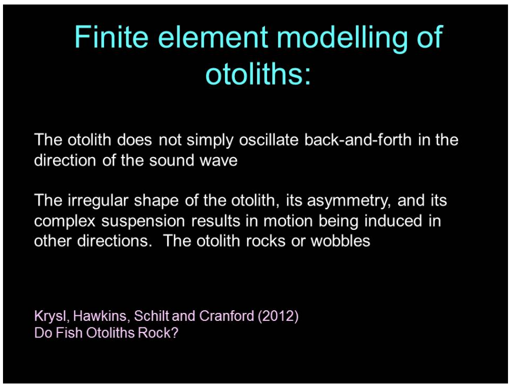

Fine structure
Each otolith sits on a membrane or macula made up of sensory hair cells

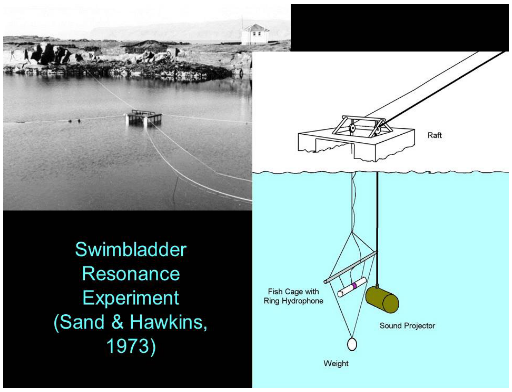

stereocilia
kinocilium
hair cell
efferent nerve fibre
afferent nerve fibre
The hair cells are sensitive to displacement of the cilia along a particular axis defined by the position of the kinocilium

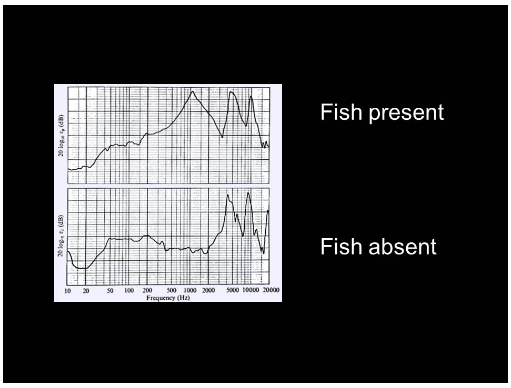

The otolithic membrane

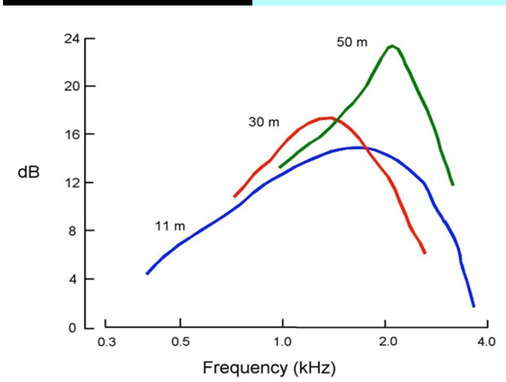

Katsuwonus pelamis
Gymnothorax sp.


Hair cell orientation in the cod
Utriculus
Sacculus
Lagena
Post

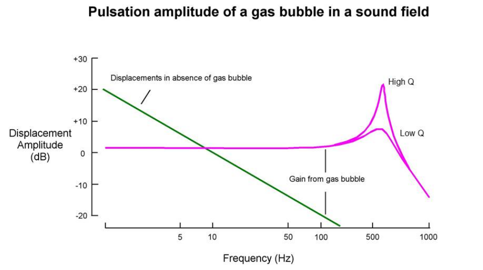

Finite element modelling of otoliths:
The otolith does not simply oscillate back-and-forth in the direction of the sound wave
The irregular shape of the otolith, its asymmetry, and its complex suspension results in motion being induced in other directions. The otolith rocks or wobbles
Krysl, Hawkins, Schilt and Cranford (2012)
Do Fish Otoliths Rock?


Raft
Fish Cage with Ring Hydrophone
Sound Projector
Weight
Swimbladder Resonance Experiment (Sand & Hawkins, 1973)


Fish present
Fish absent
Frequency (Hz)


50 m
30 m
11 m
dB
24
20
16
12
8
4
0
0.3
0.5
1.0
2.0
4.0
Frequency (kHz)

## Effect of swim bladder (Sand & Hawkins, 1973)

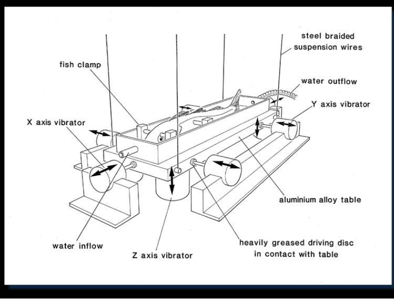



## We now know that:

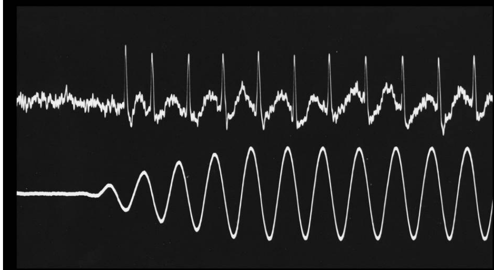
- Fish can hear and fishes with swimbladders can generally hear better than those without
- Fish can discriminate between sounds of differing amplitude and frequency and filter out sounds from a noisy background
- Fish can discriminate between sounds from different sources in the horizontal and vertical planes, and even at different distances

How do they determine sound direction?

## How do the otolith organs respond to sound direction ?

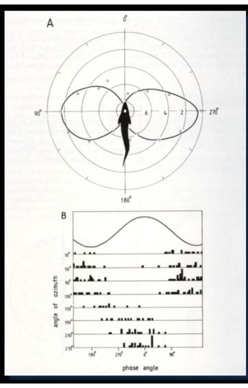



## Primary Auditory Units



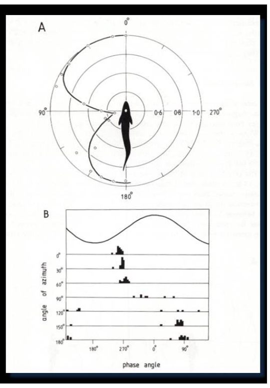
## Utricular Unit

(Hawkins & Horner, 1981)




## Saccular Unit

(Hawkins & Horner, 1981)

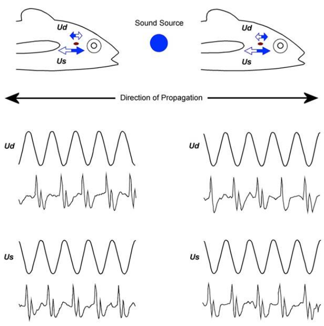



The otolith organs are directional in their response, so fish can determine the direction of a source through vector weighing (Enger, Hawkins, Sand & Chapman, 1973)

But vector weighing is subject to a 180 degree ambiguity

How can the fish resolve this ambiguity?

Fish with swimbladders may use the sound re-radiated from the swimbladder to resolve the ambiguity – the phase model




## The Phase Model

(Buwalda, Schuijf & Hawkins, 1983)

Thus:

Fish are primarily sensitive to particle motion; but some can detect sound pressure

Even those which detect sound pressure rely on detecting particle motion to determine the direction of a sound source through vector weighing

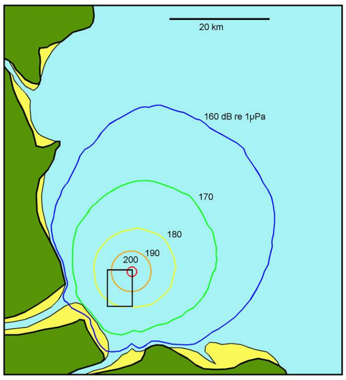
For many species, we do not know precisely how sensitive they are to sound, or what levels may injure them or evoke behavioural responses

We need particle motion detectors:

To examine the hearing abilities and responses to sounds of many more species of fish

We have to measure the sounds that we present to them with precision and accuracy. We also have to measure particle motion as well as sound pressure

We also need to improve our knowledge of the sound fields generated by human activities




Modelling of peak to peak Sound Pressure Level contours for driving a single pile

We must fully describe both the water-borne sound and substrate vibration generated by different sources;

The sound fields must be measured to agreed standards using appropriate metrics and terminology;

Particle motion must be measured

Finally, we must improve our propagation models to include the particle motion components

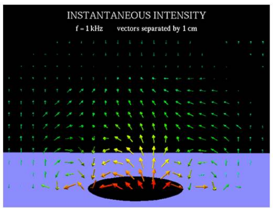
## Presentation 2: Michael Ainslie - Sound, particle motion and sound intensity

(Contains animations. Please contact the author if you require the original PowerPoint presentation).

### Sound, particle motion and sound intensity

Michael A Ainslie

NPL, Teddington, 27 November 2014




### Sound, particle motion and intensity

- What is sound?
- What is sound particle motion?
  - Plane wave
  - Standing wave
  - Spherical wave
- What is sound intensity?
  - Plane wave
  - Standing wave
  - Spherical wave
- Our little friend dB

### What is sound?

- Extracts from ISO/DIS 18405 (November 2014)

3.1.1.1
**sound**
sound wave
disturbance in pressure that propagates through a compressible medium, or a superposition of such disturbances

3.1.2.1
**sound pressure**
$p(t)$
difference between instantaneous total pressure and pressure that would exist in the absence of sound waves

### What is sound particle motion (1)?

- More extracts:

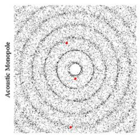
3.1.2.9
**sound particle displacement**
$\boldsymbol{\delta}$
instantaneous displacement of a material element from what would be its position in the absence of sound waves

3.1.2.10
**sound particle velocity**
$\boldsymbol{u}$
contribution to instantaneous velocity of a material element due to the action of sound waves

3.1.2.11
**sound particle acceleration**
$\boldsymbol{a}$
contribution to instantaneous acceleration of a material element due to the action of sound waves

### What is sound particle motion (2)?

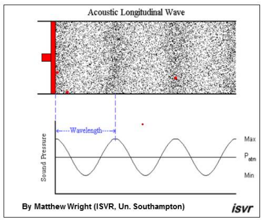
- Particle motion associated with sound usually has small amplitude
- Small amplitude Particle motion satisfies the following equations
  - $-\nabla p = \rho \boldsymbol{a}$   (***F*** = *ma*)
  - $\boldsymbol{a} = \partial \boldsymbol{u}/\partial t$
  - $\boldsymbol{u} = \partial \boldsymbol{\delta}/\partial t$




- Sound particle motion ≠ particle motion

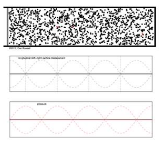
### Example 1: plane wave

- $p(t) = \cos(kx - \omega t)$
- $u(t) = \frac{1}{\rho c}\cos(kx - \omega t)$
- $p$ and $u$ are in phase
- $\frac{p(t)}{u(t)} = \rho\, c$ = constant

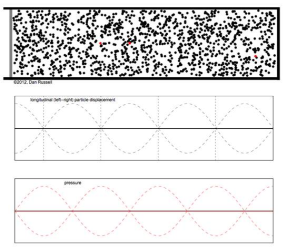



### Example 2: standing wave

- $p(t) = \cos(kx - \omega t) + \cos(kx + \omega t) = 2\cos(kx)\cos(\omega t)$
- $u(t) = \frac{1}{\rho c}[-\cos(kx - \omega t) + \cos(kx + \omega t)]$
- $\frac{p(t)}{u(t)} = \rho c \frac{\cos(kx-\omega t)+\cos(kx+\omega t)}{-\cos(kx-\omega t)+\cos(kx+\omega t)}$ ≠ constant



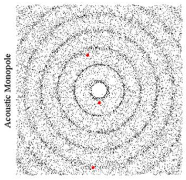
### Example 2: standing wave




By Dan Russell (Pennsylvania State University)

## Example 3: spherical wave

- $p(t) = \frac{\cos(kr-\omega t)}{r}$
- $u(t) = \frac{1}{\rho c}\left[\frac{\cos(kr-\omega t)}{r} - \frac{\sin(kr-\omega t)}{kr^2}\right]$
- $\frac{p(t)}{u(t)} = \rho c \frac{\cos(kr-\omega t)}{\cos(kr-\omega t) - \frac{1}{kr}\sin(kr-\omega t)}$



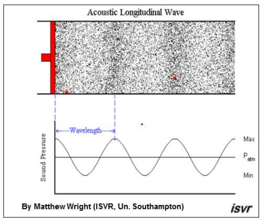

By Matthew Wright (ISVR, Un. Southampton)

## What is sound intensity (1)?

- Intensity is
  - the amount of sound power per unit area in a specified direction
  - a vector
- $\boldsymbol{i}(t) = p(t)\boldsymbol{u}(t)$ = instantaneous sound intensity
- $\boldsymbol{I} = \overline{\boldsymbol{i}(t)} = \overline{p(t)\boldsymbol{u}(t)}$ = time-averaged sound intensity

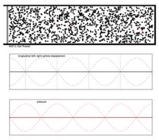
## Example 1: plane wave

- $p(t) = \cos(kx - \omega t)$
- $u(t) = \frac{1}{\rho c}\cos(kx - \omega t)$
- P and u are in phase
- $\frac{p(t)}{u(t)} = \rho\, c$ = constant
- $i(t) = p(t)u(t) = \frac{p(t)^2}{\rho c}$
- $I = \overline{pu} = \frac{\overline{p^2}}{\rho c}$



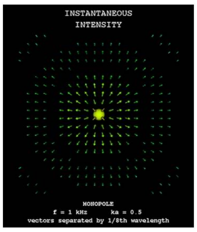

## Example 2: standing wave

- $p(t) = \cos(kx-\omega t) + \cos(kx+\omega t) = 2\cos(kx)\cos(\omega t)$
- $u(t) = \frac{1}{\rho c}[-\cos(kx-\omega t) + \cos(kx+\omega t)]$
- $\frac{p(t)}{u(t)} = \rho c \frac{\cos(kx-\omega t) + \cos(kx+\omega t)}{-\cos(kx-\omega t) + \cos(kx+\omega t)}$ ≠ constant
- $i(t) = p(t)u(t) = \frac{1}{\rho c}[\cos^2(kx-\omega t) - \cos^2(kx+\omega t)]$
- $I = \overline{pu} = 0$



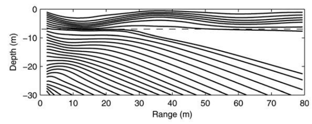
## Example 3: spherical wave

- $p(t) = \frac{\cos(kr-\omega t)}{r}$
- $u(t) = \frac{1}{\rho c}\left[\frac{\cos(kr-\omega t)}{r} - \frac{\sin(kr-\omega t)}{kr^2}\right]$
- $\frac{p(t)}{u(t)} = \rho c \frac{\cos(kr-\omega t)}{\cos(kr-\omega t) - \frac{1}{kr}\sin(kr-\omega t)}$
- $i(t) = p(t)u(t) = \frac{\cos^2(kr-\omega t) - \frac{\sin 2(kr-\omega t)}{2kr}}{\rho c\, r^2}$
- $I = \overline{pu} = \frac{\overline{p^2}}{\rho c}$



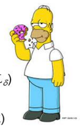

## What is sound intensity (2)?

- Use of intensity streamlines



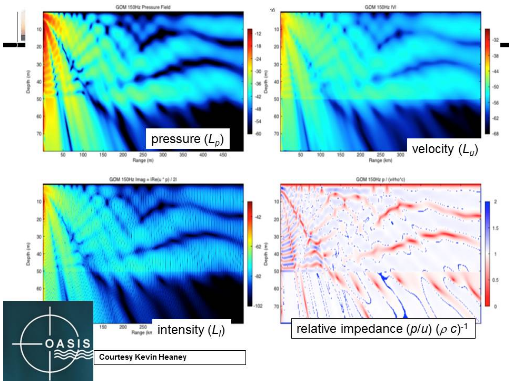

Zampolli, M., Nijhof, M. J., de Jong, C. A., Ainslie, M. A., Jansen, E. H., & Quesson, B. A. (2013). Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving. *The Journal of the Acoustical Society of America*, 133(1), 72-81.

## Our little frien**dB**



- Introduce levels in decibels:
  - (Mean-square) sound pressure level ($L_p$)
  - Mean-square sound particle displacement level ($L_\delta$)
  - Mean-square sound particle velocity level ($L_u$)
  - Mean-square sound particle acceleration level ($L_a$)
  - (Time-averaged) sound intensity level ($L_I$)
- Corresponding equations:

$$L_p = 10\log_{10}\frac{\overline{p^2}}{p_0^2}\ \text{dB},\quad p_0 = 1\ \mu\text{Pa}$$
$$L_\delta = 10\log_{10}\frac{\overline{\delta^2}}{\delta_0^2}\ \text{dB},\quad \delta_0 = 1\ \text{pm}$$
$$L_u = 10\log_{10}\frac{\overline{u^2}}{u_0^2}\ \text{dB},\quad u_0 = 1\ \text{nm/s}$$
$$L_a = 10\log_{10}\frac{\overline{a^2}}{a_0^2}\ \text{dB},\quad a_0 = 1\ \mu\text{m/s}^2$$
$$L_I = 10\log_{10}\frac{|I_{av}|}{I_0}\ \text{dB},\quad I_0 = 1\ \text{pW/m}^2$$



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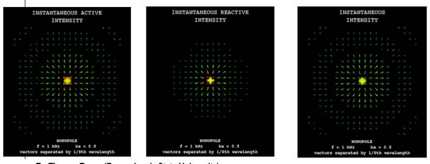
## Active and reactive intensity

- Active and reactive intensities
- p and u in phase -> active intensity
- p and u out of phase (in "quadrature") -> reactive intensity




By Thomas Burns (Pennsylvania State University)

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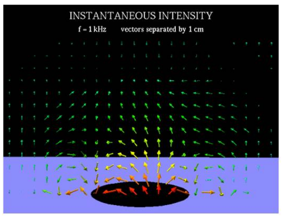
## Intensity field close to a boxed loudspeaker




By Thomas Burns (Pennsylvania State University)

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## Acknowledgements

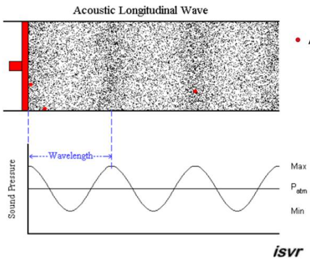
- Matthew Wright
- http://www.lordgrey.org.uk/~f022/usefulresources/soundwaves/StartCD.htm

- Dan Russell
- http://www.acs.psu.edu/drussell/demos.html

- Thomas Burns
- http://www.acs.psu.edu/drussell/Demos/Burns_PhD_animations/Burns_PhD_anim.html

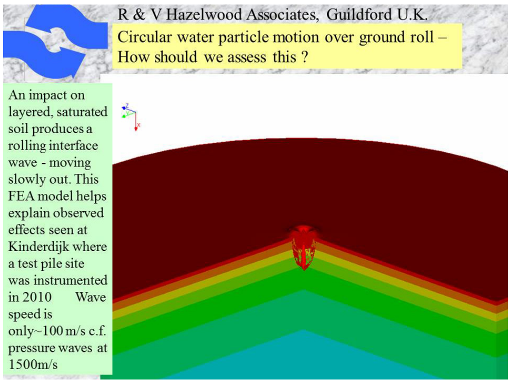
20

## Questions?

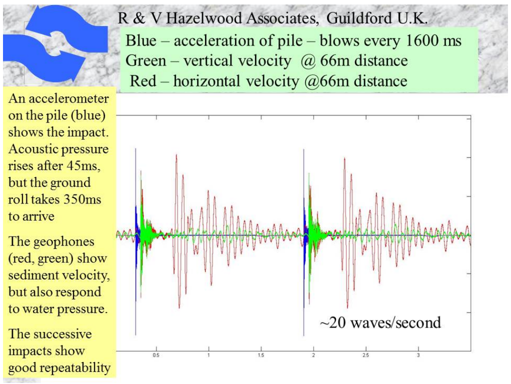


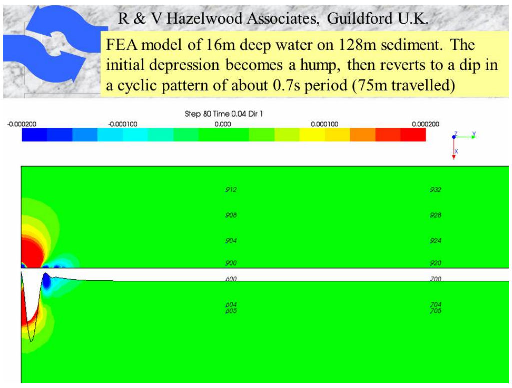

- Acoustic particles

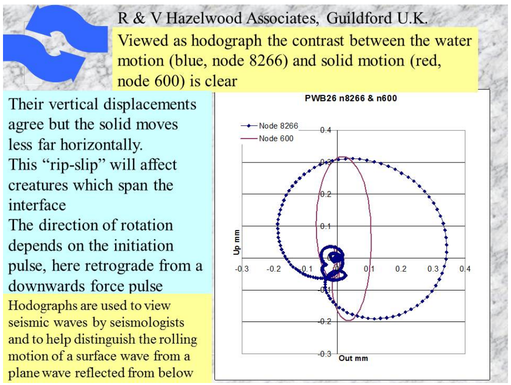
**Presentation 3: Dick Hazelwood - Circular water particle motion and ground roll – how should we assess this?** (Contains animations. Please contact the author if you require the original PowerPoint presentation).

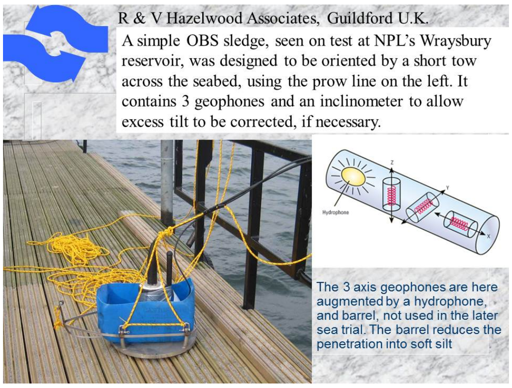


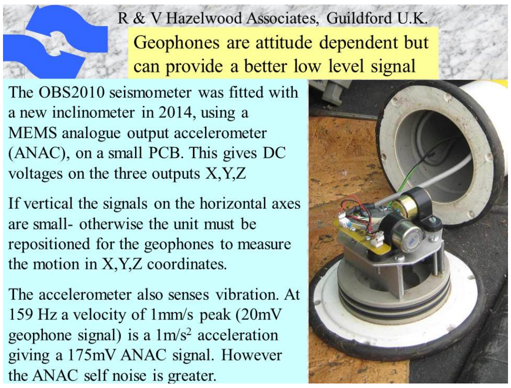


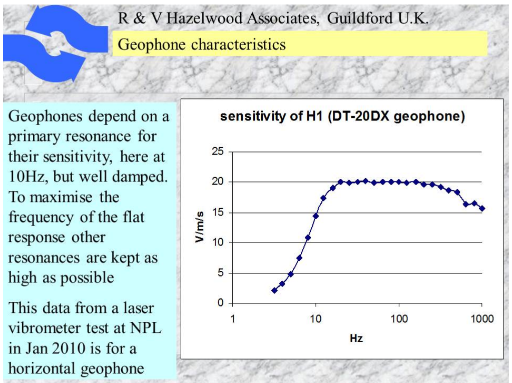


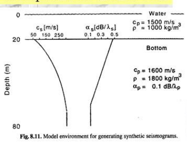



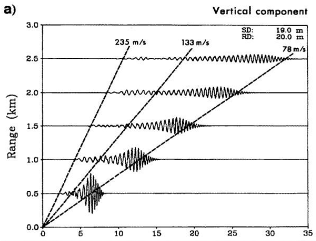
R & V Hazelwood Associates, Guildford U.K.

Ground roll from test explosions in the Mediterranean near SACLANT was measured and modelling by wave number integration to provide best fit sediment data.

Note the lower frequencies of ~3 Hz but wavelet speeds still ~ 100m/s

Sediment data is similar to Hamilton (JASA) – the shear wave depth profiles vary both in speed & absorption over the first 60m



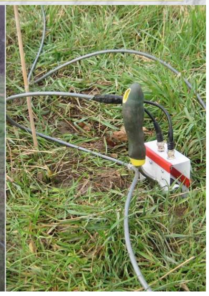




"Computational Ocean Acoustics" p475

Jensen, Kuperman, Porter, Schmidt Springer 1993

R & V Hazelwood Associates, Guildford U.K.

Ground roll in saturated clay soil - Pink's Hill trial
This site showed limited range for ~ 1kJ impacts - (~50kg dropped from ~2m)



R & V Hazelwood Associates, Guildford U.K.

**In water, directionality sensitivity to low frequencies (<100Hz) is very limited** (wavelength $\lambda \approx 150$m at 20Hz in water)

•Whilst LF pressure waves give little directional data, aquatic life can get much more information from vibration – the water particle velocities – a vector field.

•Triaxial accelerometer packages record wave directions - azimuth directions are given by the x/y amplitude ratio, but there remains an ambiguity for plane wave tones. These include the P (primary, pressure) and S (secondary, shear) waves within the sediment.

• However, for ground roll, with out-of-plane z axis data, the left/right wave direction **ambiguity is resolved by a phase analysis of the rolling motion**.

• **Many creatures may have evolved to use this vital directional information on the activities of potential predators and prey.**

•*Kotas, Rogers, and Yoda ( J.A.S.A. 2011) say "..... their ears are too close together for underwater sounds to provide a meaningful time delay"*

•*But also "Detecting the motion of the otolith ... and thereby the acoustic particle motion, enables the fish to determine the line of bearing of an incident far-field sound, but not the direction, due to the 180° ambiguity"*

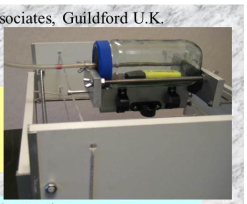
R & V Hazelwood Associates, Guildford U.K.

Testing the bio-sensitivity to motion - a potential solution using a jar shaker

- As has been shown there is an urgent need for more work on the sensitivity to vibration underwater
- This will be difficult especially at higher frequencies. But issues become simpler at low frequencies with wavelengths larger than the test jig, so that motions of all parts are substantially in phase
- Many creatures can then also be treated as rigid bodies which contain inertial sensors that detect motion. There will be relative motion within the sensors but this will be negligible
- A major practical problem is to isolate the jig from environmental low frequency motion. This can be done by soft suspension systems with a natural resonance below the frequency band of interest

R & V Hazelwood Associates, Guildford U.K.

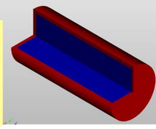
The use of "rigid body" motion - All solids and fluids show some elasticity -"rigid" is an idealised concept, used to help understand low frequencies

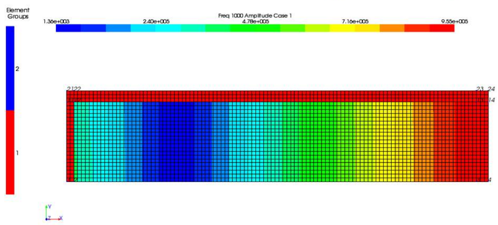


- The motion of a rigid body is simple. Motion sensors at any point suffice to define it. 3 axes (X,Y,Z) give the vector motion. For a full definition 3 rotary sensors are also required. There are six marine terms – pitch, roll, yaw, heave, surge and sway - of which the jig shown only measures the last three.
- An enclosed fluid will follow this motion at low frequency
- As the frequency rises, both fluid and elastic solids will deviate from this simplicity dependent on the nature of the drive forces

R & V Hazelwood Associates,

Jar modelling – this model, with fluid (blue) and walls (red), shows pressure distribution at 1kHz. The pressure differences remain small





R & V Hazelwood Associates, Guildford U.K.

Creature comforts

- Our plan is to encourage the testing of bio-sensitivity by those more qualified in the difficulties of biological experiment
- I also plan to do further analysis of the physics and engineering needs in support of this work
- The jar is carefully filled with water of a suitable oxygen content, not enough to promote free bubbles but sufficient for creature comfort in the short term. The vent avoids pressure changes occurring with temperature, without undue loss of coupling between the water and the frame
- The recording of the motion needs to be simplified. I like using a digital storage oscilloscope, but recognise that this may not be essential
- Current work is to provide a digital panel readout from the chosen geophone, for a standard one second tonal burst at different levels

R & V Hazelwood Associates, Guildford U.K.

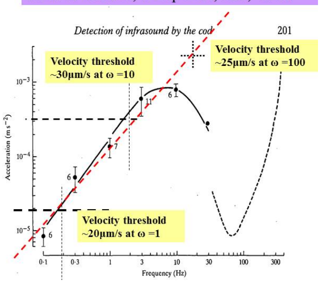
**Detection of infrasound – acceleration or velocity?**

These infrasound acceleration thresholds are for cod but may also apply to others without buoyancy. Their basic otolith response is enhanced by the cod's swimbladder resonance at higher frequencies, improving its sensitivity to pressure waves.

But at 0.1- 10Hz the power law (red) indicates a fixed threshold at ~25µm/s particle velocity. For a plane water wave, intensity is ~ 1mW/m²

This is much more sensitive than a human response (x20?)

Sand & Karlsen, J Exp Biol, 127, 1986

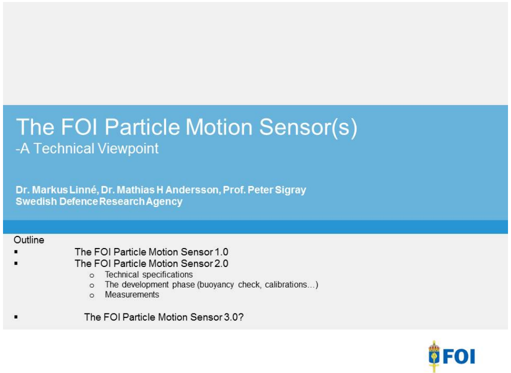


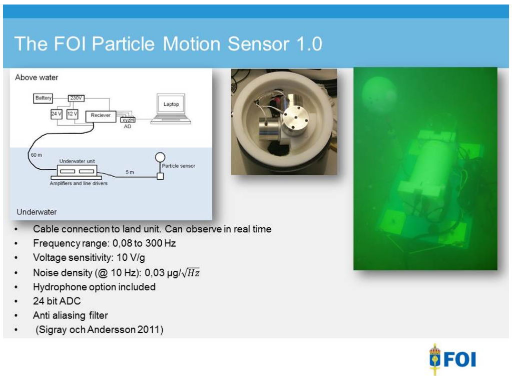

R & V Hazelwood Associates, Guildford U.K.

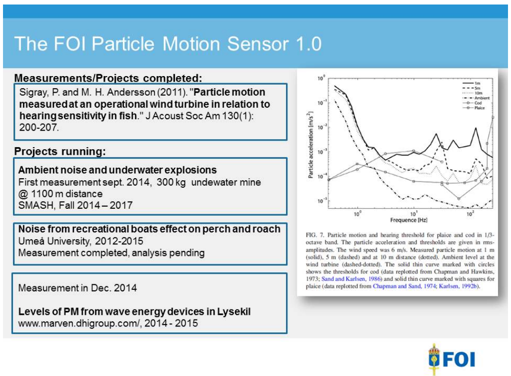
Presentation of results

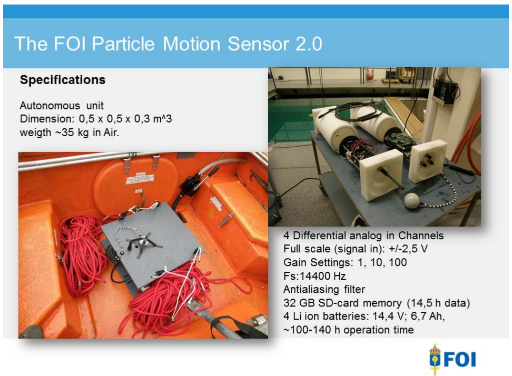
- Geophones exhibit a flat sensitivity over their optimal bandwidth in units of V/(m/s), a velocity sensitivity
- "Water particle velocity" can thus be recorded easily, and presented in S.I. units such as mm/s. I prefer to avoid the use of decibels, given the widespread misuse and misunderstanding thus created but if necessary the relevant reference level should be the nm/s (nanometre per second). It seems unlikely that any creature can detect this, so all decibel results will be positive
- Logarithmic scales are commonly used for audiograms and related "vibrograms" will need this too. But data can be plotted with such axes and tick-marks such as 1 nm/s, 1 µm/s and 1 mm/s as appropriate. My interpretation of the Sand & Karlsen cod data is to expect a flat line around 25µm/s

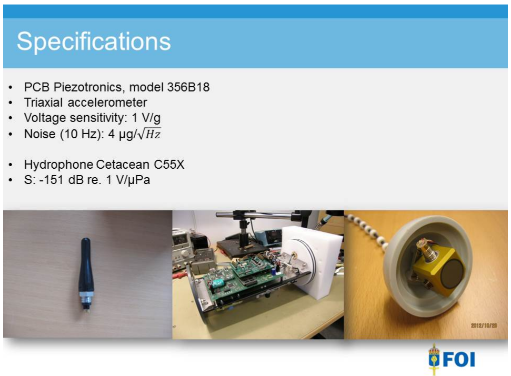
## Presentation 4: Markus Linné - The FOI particle motion sensor - a technical viewpoint

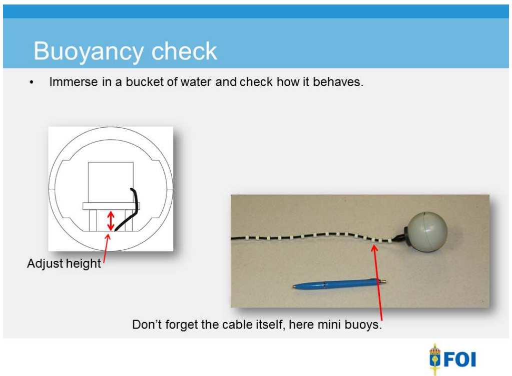


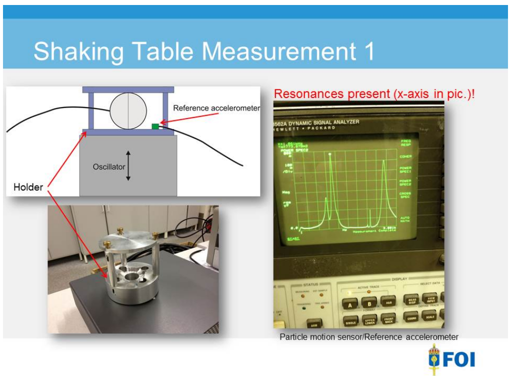



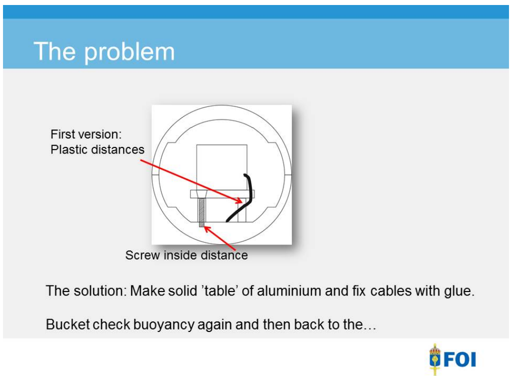



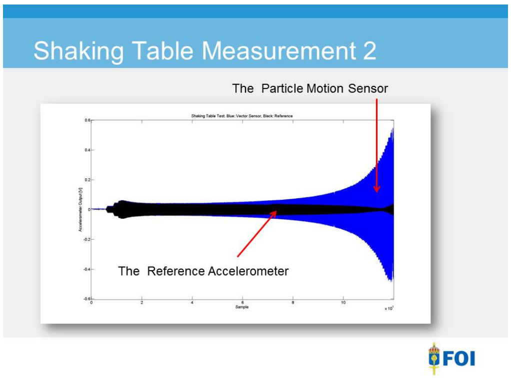



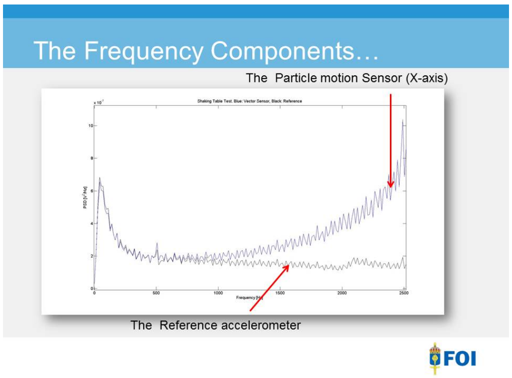



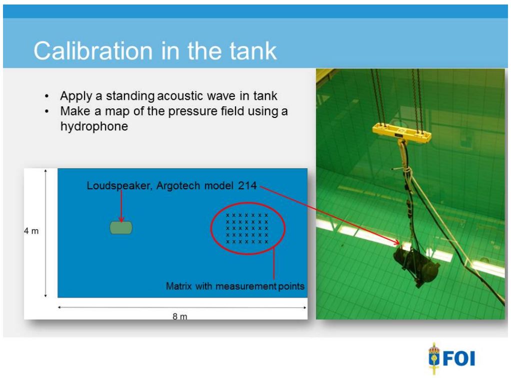



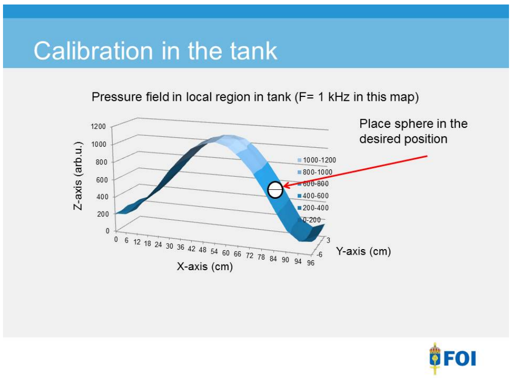



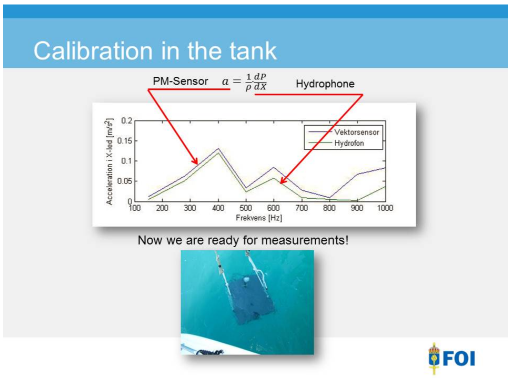



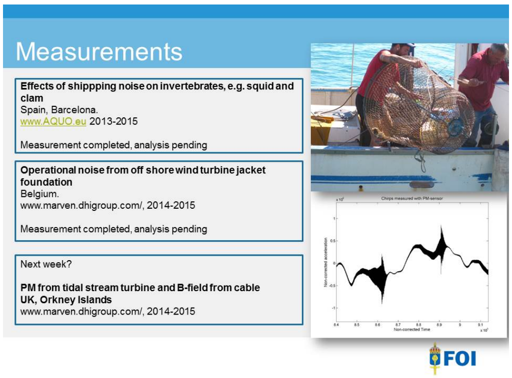

Shaking Table Measurement 2
The Particle Motion Sensor
The Reference Accelerometer
FOI

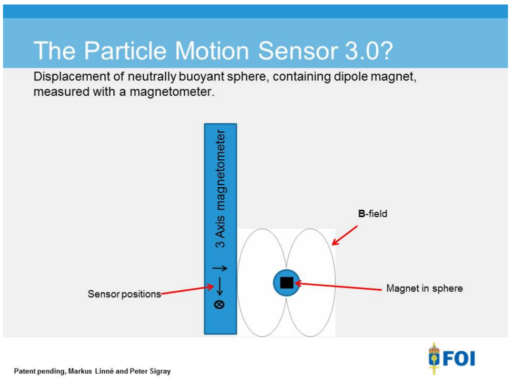

The Frequency Components…
The Particle motion Sensor (X-axis)
The Reference accelerometer
FOI

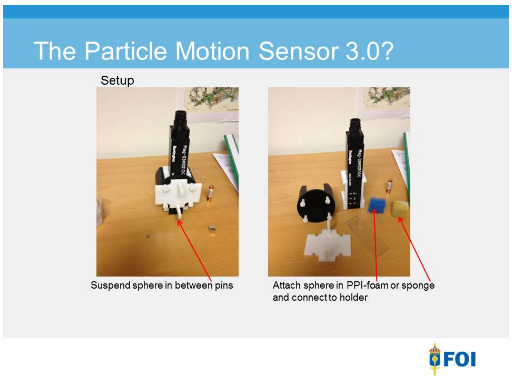

Calibration in the tank
• Apply a standing acoustic wave in tank
• Make a map of the pressure field using a hydrophone
Loudspeaker, Argotech model 214
4 m
Matrix with measurement points
8 m
FOI


Calibration in the tank
Pressure field in local region in tank (F= 1 kHz in this map)
Place sphere in the desired position
Z-axis (arb.u.)
X-axis (cm)
Y-axis (cm)
1000-1200
800-1000
600-800
400-600
200-400
0-200
FOI


Calibration in the tank
PM-Sensor
$a = \frac{1}{\rho}\frac{dP}{dX}$
Hydrophone
Vektorsensor
Hydrofon
Acceleration i X-led [m/s²]
Frekvens [Hz]
Now we are ready for measurements!
FOI


Measurements
Effects of shippping noise on invertebrates, e.g. squid and clam
Spain, Barcelona.
www.AQUO.eu 2013-2015
Measurement completed, analysis pending
Operational noise from off shore wind turbine jacket foundation
Belgium.
www.marven.dhigroup.com/, 2014-2015
Measurement completed, analysis pending
Next week?
PM from tidal stream turbine and B-field from cable
UK, Orkney Islands
www.marven.dhigroup.com/, 2014-2015
FOI


The Particle Motion Sensor 3.0?
Displacement of neutrally buoyant sphere, containing dipole magnet, measured with a magnetometer.
3 Axis magnetometer
B-field
Sensor positions
Magnet in sphere
FOI
Patent pending, Markus Linné and Peter Sigray


The Particle Motion Sensor 3.0?
Setup
Suspend sphere in between pins
Attach sphere in PPI-foam or sponge and connect to holder
FOI

## Motivation

Sensor based on: Acceleration ⟷ Velocity ⟷ Displacement :Sensor based on

Check consistency between methods!

- No electronics inside buoyant sphere: Reduce resonances in sphere.
- Relatively easy to keep track of orientation and DoA of signals.

Limitations:
- Need highly sensitive magnetometer, fluxgate ok?
- High accuracy in magnet position relative to magnetometer needed.

FOI

## Thank you for your attention!

Markus Linné

Underwater technology
Defence and Security
Systems and Technology

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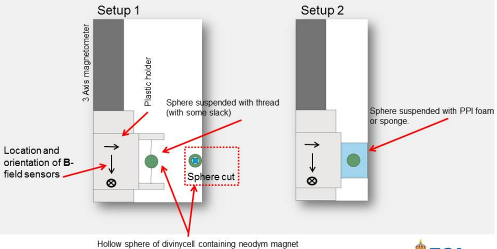
mobile:+46-(0)73-4447709

FOI

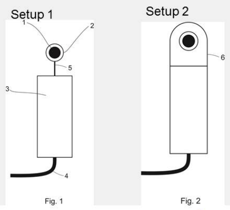
## The Particle Motion Sensor 3.0?

Displacement of neutrally buoyant sphere, containing dipole magnet, measured with a magnetometer.




Patent pending, Markus Linné and Peter Sigray

FOI




FOI

# Presentation 5: John Dalen - Sound exposure and its level

## Sound exposure and its level - a "fringe" contribution

**The need for a consistent term applicable both in the acoustic near field and far field**

**John Dalen**
**Bergen, Norway**

**Workshop on underwater vector sensing**
**NPL, Teddington, 27 Nov 2014**

SoundMare

## Sound exposure - impetus for this initiative

Working with impact and effects in zooplankton, fish eggs, larvae and fry from seismic airgun sources (1992 & 2010)

Acoustic near field - far field transition range; $r_{nf}$-$r_{ff}$

Example:
Airgun cluster of 2 airguns / at 6 m depth / supply pressure 13.8 MPa (2000 psi).
Estimation of $r_{nf}$-$r_{af}$

| Frequency, [Hz] | Near field/far field range; $r_{nf\text{-}ff}$ [m] |
|---|---|
| 10 | 1.6 |
| 50 | 8.1 |
| 100 | 16.2 |
| 300 | 48.7 |
| 1000 | 162.3 |

SoundMare

## Sound exposure - present

Present definition (an acoustic energy/power like quantity):

$$se = \int_0^t p(t)^2\, dt \qquad [\mu Pa^2\ s]$$

$$SEL = 10 \lg \left( \int_0^t p(t)^2\, dt \right) \qquad [dB\ re\ 1\mu Pa^2\ s]$$

When it comes to total acoustic impact (energy/power/ intensity) in organisms in the acoustic near field, the present defined and applied term/function of the sound exposure will not be true or valid with these definitions.

Now research groups realize the need for measuring the particle motion components both in relations to hearing and harmful impacts in fish from close to the source and R =>!

SoundMare

## Sound exposure - and equivalent terms

Example from the acoustic intensity, **I** - a vector:
General definition - also valid for the nearfield: - the particle velocity and pressure are out of phase:

$$\mathbf{I} = (1/t) \int_0^t \mathbf{v}(t)\, p(t)\, dt \qquad [W/m^2]$$

In the farfield: - the particle velocity and pressure are in phase:

$$I = (1/t) \int_0^t (p(t)^2/\rho c)\, dt \qquad [W/m^2]$$

SoundMare

## Sound exposure - proposal for the future

A definition to be valid both in the acoustic near field and far field!

General definition:

$$\mathbf{se} = \rho c \int_0^t \mathbf{v}(t)\, p(t)\, dt \qquad [\mu Pa^2\ s]$$

$$SEL = 10 \lg \left( \rho c \int_0^t \mathbf{v}(t)\, p(t)\, dt \right) \qquad [dB\ re\ 1\mu Pa^2\ s]$$

In the farfield:

$$se = \int_0^t p(t)^2\, dt \qquad [\mu Pa^2\ s]$$

$$SEL = 10 \lg \int_0^t p(t)^2\, dt \qquad [dB\ re\ 1\mu Pa^2\ s]$$

SoundMare

## Think it over - - - deeply!

**Thank you for your attention!**

by John

SoundMare
Sound in Marine Environments

## 10 Annex B – List of workshop participants

| Name | Association | Country |
|---|---|---|
| Michael Ainslie | TNO | Netherlands |
| Fabrizio Borsani | Cefas | UK |
| Rick Bruintjes | University of Exeter/HR Wallingford | UK |
| Michael Butler | Loughborough/EMEC | UK |
| James Campbell | Leiden University | Netherlands |
| Mike Cowling | The Crown Estate | UK |
| John Dalen | Soundmare | Norway |
| Ian Davies | Marine Scotland | UK |
| Elisabeth Debusschere | Ghent University | Belgium |
| René Dekeling | Ministry of Infrastructure and the Environment | Netherlands |
| Ingebret Gausland | Independent Advisor | Norway |
| Nicolas Goujon | Schlumberger | UK |
| Tony Hawkins | Loughine Marine Research | UK |
| Dick Hazelwood | R&V Hazelwood Associates | UK |
| Victor Humphrey | Institute of Sound and Vibration Research | UK |
| Julia Hunt | Defra/Cefas | UK |
| Erwin Jansen | TNO | Netherlands |
| Monika Kosecka | DHI Poland | Poland |
| Paul Lepper | Loughborough University | UK |
| Markus Linné | Swedish Defence Research Agency | Sweden |
| Terry Mayor | Reeves Wireline Technologies | UK |
| Sonia Mendes | JNCC | UK |
| Nathan Merchant | Cefas | UK |
| John Moloney | JASCO Canada | Canada |
| Andreas Müller | Müller- BBM GmbH | Germany |
| Sophie Nedelec | University of Bristol | UK |
| Errol Neo | Leiden University | Netherlands |
| Alain Norro | OD Nature | Belgium |
| Andy Radford | University of Bristol | UK |
| Özkan Sertlek | TNO/ Leiden University | Netherlands |
| Steve Simpson | University of Exeter | UK |
| Frank Thomsen | DHI | Denmark |
| Ursula Verfuβ | SMRU Marine | UK |
| Irene Voellmy | University of Bristol | UK |
| Peter Ward | Kongsberg Maritime Ltd. | UK |
| Paul White | Institute of Sound and Vibration Research | UK |
| Maria Wilson | University of Oslo | Norway |
| Pete Theobald | National Physical Laboratory | UK |
| Stephen Robinson | National Physical Laboratory | UK |
| Lian Wang | National Physical Laboratory | UK |
| Tanja Pangerc | National Physical Laboratory | UK |