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Observing the ocean interior in support of integrated management

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Abstract :

Active- and passive-acoustic methods are widely used tools for observing, monitoring, and understanding marine ecosystems. From 25 to 28 May 2015, 214 scientists from 31 nations gathered for an ICES symposium on Marine Ecosystem Acoustics (SoME Acoustics) to discuss three major themes related to acoustic observations of marine ecosystems: (i) recent developments in acoustic and platform technologies; (ii) acoustic characterisation of aquatic organisms, ecosystem structure, and ecosystem processes; and (iii) contribution of acoustics to integrated ecosystem assessments and management. The development of, and access to new instruments, such as broad bandwidth systems, enables insightful ecological studies and innovative management approaches. Unresolved ecological questions and the increasing move towards ecosystem based management pose further challenges to scientists and instrument developers. Considering the SoME Acoustics presentations in the context of three previous ICES symposia on fisheries acoustics, topics increasingly emphasize ecosystem studies and management. The continued expansion of work and progress in marine ecosystem acoustics is due to the cross-disciplinary work of fisheries acousticians, engineers, ecologists, modellers, and others. An analysis of the symposium co-authorship network reveals a highly connected acoustic science community collaborating around the globe.

Keywords : acoustics, broadband, multi-frequency, passive and active acoustics, ecosystem approach to management, ecosystem monitoring, pelagic ecosystem, echosounder, sonar.

Introduction

Acoustic methods are widely used tools for observing, assessing, monitoring, and understanding marine ecosystems. These tools are key contributors of data needed for operational Ecosystem Based Management (EBM) (Trenkel et al., 2011). The full potential of acoustic methods can only be realized with systematic cross-disciplinary collaboration, joining expertise in fields like fisheries acoustics, physics, engineering, biology, oceanography, ecology, and ecosystem modelling. This special issue of the ICES Journal of Marine Science contains 17 articles stemming from the 2015 ICES Symposium on Marine Ecosystems Acoustics (2015 SoME Acoustics). The papers cover the three major themes of the symposium, including: i) recent developments in acoustics and platform technologies; ii) acoustic characterisation of aquatic organisms, ecosystem structure, and ecosystem processes; and iii) contribution of acoustics to integrated ecosystem assessments and management. The abstracts of all the symposium contributions are available as Supplementary Material.

SoME Acoustics was the 7th symposium on fisheries acoustics and technology for aquatic ecosystem investigations sponsored by ICES. All of the symposia have addressed acoustic estimations of marine fish distributions and abundances. The acoustic technologies and their applications have evolved from aids to fishing (1955), echo-integration estimates of fish biomass (1973), single-frequency target classification and calibrated dual-beam target strength estimation (1982), split-beam target strength estimation (1987 and 1995), multi-frequency target classification (2002), multi-beam sonar imaging (2008), to broad bandwidth target classification (2015) (Figure 1). Over the years, while the ICES fisheries acoustics community continued developing acoustic technologies, the community focus has shifted towardcharacterizing fish, their ecosystems, and their management. The symposium further demonstrated this trend.

A more detailed view of the changes in focus of the ICES fisheries acoustics community is obtained by comparing the topics of talks and posters presented in 2015 with those of three previous ICES acoustic symposia (2008, 2002, and 1987). For this we analysed the list of the 25 most common words in the abstracts of each symposium (titles only for 1987) (Figure 2a).

The 10 most common words in the abstracts (or titles in 1987) of all four symposia include: *measur*ement, *survey*s, *distribut*ion, *abund*ance, *estim*ation, *targets*, *fish*, *school*s, and *sea*.

Additionally, papers from the 1987 symposium often included the root words *behaviour* and *river*, indicating an emphasis on animal behaviour, especially in the riverine environment. The root words *species* has been commonly used since 2002, but *ecosystem* appeared more frequently since 2008 and *process* and *characteris** since 2015 indicating that acoustic methods have been increasingly applied in ecological and ecosystem investigations for fisheries management. In 2015 the word *marin*e was used more frequently, indicating the focus on oceanic environments. A multivariate analysis was also performed on the 50 most common words found in the abstracts (or titles in 1987) of the four symposia (Figure 2b). The first major trend (abscissa) contrasts studies focusing on acoustic layers and migrations as well as studies in rivers (right hand side) from those focused on schools, individual species (capelin, anchovy) and zooplankton (left hand side). The second major axis distinguishes technological related studies of signals and sonars (top) from ecological studies of spatial distributions, krill, but also management issues (bottom). The inset in figure 1b reveals significant temporal variation (randomization test, $p = 0.001$) with an overall temporal trajectory of symposia contributions towards more species-oriented studies and more emphasis on ecosystem and management aspects with increasing focus on zooplankton/krill, assessment, management, and spatial distributions.

We also analysed the structure of the research community that participated in the 2015 symposium. The co-authorship network (talks and posters) was built and then analysed to identify groups of co-authors. Based on the Integrated Completed Likelihood criterion, 14 groups of co-authors were identified (Figure 3). Remarkably, only 7% of contributions had a single author (isolated dots in Figure 3) while 21% had six or more co-authors (1987: 43% and 0.7%; 2002: 8% and 9%; 2008: 7% and 14%), demonstrating the high degree of collaboration within the acoustic community forged over many years and indicating a state of maturity of the field. Two large meta-communities emerged from the analysis. The first meta-community consisted of three groups of Asian authors (salmon, pink and red groups in Figure 3). The core of the second meta-community (centre of graph) was formed by seven groups with authors from the traditional ICES acoustics community in Europe, America, Australia and New Zealand.

Recent developments in acoustic sensor and platform technologies

The symposium began with oral presentations describing recent developments in acoustic sensor and platform technologies, and one quarter (9 out of 36) of these presentations described developments in broad bandwidth acoustic technologies. The use of broad bandwidth acoustic signals, defined here as signals with a bandwidth that is ~1/2 or more of the center frequency, may result in increased signal-to-noise and range resolution, using pulse compression, and improved target classification, e.g. fish with swim bladder versus plankton, using the target frequency response. Although field observations of the broadband frequency response of fishes are not new (e.g., Holliday (1972)) recent efforts by Lavery et al. (2010) and Stanton et al. (2010) using commercially available echo sounder equipment have reinvigorated this type of approach amongst both practitioners and manufacturers. At the same time, progress towards calibration procedures has been made (Chu and Eastland, 2015).

The challenges associated with broadband acoustics include transducer technologies, observing targets near boundaries, susceptibility to noise, and species classification. It is, perhaps, too early to say what the impact of these new broadband approaches will have for stock assessment and ecosystem characterization, including what benefit they will have over current multi-frequency approaches (e.g., De Robertis et al. (2010), but given the high level of interest it seems likely that the impact will be felt soon.

Data storage and processing techniques are an area of continual development for all sensor-types and applications. Renfree and Demer (this issue) propose an algorithm for dynamically adapting the data logging range and transmit-pulse interval which can increases the horizontal resolution and reduce the data volume. Cutter et al. (this issue) explore ways to improve acoustic seabed classification by combining information from ship-mounted multi-frequency split-beam echosounders with ROV-mounted cameras.

The use of multiple beam sonars, including both multibeam echo sounders (MBES, e.g. Trenkel et al. (2008)) and omni-sonars (Simmonds and MacLennan, 2005) for quantitative estimates of fish biomass and behavior has been maturing (see, for example, Colbo et al. (2014); Melvin (this issue)), including the integration of traditional single and split-beam echosounders with MBES. Developments of quantitative methods with somni-sonars, including calibration, use, and post-processing techniques, are also ongoing. Although omni-sonars have been used previously for scientific studies of fish abundance and behavior (e.g., (Soria et al., 1996; Gerlotto et al., 1999; Gerlotto et al., 2004; Stockwell et al., 2013), they have typically suffered from a lack of quantitative calibration and processing methods. Several symposium presentations suggested that these roadblocks to the quantitative use of omni-sonars will likely be soon overcome.

Whether the acoustic sensor is passive (listening only) or active (emitting and receiving), it requires a platform for its deployment. Although traditional ship-based sensor deployments are still prevalent, new platforms include moorings, robotic vehicles, and fish tags. These platforms are being developed rapidly and are becoming increasingly available to this community. These new platforms increase the diversity and often the quantity of data available, as evidenced by long-time-series measurements from moorings, e.g. Stauffer et al. (2015) and close-range high-resolution measurements from underwater vehicles (Moline et al., 2015). Although the potential seems high, one of the main challenges in the use of these new platforms is how the data from these platforms can be transformed into science and management advice in similar fashion to what is typically done with the traditional acoustic-trawl survey (Simmonds and MacLennan, 2005).

Acoustic characterisation of aquatic organisms, ecosystem structure, and ecosystem processes

There has been a shift from technology developments for informing single species stock assessments to using acoustics to resolve ecosystem structure and processes (Figure 1) (Godø et al., 2014; Benoit-Bird and Lawson, 2016). Whereas the traditional fisheries acoustics approach has been directed to measuring abundance and distribution of species as input to fish stock assessments, recently the emphasis has expanded to studying structure, e.g. the distribution of different taxonomic groups in relation to the physical environment, and processes, e.g. species overlap and potential species interactions, to gain understanding of the underlying processes. This direction is further strengthened by improved spatial, temporal and taxonomic resolution of the new platforms and instruments as described above (Figure 1).

Acoustics have improved in taxonomic resolution. A prerequisite for this is a thorough understanding of species- or group-specific acoustic properties, i.e. the frequency response discussed above. Understanding frequency response is important both for traditional multi-frequency methods (Trenkel and Berger, 2013; Sato et al., 2015) and state-of-the-art broad bandwidth systems (Ito et al., 2015). It also plays a role for target strength (TS) studies of species monitored with acoustic-trawl surveys (Doray et al., this issue) and for the observation (Scoulding et al., 2015) and modelling (Jech et al., 2015) of acoustic properties of individuals across taxa, ensonification angles and frequencies. A related approach is to measure the emergent acoustic properties of fish aggregations and use those properties to classify the backscatter to taxa, e.g. Fallon et al. (this issue). This usually involves using auxiliary information for ground truthing and validation of the acoustic classifications (Fernandes et al., this issue).

Acoustics offer capabilities to observe large scale distributions of various taxa when deployed on platforms covering larger areas (Trenkel and Berger, 2013; Petitgas et al., 2014). Combined with the improved taxonomic resolution, the spatial distribution, both horizontally and vertically, can be much better resolved compared to other methods. An example is the mapping of zooplankton distributions (Sakınan, this issue; Simonsen et al., this issue), which is often not the primary objective of vessel based acoustic-trawl surveys. The different acoustic signature relative to, e.g. fish, makes it possible to generate indices of krill abundance from historical data (Ressler et al., 2012; Ressler et al., 2015), and the results are indices of important prey species that augment the data of the survey at very limited extra costs.

Mesopelagic organisms, or the ubiquitous deep sound scattering layers (DSLs) has drawn increasing attention in the acoustic community lately. Acoustics transects at basin scales have been reported (Davison et al., 2015), including comparisons between biogeographic provinces (Irigoien et al., 2014). In addition to the desire to understand the species composition of this layer, the interest is also driven by the potentially large amounts of biomass represented by mesopelagic fish. Mesopelagic species differ in their vertical migrations. Using acoustic data collected at multiple frequencies, theoretical scattering models and net trawls, the behavioural differences can be used to differentiate between the different layers. An important challenge when using acoustics to resolve mesopelagic fish at this depth is the swim-bladder resonance (Godø et al., 2009; Kloser et al., this issue) and small gas bearing organisms like siphonphores; the resonance can also be utilized for sizing (Stanton et al., 2010). This needs to be kept in mind when further investigating the distribution and composition of the DSL using acoustics. Despite the challenges, acoustic measurements offer great potential to help understand the global mesopelagic habitat, where continued detailed regional studies and better acoustic coverage are needed.

Acoustic instrumentation is increasingly being used to observe fine scale (of the order of several meters) processes of *in situ* organisms or those in controlled mesocosm experiments. The applications range from behavioural processes and distribution patterns, such as overlap between predator and prey distributions (Benoit-Bird et al., 2004; Bertrand et al., 2014; Ressler et al., 2015), to investigations of the effect of marine protected areas, subsea structures, noise and other anthropogenic stressors. Fine scale social behaviours have been observed by both high frequency sonar (Handegard et al., 2012) and split-beam echo sounders (Kaartvedt et al., 2015). Importantly, individual swimming behaviour affects TS values (Tomiyasu et al., this issue) and provides clues on species composition of fish schools. Acoustics can thus be used to study fine scale patterns as well as utilize these patterns for classification and target strength estimation.

Part of the marine ecosystem in which fishes and marine mammals reside is the underwater soundscape. Passive-acoustic monitoring of this soundscape offers potential clues about the presence and behavior of animals. Examples presented in this issue include the study of fish vocalisations (Parsons et al., this issue), the interaction between cetaceans and forage fish (Lawrence et al., this issue) and the timing of the migration of fin whales (Tsujii et al., this issue).

The contribution of acoustics to integrated ecosystem assessments and management

Traditionally active acoustics have been used for estimation abundance of targeted species (Simmonds and MacLennan, 2005). Though species abundance estimation is still an important application of acoustics for fisheries management and new applications continue to emerge (O'Driscoll et al., 2012), the use of acoustic methods has been enlarged to encompass the assessment of a wider range of ecosystem components (e.g. plankton, micronekton), characteristics (e.g. diversity) and dynamics (e.g. predator-prey), at different spatial and temporal scales (Trenkel et al., 2011; Godø et al., 2014).

This wider view of the use of acoustics is essential for integrated ecosystem assessments, which encompass the biological ecosystem, human activities and ecosystem services (fundamental services such as regulating food web dynamics and recycling nutrients and human demand-derived services such as production of food and supply of recreational activities). The first steps of an integrated assessment are to define the elements of the system to assess and identify achievable management objectives, in collaboration with society and stakeholders (Trenkel et al., 2015). Major challenges are the easy wide availability and accessibility of acoustics data (Wall et al., this issue), conversion of information (data) into knowledge and appropriate methods for the integration of partial assessments. For acoustics many steps and assumptions are needed to turn the physical signal into knowledge.

Acoustic-based abundance estimates result from the combination of various data sources and parameters including target strength, length distributions, age-length keys, identification of echo sources and the vertical and spatial distribution of backscattered energy (Simmonds and MacLennan, 2005). There are no standard methods for propagating resulting uncertainties (systematic and random error) to stock abundance estimates, but progress is being made using Bayesian hierarchical models (Sullivan and Rudstam, this issue). A major unresolved issue is accounting for the correlation between error sources.

Acknowledging that acoustic biomass estimates can be imprecise (Stenevik et al., 2015), one active domain of research is the combination of several observation methods (echosounder, sonar, video, photographs) (Letessier et al., this issue; Ryan and Kloser, this issue). Population biomass estimates can also be improved by adapting the acoustic transect design to the spatial distribution (Demer et al., 2012). Spatial distributions are determined by abiotic factors (Bonanno et al., 2014; Zwolinski and Demer, 2014), but also by density dependence as demonstrated for small pelagic species (Petitgas et al., 2014; Saraux et al., 2014).

Integrated ecosystem assessments encompass non-fishery targeted species such as zooplankton and the potential for indirect effects of stock management via top-down control of predators on their prey. For example, Ressler et al. (2014) investigated whether there was evidence for a local top down effect of walleye pollock on euphausids, but did not find much evidence for such an effect. More studies of this type are needed to gain a wider understanding of potential indirect effects of fisheries exploitation.

Use of acoustic and other data collected by fishers during ordinary fishing operations for monitoring and assessment is increasingly being trialled (Joo et al., 2014; Surette et al., 2015). However, this can cause challenges for data quality (noise, echosounder calibration), analysis (non-random sampling, no identification hauls), and availability (storage, ownership). ICES led initiatives have provided protocols for acoustic data collection and analysis on fishing vessels (ICES, 2007) and meta-data formats (ICES, 2014), but more work is needed for standardising data collection and analysis methods.

Conclusion

The world of fisheries acoustics is expanding to meet the increasing needs for ecosystem studies and ecosystem based management. As demonstrated by the presentations and posters at the symposium, and reflected in the papers presented in this issue, the community has responded to this need by developing new technologies and methods, and by applying them to an increasing range of organisms and ecosystems. The synergy of these technological, scientific and management developments seem likely to fuel continued advancement in marine ecosystem acoustics far into the future.

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Figure legends

Figure 1. Time line for the development of the marine ecosystem acoustics. The right part of the figure depicts the general trend, important milestones in the development of fisheries acoustics are shown on the left hand side with an emphasis on the uptake of technologies by the general fisheries community. (a) Sund (1935) (b) Dragesund and Olsen (1965); (c) Holliday (1977); (d) Foote et al. (1987); (e) Foote (1983); (f) Brierley et al. (1998) Kloser et al. (2002); Korneliussen and Ona (2003); (g) Trenkel et al. (2008); (h) Stanton et al. (2010) (i) MacLennan (1990); Simmonds and MacLennan (2005) (j) Benoit-Bird and Lawson (2016). Figures reprinted with permissions.

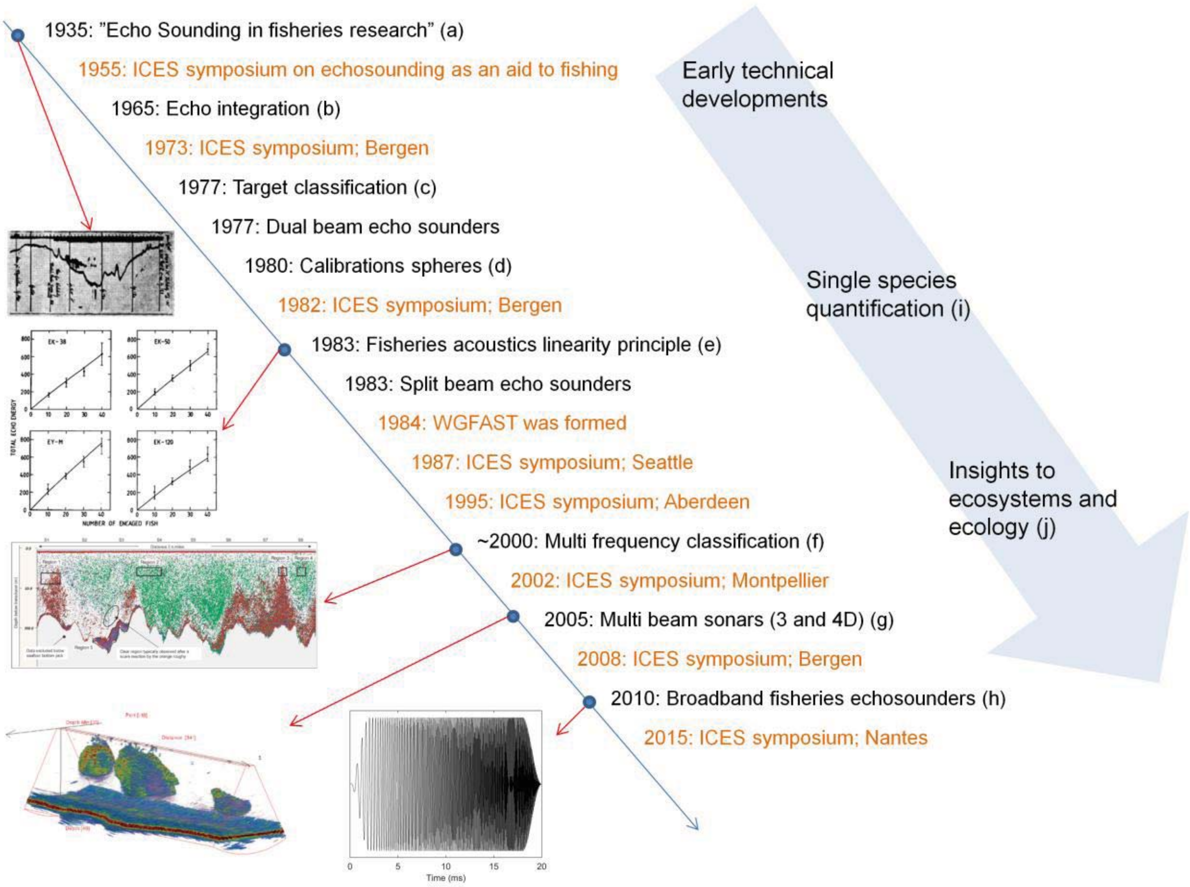

Figure 2**.** Text mining of the abstracts of four recent ICES acoustic symposia (titles only for 1987). a) Visualization of the 25 most frequent words using a Venn diagram. The ten root words common to all symposia are: *abund*, *distribut*, *estim*, *fish*, *measur*, *school*, *sea*, *survey*, *system*, and t*arget*. b) Semantic variations across symposia found among the 50 most common words of the abstracts and titles identified by a non-symmetric correspondence analysis (implemented in R package ade4; Dray et al. (2007)). In the factorial map the size of labels is proportional to the contribution of each word to the first two axes representing 9% of the overall variation. Inset: 90% convex hulls of symposia based on the scores of their abstracts.

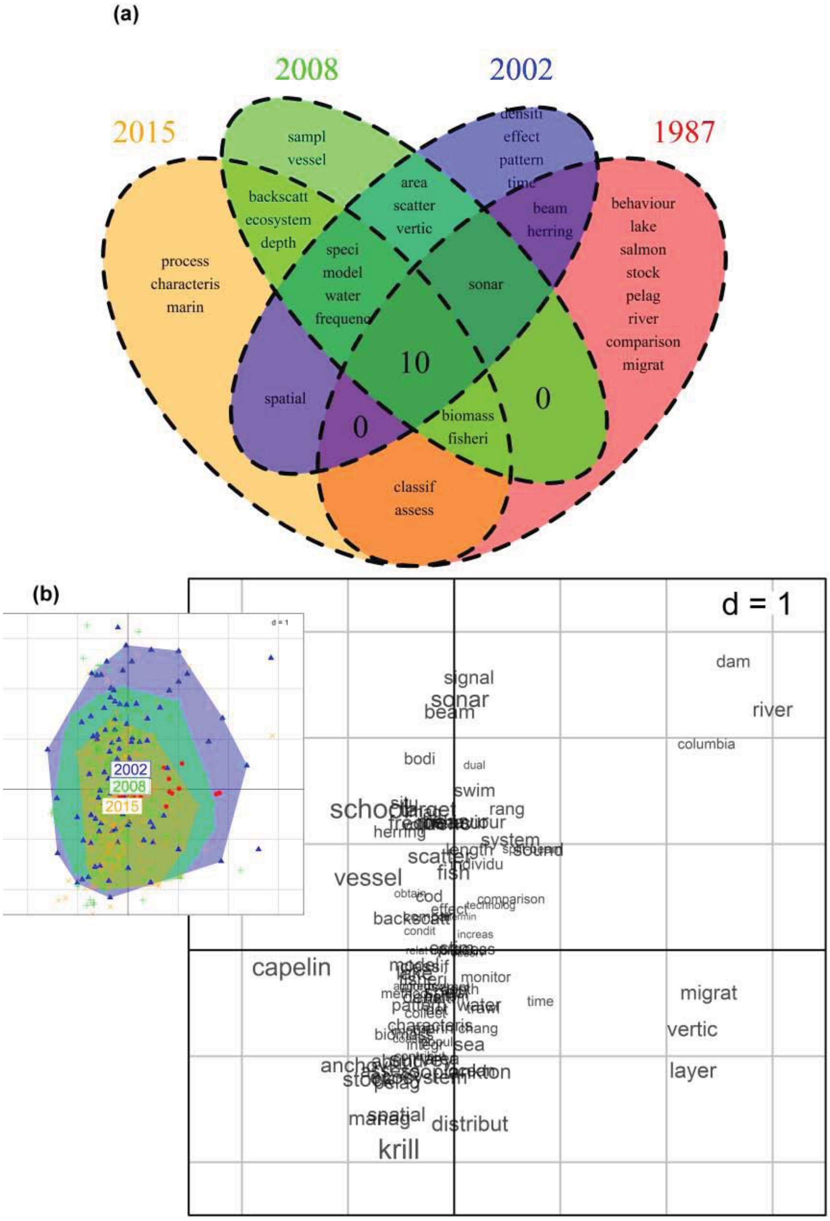

Figure 3. Network of 2015 symposium co-authorships (talks and posters) obtained using a stochastic block model (R package blockmodels, Leger (2015)). Each vertex represents a contributor. The colours indicate the clusters detected by a stochastic block model analysis. The size of each vertex is proportional (on log-scale) to the number of co-authors.