Analysis of multi-beam sonar echos of herring schools by means of simulation

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Abstract

The synchronized behavior of large schools of fish can be a fascinating sight and has caught the attention of researchers for decades. Schools of thousands, or even millions of fish can seemingly function as a single entity, by mechanisms that are still not entirely understood. Models describing the individual behavior (individual based models) have been shown to predict certain schooling features such as predator avoidance, whereas experiments with fish schools in tanks have revealed rules governing the interaction between neighboring fish. However, the step from an individual based model or a school of a limited number of fish in a tank experiment, to large free swimming schools in the ocean, may include challenges with regards to the observation techniques and to conditions of the environment that are not necessarily reproduced in the individual based model or in the tank.

The latest technological advances in underwater acoustic observation has introduced the potential of observing schools of fish of size up to a few hundred meters by three-dimensional images generated by multi-beam sonars. The Simrad MS70 multi-beam sonar provides true three-dimensional images at a temporal resolution down to approximately one image per second, enabling observations of the dynamic behavior of large fish schools in situ, at a spatial and temporal resolution that has not been previously available. In this thesis, data from the MS70 sonar are analyzed by means of simulation, and steps are taken towards establishing a link between the modeled behavior of an individual and the observed behavior of real fish schools.

The principal analytical tool utilized in the thesis is a simulation model developed by the author (and co-authors), which simulates observations from multi-beam sonars based on the positions, orientations, and acoustical properties of arbitrary groups of individual fish, and the configuration and acoustical properties of the sonar and the environment. The framework of the simulation model is presented in the first of three papers in the thesis, along with examples of its use as implemented for the EK60 multi-frequency echosounder, the ME70 multi-beam echosounder, and the MS70 multi-beam sonar, all manufactured by Simrad. The simulation experiments shown in the first paper illustrate for example the potential of the MS70 sonar to provide information about the behavior of fish schools. Specifically, in one of the experiments, a herring school with original mean heading perpendicular to the central sonar beams is modified to represent eight different idealized orientation scenarios, obtained by rotating the fish in specific sections of the school by 90° towards the sonar. This produced reduced backscatter in the sections of the school which were rotated, due to the directionality of the scattering from herring at the acoustic frequencies of the sonar, showing the potential for falsely interpreting orientation changes as fish density changes, but also the potential for extracting information about the local orientation distribution of the school.

In the second paper, the parameters and stochastic properties of the noise (defined as all contributions to the received acoustic intensity *not* backscattered from targets) present in data from the MS70 sonar and EK60 echosounder are estimated from passive recording sequences, motivated by the following three potential uses: (1) subtraction of noise from real data, (2) simulation of noise in synthetic data, and (3) to provide a basis for the development of methods for segmentation of MS70 data of fish schools (applied in the third paper). Particularly, a simulation experiment from the first paper is repeated with addition of noise, in which the polarization (degree of alignment of the individual fish) of a real school which had been circumnavigated by the vessel for several rounds, was estimated by matching the total backscatter of the real school and the total backscatter of simulated schools with a variety of polarizations and packing densities. The experiment illustrates the effect of noise on the estimated polarization, and the potential to infer packing density of the school from the simulation experiment.

The estimated noise from the second paper is utilized in the third and final paper, in the development and testing of a new segmentation method for multi-beam sonar data, which is compared to an existing segmentation method implemented in the post processing system LSSS (Large Scale Survey System). The new method applies a Bayesian approach, where the cumulative distribution function (CDF) of the packing density of omnidirectional targets (scattering equally in all directions) in a voxel is estimated based on the observed data, the estimated noise, and a prior probability distribution of the signal. The CDF is evaluated at a specified lower schooling threshold, and the resulting probabilities that the packing density is below the schooling threshold is smoothed by a Gaussian kernel in the logarithmic domain (implying products of the probabilities in the neighborhood around the voxel). Voxels for which the smoothed probability is below a segmentation threshold, are identified to contain the school. The two segmentation methods are tested on simulated data of 240 herring schools of various shapes, sizes, packing densities, and depths, and compared with ground truth segmentation data generated from the fish positions used as input to the simulation model to identify recommended parameter settings for both methods, and to determine differences in the performance between the methods. The new method is shown to produce estimates of the school extent, total volume, total target strength (total echo), and mean volume backscattering strength (mean echo density) which are generally closer to the corresponding theoretical values estimated from the ground truth segmentation data.

List of papers

1. Arne Johannes Holmin, Nils Olav Handegard, Rolf J. Korneliussen, Dag Tjøstheim *Simulations of multi-beam sonar echos from schooling individual fish in a quiet environment*, The Journal of the Acoustical Society of America **132**, 6 (2012), 3720-3734, URL: http://link.aip.org/link/?JAS/132/3720, DOI: 10.1121/1.4763981.

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2. Arne Johannes Holmin, Rolf J. Korneliussen, Dag Tjøstheim *Stochastic modeling and simulation of noise and signal in multibeam sonar data*, planned for submission to The Journal of the Acoustical Society of America.

3. Arne Johannes Holmin, Rolf J. Korneliussen, Dag Tjøstheim *Improved morphological fish school characterization by use of simulated multibeam sonar data*, planned for submission to The Journal of the Acoustical Society of America.

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Contents

Chapter 1

Introduction

1.1 Multi-beam sonar measurements

Underwater acoustic measurements are important for fisheries science, and have evolved from single-beam echosounders operating at a single acoustic frequency [25], to multi-frequency echosounders enabling species identification at resonant frequencies [17] and multi-beam sonars capable of representing entire fish schools in a single recording [18]. The basic mechanism of an echosounder is that a (short) sound pulse is transmitted into water in a (narrow) beam, and the backscattered sound from targets in the water is recorded and processed to measure the ability of the targets located in specific volume elements (voxels) to scatter sound in the direction of the echosounder. Specifically, the received sound is sampled in intervals of constant duration, and the time between emission and reception is interpreted as the distance to the voxels. If the echosounder is mounted on a moving vessel, a two-dimensional image can be generated from the recordings. Multi-beam echounders and sonars transmit sound in multiple narrow beams, expanding the data to aggregated [27] or true [18] three-dimensional acoustic images. By convention the difference between an echosounder and a sonar is that an echosounder is oriented mostly vertically downwards, whereas a sonar is oriented mostly horizontally.

Acoustic observations are primarily represented in terms of the backscattering cross-section σ_{bs} of individual targets, measuring the ability of a target to reflect sound; or the volume backscattering coefficient $s_{\mathrm{v}} = \sum_V \sigma_{\mathrm{bs}}/V$ [19], quantifying the density of acoustic backscatter in the voxel with volume V. Considering an optimally scattering spherical target, which may be approximated by a bubble of air in water, the backscattering cross-section σ_{bs} can be thought of as the cross-sectional area of the bubble, while the volume backscattering coefficient s_{v} can be thought of as the density of bubbles of a particular size. For a swim bladdered target, the majority of the scattering can be caused by the swim bladder [7], and σ_{bs} can thus be compared to the cross-sectional area of the swim bladder. However, a series of factors influence the backscatter from individual targets, such as frequency dependent resonance of the target [20], and directional scattering, e.g., higher backscattering from herring at side aspect compared to head aspect [23]. Directionality in the scattered sound increases with frequency and oblongness (ratio between length and width) of a target, and can be highly influential on the total backscatter from polarized schools [12]. The decibel representation of σ_{bs} is the target strength $\mathrm{TS} = 10\log_{10}(\sigma_{\mathrm{bs}})$, and the decibel representation of s_{v} is the volume backscattering strength $S_v = 10\log_{10}(s_v)$, which are both often preferred when reporting and visualizing acoustic data. For detailed definitions of TS and S_v see Paper 1 [12].

1.1.1 The Simrad MS70 multi-beam sonar

The work presented in this thesis considers principally measurements from the Simrad MS70 multi-beam sonar, which transmits sound in 500 beams distributed in 20 fans of 25 horizontally aligned beams in each fan. The lowest fan is oriented 45° downwards relative to the surface, and the uppermost fan is oriented parallel to the surface, each fan covering 60° horizontally. The dimensions of the voxels in the middle of the sonar sampling volume are approximately 10 m by 10 m by 0.38 m, bounded by the widths of the beams and the duration of the sampling intervals. Absorption and attenuation of the sound results in decreasing signal to noise ratio with increasing range, and data outside of a range of 500 meters can be regarded as dominated by noise. Fig. 1.1 illustrates the volume covered by the MS70 sonar.

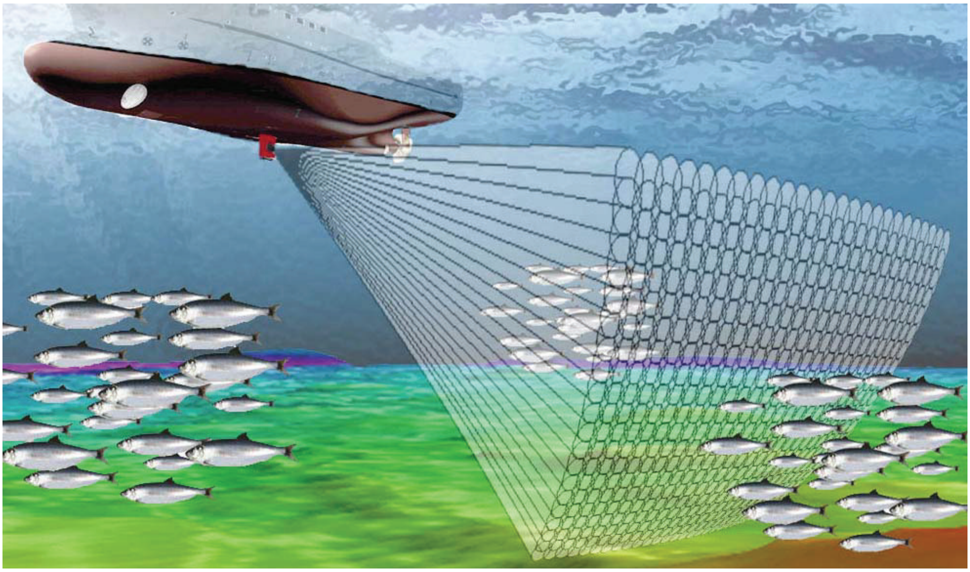

Figure 1.1: Illustration of the volume insonified by the Simrad MS70 multi-beam sonar.

The MS70 sonar can capture an entire fish school of size up to a few hundred meters in diameter in one single transmission, and the time between transmissions can be as low as 1.2 s, providing four-dimensional data at a temporal resolution that enables detailed study of the inner structure and dynamics of large fish schools.

1.2 Fish school behavior models

Aiming at fully exploiting the potential for studying the behavior of fish with the MS70 sonar, models linking the behavior of the school and the behavior of the individual fish were considered to be an important motivation for the work in this thesis. This type of individual based modeling has been shown to provide important knowledge about the behavior of fish and other socially interacting species, and was suggested by Parr [21] who described rules for the behavior of the individual fish in a school which could result in characteristic schooling behaviors such as milling, where an entire school rotates around a an empty core. The concept of individual based modeling was concretized by Aoki [1], who defined a zone of attraction, a zone of alignment, and a zone of repulsion around the individual fish, similar to the zones shown in Fig. 1.2, within which a different fish provokes a change of heading of the fish in agreement with the types of the zones. The speed of the fish was assumed to be unaltered by the influences from the neighbors, which has been adopted in many later simulation studies [5, 15, 26]. Through simulations, he concluded that removing the zone of alignment was incompatible with efficient propagation of the simulated school, although the fish still stayed close to each other. The model of Aoki [1] was restricted to two dimensions and considered 8 and 32 individuals, and the probability density function (PDF) of the new heading of an individual was defined as a mixture of normal distributions related to the influences from each of at most 4 neighbors (conforming to fish deciding to respond to the influence from one of the neighbors).

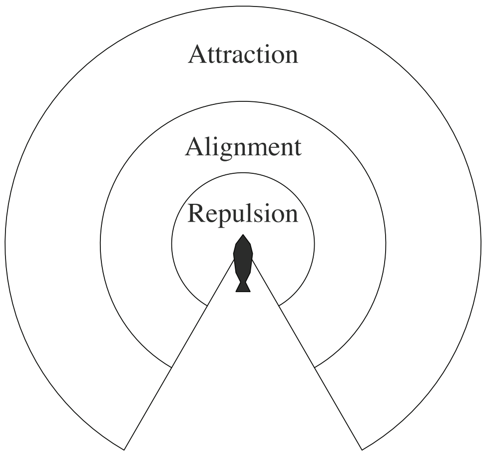

Figure 1.2: Schematic representation of the zones of repulsion, alignment, and attraction used in many individual based behavior models.

The number of influential neighbors in individual based models was discussed by Huth and Wissel [15], who simulated schools of 8 individuals by a three-dimensional model with rules similar to those used by Aoki [1]. They concluded that the polarization of the school, defined by the mean angle deviation between the headings of the individuals and the school [15, 22], was nearly constant as a function of the number of influential neighbors when this number was larger than or equal to 3, suggesting that the information contained in the positions and headings of the three nearest neighbors was nearly equivalent to the information contained in the positions of all of the fish in the simulated school. Huth and Wissel [15] also made the fundamental distinction between responding to one of the neighbors (decision-model or D-model) as applied by Aoki [1], or by averaging the influences from at most 4 neighbors (averaging-model or A-model), i.e., by choosing the new heading of the individual based on a single normal PDF with mean based on an average of the influence from its neighbors.

The advances in computer technology over the past decades has increased the potential for simulating collective behavior of fish schools of a large number of individuals. Using a similar three-dimensional model as the one described by Huth and Wissel [15], Couzin et al. [5] simulated schools of up to 100 fish. By varying the size of the zones of alignment and attraction, they demostrated sharp transitions between four states of dynamic behavior; swarm (cohesion but low polarization), milling, dynamic parallel state (polarized and mobile school), and highly parallel state. They also discovered that while keeping the zone of attraction constant, transitions between the states depended on whether the zone of alignment increased or decreased, interpreted as evidence of a potential collective memory within animal groups. These important results inspire the concept that dynamic behavioral characteristics may emerge from a simple set of rules of the behavior of the individuals. This concept of emergent properties [22] was illustrated in particular by Simpson et al. [24], and Bazazi et al. [2], who showed through experimental results that cannibalism is a driving force for migration of Mormon crickets and locusts, respectively. Torney et al. [26] demonstrated the ability of groups of individuals to locate the source of a noisy and turbulent chemical signal, through simulations with a 2-D individual based model where the size of the zones of alignment and attraction were modified depending on the change in the concentration of the chemical signal as observed by the individual. In their model, an individual experiencing an increase in the concentration would continue in the direction of the increase, neglecting its neighbors, whereas an individual experiencing a moderate or sharp decrease would essentially increase its zone of alignment or attraction, respectively. The result of Torney et al. [26] is in agreement with the observation that groups with a low proportion of informed individuals can successfully locate a food source, shown by Couzin et al. [4] through simulations with an individual based model similar to the ones used by Couzin et al. [5] and Torney et al. [26].

Inferring the rules governing the interaction between individuals in fish schools has lately been shown to be a productive and promising approach. Berdahl et al [3] experimented with golden shiners of various group sizes in a tank illuminated with a light field containing a moving dark region, and showed that the larger schools were more successful in locating the preferred darker regions [10]. Furthermore, they demonstrated that the individuals responded to the environment only by correlating their speed with the local light level while simultaneously interacting socially with their neighbors in the usual manner required for schooling. These results illustrate an emergent property where the school functions a tool for the individuals to locate preferred regions, without any additional actions applied by the individuals other than slowing down in the preferred darker regions, as would single fish do as well.

A more direct approach was taken by Herbert-Read et al. [11] and Katz et al. [16], who, independently, applied machine learning techniques and force matching techniques, respectively, to determine the behavior rules governing the individual fish in schools of 2, 4, and 8 mosquitofish in the study by Herbert-Read et al. [11], and 2, 3, 10, and 30 golden shiners in the study by Katz et al. [16]. Both groups uncovered two important results which contradict common assumptions made by many individual based models. First, a focal individual was shown to respond to a neighbor by adjusting speed as a function of the position of the neighbor as projected onto the heading of the focal individual. This involves that the focal individual speeds up to prevent an individual approaching from behind to get too close (repulsion) and to catch up with an individual getting too far ahead of the focal individual (attraction). In many simulation studies with individual based models [1, 5, 15, 26], the fish react to the impulses from neighbors by altering heading only, inconsistent with the findings of Herbert-Read et al. [11] and Katz et al. [16]. Second, both groups were unable to isolate a specific alignment behavior between the individuals, as predicted by Aoki [1] and employed by Couzin et al. [5] to demonstrate sharp transitions between behavior states of fish schools. Together, these results call for a new generation of individual based behavior models with model assumptions rooted in empirically determined interaction rules between the individuals.

In light of the recent findings of the experimental studies by Herbert-Read et al. [11], Katz et al. [16], and Berdahl et al [3], a number of unanswered questions should be addressed in the near future. For example, Katz et al. [16] specifically proposes that their approach of force matching should be applied to other species than the golden shiner, in order to reveal whether alignment or constant speed [1, 5, 15, 26] may exist in other species. The work of Herbert-Read et al. [11] added mosquitofish to the list of species with no clearly shown alignment behavior. However, both Herbert-Read et al. [11] and Katz et al. [16] investigated fish which were not disturbed in any way, and applying their techniques to fish schools responding to predators or to other external stimuli, may identify additional individual behavior rules necessary for hasty predator escape maneuvers.

Even if the local interactions between individuals were to be fully understood, there may still exist effects related to school size when schools of millions of fish are considered, as obtainable by the MS70 sonar [13]. Simulation studies with individual based modeling has so far considered a maximum of 16 000 fish [28], whereas existing models have been reported to possibly simulate millions of individuals per second [6]. Developing methods for identification of the dynamic behavior of large fish schools observed with the MS70 sonar, and evaluation of the feasibility of individual based modeling to recreate the behavior by use of simulated MS70 data, was a key objective for the work of this thesis.

1.3 Motivation and objective of the work

The MS70 multi-beam sonar provides the unique possibility of observing schools of fish consisting of millions of individuals in situ by four dimensional data. The sonar observes targets at angles between 0° and 45° below the surface (Sec. 1.1), introducing additional variability to data of fish schools due to the heading and the related backscattering directivity of individual fish, compared to conventional echosounders aiming mostly downwards. Whereas echosounder data can be interpreted largely in terms of the density of the fish [8], an apparent change in the fish density as observed by the MS70 sonar may be caused by a change in the mean orientation of the fish. This introduces the possibility of estimating the local orientation distribution of a fish school observed with the MS70 sonar, required that the scattering from the individual fish and the local polarization of the school are estimated as well. Further, local orientation changes may be indications of dynamic behavior patterns such as evasive maneuvers in response to predators [9], making the MS70 a potential tool for behavior analysis of large free swimming fish schools. In this thesis, steps are made towards establishing a method for estimation of the local orientation distribution, aided by a simulation model developed by the author (and co-authors), in which the individual positions, orientations, and acoustical properties of arbitrary fish schools are translated into MS70 data by taking the specifics of the sonar and the environment into account. The simulation model framework and some results of its application are presented in Paper 1 [12]. In addition to generating MS70 data, the simulation model was used to obtain synthetic data of the Simrad ME70 multi-beam echosounder and the Simrad EK60 multi-frequency echosounder.

The noise in the data from the MS70 sonar is generally higher than the noise in the EK60 echosounder [14]. This poses a challenge to the interpretation of the data, particularly for schools with low packing densities or with mean orientation headed towards or away from the sonar (implying reduced backscatter, as described in Sec. 1.1). Accordingly, in Paper 2 [14], the noise in passive (only reception) and active (both emission and reception) MS70 data was estimated and modeled stochastically, and implemented in the simulation model presented in Paper 1 [12]. The effects of the implementation of noise in the simulated data were illustrated by repeating some of the experiments of Paper 1. The estimated and modeled noise was also subtracted from real MS70 and EK60 data, showing that fine scale variations in the noise, primarily caused by a periodic noise component along some some beams of the MS70 sonar and the EK60 echosounder, were well accounted for by the estimated noise.

Estimation of the noise in the MS70 sonar data was also motivated from the objective of establishing methods for identification of the orientation distribution of a fish school, which can be used to infer the dynamic behavior of the school. A crucial step towards such a methodology is to accurately estimate the true extent of the school (segmentation), in particular in the regions where the backscatter may be low due to the orientation of the fish. Accurate knowledge of the stochastic properties of the noise can improve segmentation, as shown in Paper 3 where a new method for segmentation of fish schools observed with the MS70 sonar is developed and compared to the existing segmentation method employed by the post processing system LSSS (Large Scale Survey System).

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