Multiple Scattering of Underwater Sound by Clouds of Suspended Scatterers

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LONG-TERM GOALS

Improve our understanding of sound scattering by clouds of suspended objects (e.g. bubble clouds under breaking waves or ship wakes, fish, sediment grains, etc.) in the ocean to aid the identification, parameterization and discrimination of different types and to improve the modeling of oceanic acoustic environments.

OBJECTIVES

1. To improve techniques to extract estimates of abundance, size, and density of various scatterers from simple active and possibly passive acoustic measurements.
2. To improve our understanding of the influence of cloud geometry and spatial correlation statistics on the scattering returns.
3. To explore the possibility of obtaining crucial parameters of the cloud from large range or from permanent acoustic observation systems.
4. To examine and possibly improve or modify existing multiple scattering theories to aid the progress towards the above goals.
5. To conceptually prepare experimental procedures and techniques exploring the potential of object detection and discrimination.

APPROACH

In order to address the objectives of the proposed research the following two-fold approach is taken:

First, numerical studies based directly on Foldy's fundamental equations of multiple scattering are conducted to compute scattering amplitudes as well as differential- and total cross-sections. In the simplest case of N identical, isotropic scatterers of strength f_s, these equations, written in $N \times N$ matrix, form are

$$p_s(\bar{r}) = f_s\left[(\mathbf{1} - f_s\mathbf{G}^k)^{-1}\mathbf{p_0}\right]^{\mathrm{T}} \bullet \mathbf{G}^k(r)\,.$$

Therein, the matrix $\boldsymbol{G}^k$ and the vectors $\mathbf{p_0}$ and $\boldsymbol{G}^k(r)$ are defined in terms of the free-field Green's function $G(k;r_i\text{-}r_j)$ and the incoming acoustic field $\mathrm{p}_0(\mathrm{r}_\mathrm{i})$ at the locus, r_i, of the i^{th} constituent:

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14. ABSTRACT
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15. SUBJECT TERMS

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$$\mathbf{G}^{k}_{i,j} = \begin{cases} G(k;r_i - r_j) & i \neq j \\ 0 & i = j \end{cases}$$

$$\mathbf{p_0} = p_0(r_i) \qquad .$$

$$\mathbf{G}^{k}(r)_i = G(k;r_i - r)$$

These equations are implemented and solved in MATLAB on a personal computer. Clouds containing up to several thousands constituents are studied. Coherent and diffusive cross-sections are evaluated using as many realizations of the scattering geometries as necessary to obtain 1% accuracy. To simulate multiple scattering phenomena that occur at higher constituent numbers it is highly beneficial to carefully optimize code and to use parallel algorithms. To gain insight into the underlying scattering physics several scenarios are computed with varied geometrical parameters, such as:

- *Number density and scattering strength* and, if feasible, also individual scattering characteristics, modeling bubble- and sediment-clouds, as well as fish schools.
- *Cloud geometry* (spherical, elliptical, random, etc.) to investigate the sensibility of multiple scattering features to the overall shape of the ensemble. The goal of this analysis is to identify signal features that are stable with respect to the geometry, which might not be known a priori.
- Degree of *spatial correlations* (random, hard-sphere, etc.), to investigate the dependence of the scattering return on the internal organization of the ensemble. Ideally, one would like to be able to systematically investigate the entire regime, spanning from a purely random configuration to the Bragg domain for highly ordered systems. This requires the generation of ensembles with fixed correlation length. The clarification of this problem will also be part of this analysis.
- Degree of transition from cloud-core number density to constituent-free medium. This analysis will test the dependence of the *occurrence* of collective modes on the “compactness” of the ensemble.

Complimentary to the numerical investigation an analytical approach based on the assumptions of the effective medium theory is followed to extend the range of predictions into the domain of very high constituent numbers, which cannot easily be studied numerically due to limitations of computational resources. Furthermore, a comparison of analytical and numerical results allows an assessment of several approximations intrinsic to the effective medium models. Naturally, analytical expressions can only be derived for simple canonical geometries.

Finally, experimental procedures to test the potential of inversion for cloud- and constituent-properties in the lab and in the field must be conceptualized. This module depends on future funding of laboratory and field acoustic equipment, e.g. by DURIP grants.

WORK COMPLETED

1. Implementation of the computational scheme in MATLAB
2. Optimization of early versions of the MATLAB code and parallelizing some code modules
3. Numerical and analytical exploration of spherical clouds of isotropic scatterers (e.g. bubbles and fish schools at wave-numbers small compared to their size)
4. Investigation of the effects of short-range correlations on the scattering cross-sections for the case of spherically shaped clouds
5. Investigation of frequency shifts as a function of constituent densities
6. Design of an inversion scheme to estimate total constituent numbers based on low-frequency collective resonances, particularly using the quality factor of the resonances
7. Exploration of multiple scattering effects on the signal of acoustically active clouds of scatterers
8. Application to passive acoustic signatures of large acoustically active fish schools and comparison with events recorded in PWS, Alaska, related to bubble release of herring aggregations
9. Preliminary adaptation of the numerical computation to non-spherical clouds

RESULTS

Some results of this ongoing project have been published (Hahn 2007, and Hahn and Thomas 2008). In these publications a more detailed discussion can be found. For this reason, only the core results are reviewed here, and also some results that have not yet been published.

Since the effective medium theory is valid over a wide range of constituent densities it is an ideal tool to study important multiple scattering effects that concern scattering cross-sections. Figure 1 shows the results for a spherical cloud in which the constituent density is gradually increased. (The example of a fish school is simply chosen to be specific and to use objects with well-investigated scattering characteristics. The results, however, also apply to other resonant constituents.) Two scenarios are shown, a small cloud with only 66 constituents (top row) and a larger one with 3000 (bottom row). With increasing density, only the larger one shows collective modes at higher densities. In both cases the scattering strength increases at first with increasing density, followed by a downward shift of the peak associated with the resonance of individual constituents. The knowledge of these frequency shifts is of great importance for practical applications such as long-range absorption spectroscopy. Ignored, the inversions for individual constituent properties based on their (individual) resonances are erroneous.

If the lowest mode resonance is clearly visible without much interference from neighboring resonances, a direct inversion for the total constituent number can be performed, given the overall geometry is approximately known. For very dense clouds (here we show a rather unrealistically dense fish school for demonstration purposes) as drawn in the top panel of Figure 2, the spacing can, in this example, be reconstructed to about 1% and the cloud radius to about 2%, yielding a constituent number estimate good to roughly 10%. For smaller densities, the accuracy degrades somewhat (see lower panel). The inversion is mathematically unique but might suffer from the fact that the “hot spot” region of small error is fairly elongated. In practice, this could lead to larger uncertainties, mistaking a small dense cloud for a larger one of smaller density. The basis for such an inversion from collective modes is a good analytical understanding of the functional shape of the used resonances. This problem has been solved approximately for spherically shaped clouds.

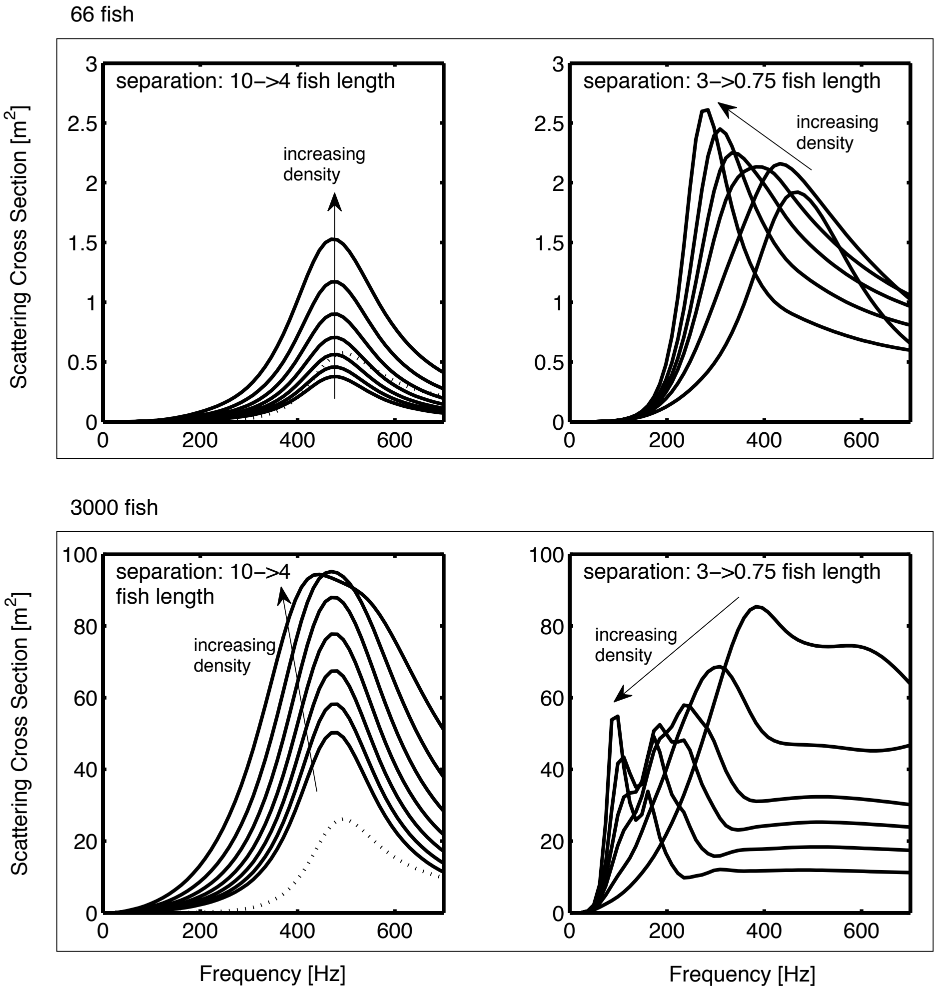

Figure 1. Effective medium computation for the scattering cross-section of a fish school [graph: the resonance shifts downwards with increasing constituent density and collective modes occur for large enough schools]

Figure 3 shows a plot of the mode model results (dashed line) for a sample cloud consisting of 3000 objects together with the full effective medium computation. The mode shapes have been derived in closed form well suited for the desired inversion. Compared to previously published results that utilize only the collective mode resonance frequency, this is a much more powerful inversion procedure that, in principle, uniquely yields the total constituent number of the cloud.

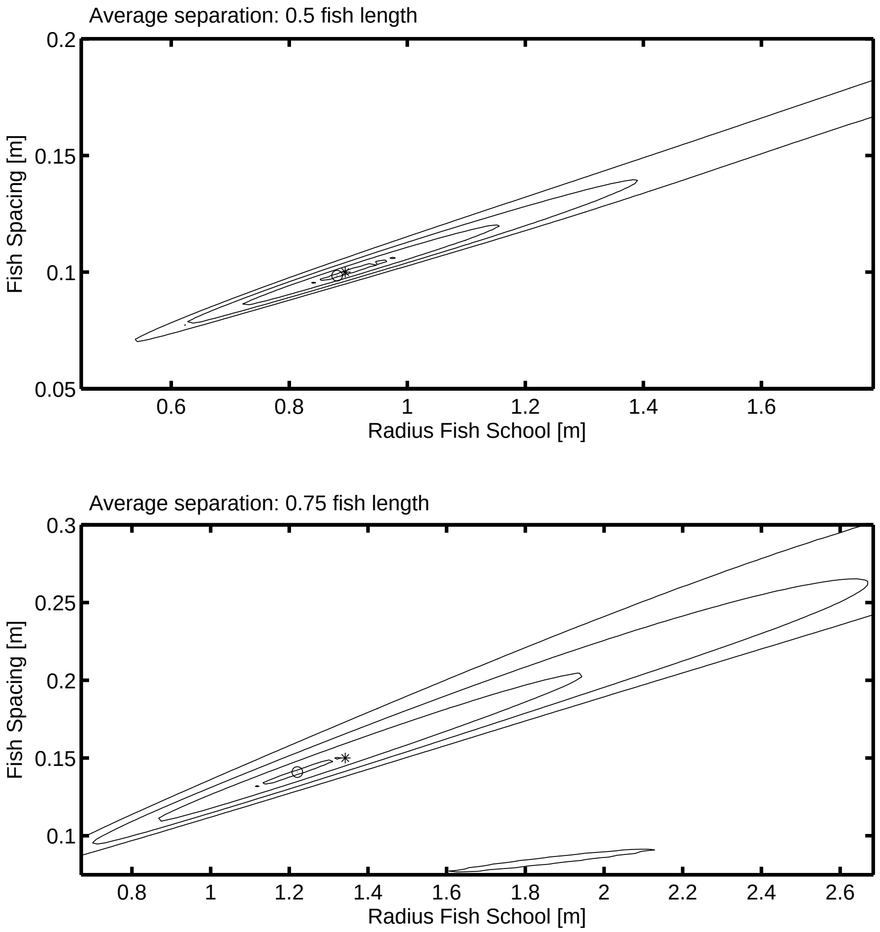

Figure 2. Inversion for total constituent number for the case of a dense fish school [graph: the resonance model allows an inversion for constituent density and cloud radius, hence, for the total constituent number. The precision of the inversion is better for smaller densities.]

To demonstrate the utility of a good understanding of sound scattering within clouds of suspended objects for “real-world” problems, the effective medium approach was incorporated into a theory describing sound emissions from acoustically active herring schools. Herring schools, under some circumstances, release bubbles from their swim bladders, which produces the sound. These events are strong sound sources and play an important role in the ambient acoustic environment where these schools aggregate.

To predict the source levels and spectral shape of these events, scattering of sound within the school has to be taken accounted for, since most of the sound has to travel through parts of the cloud before reaching the observer. Figure 4 shows resulting dispersion curves for a realistic scenario of a high-intensity gas release that is triggered by predators, exciting the herring schools to exhibit their gas-release behavior. In these computations, the released bubbles as well as the fish bladders have been taken into account.

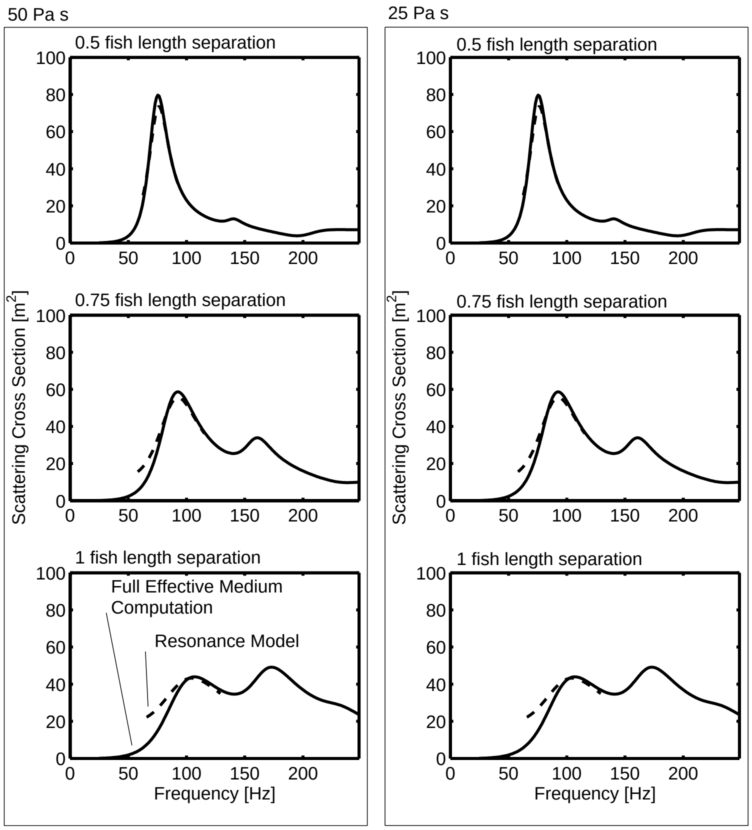

Figure 3. Comparison of the resonance model with effective medium results [graph: the resonance model correctly captures the resonance frequency and width (Q) of the lowest-order collective mode, even at high densities]

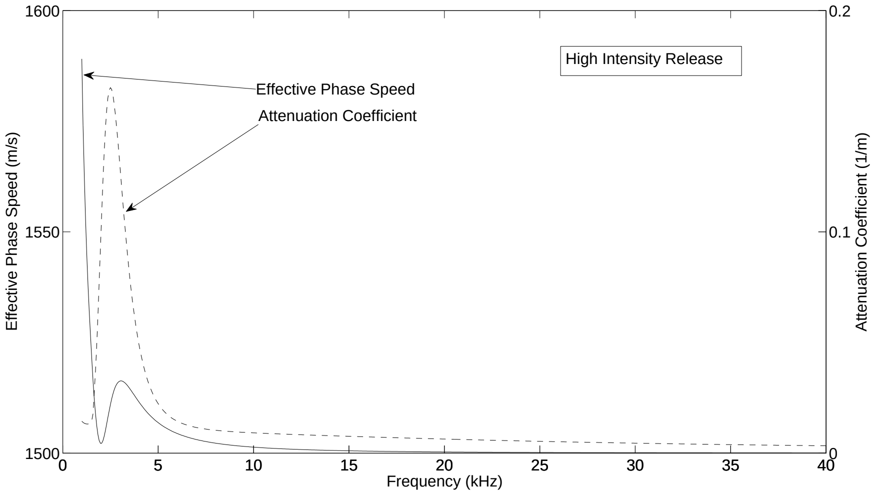

Figure 4. Effective phase speed and attenuation as a function of frequency for a dense, acoustically active, "real-world" fish school [graph: graph of dispersion curves for a gas releasing herring school with an attenuation coefficient of up to about 0.2 m^{-1}]

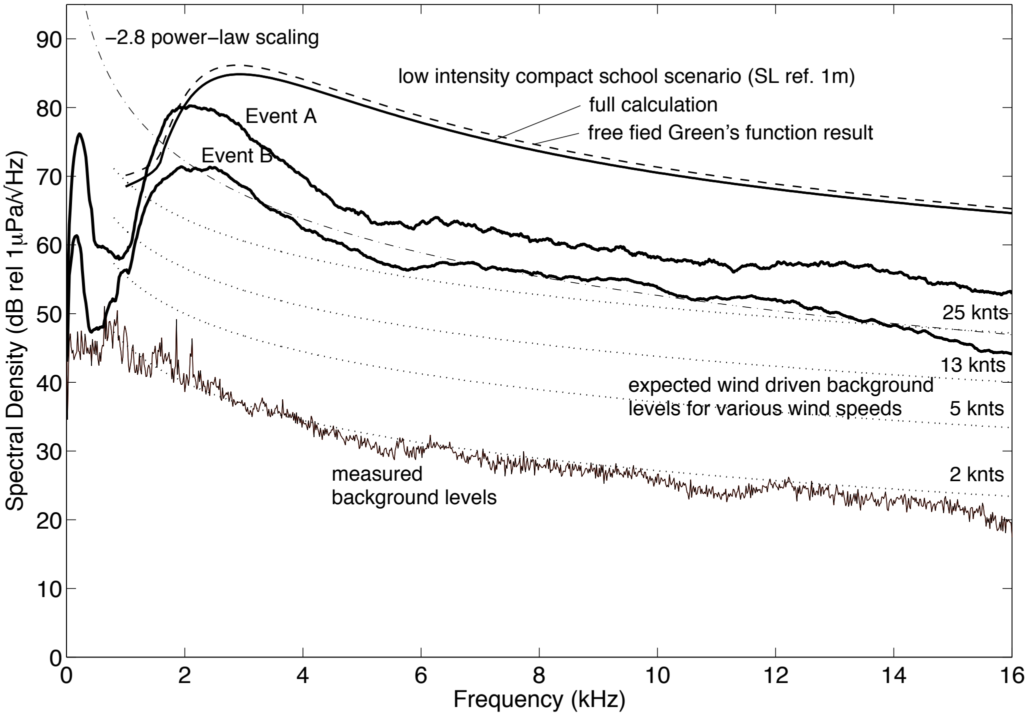

Figure 5. Measured spectral density of a gas releasing herring school compared to predicted source levels
[graph: predicted source levels quickly rise to about 90dB at 2-3 kHz and follow a -2.8 power-law at higher frequencies.]

The combined effects of attenuation and sound-speed alterations in these clouds needs to be taken into account to correctly predict spectra and levels. Figure 5 gives an example, which is currently in print (Hahn and Thomas 2008). The solid lines labeled *Event A* and *Event B* are data collected from a single hydrophone, at a depth of 10 m in PWS, Alaska. The modeled signatures clearly reproduce the spectral shape as well as the overall source levels within uncertainties of the underlying geometrical assumptions.

IMPACT/APPLICATIONS

A better understanding of scattering from clouds of suspended objects of various types will increase the power of underwater acoustics as a *remote sensing tool*. Examples are the determination of constituent numbers or number densities from afar, e.g. in fish schools, plankton, sediments clouds, or in bubble plumes from ship wakes or breaking waves. In addition, this work will support a better understanding of active and passive ambient acoustic environments that contain a large number of submerged objects such as massive aggregation of fish in coastal environments.

RELATED PROJECTS

This work is closely related to parallel work of the PI on applications of this work to passive acoustics of fish aggregation.

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