Statistical Characterization and Classification of Fish School Clutter

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LONG-TERM GOALS

To significantly reduce the probability of false alarm in Navy active sonar systems. This goal will be achieved through developing signal processing algorithms for active sonar systems which can account for the non-Rayleigh nature of clutter from fish schools. Part of this goal will involve characterizing the performance of the algorithm.

OBJECTIVES

To develop and apply probability density functions (PDF's) to describe non-Rayleigh echoes from patchy clutter for eventual use in classifiers. The general methods are applied principally to clutter from aggregations of fish.

APPROACH

This study involved a combination of investigating existing PDF's, developing a new physics-based formulation for a PDF that is matched to the problem of echo statistics due to patches of scatterers in a directional sonar beam, and applying those theoretical distributions to active acoustic data collected in the ocean. Data set #1 (scientific): This study took advantage of broadband acoustic data collected in another program (N00014-1-10-0127). The downward-looking active sonar was towed over aggregations of fish and direct-path echoes were recorded from 1000's of transmissions. Most of the acoustic

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energy was in the frequency range 2-4 kHz, which coincided with the resonance frequency of the swimbladder of the fish, giving rise to strong echoes. The echoes were observed to be strongly non-Rayleigh. Net samples of the fish were collected in concert with the acoustic measurements. The data were analyzed for a range of direct path scattering geometries and the degree to which the data are non-Rayleigh. In addition, the PDF that best characterizes the echo statistics was determined for each geometry. Data set #2 (Navy): In collaboration with Dr. Jim Gelb of ARL/UT, data from a Navy active mid-frequency sonar were analyzed. The data were analyzed for the direct path scattering geometry, as well as different types of clutter features—bottom-like, compact stationary, and compact non-stationary (mobile). Theoretical probabilities of false alarm were calculated using various statistical formulations and compared with the data. Statistics of fish patches: Integral to describing the echo statistics is understanding the statistics of the size and spatial distribution of fish patches. Published models were investigated to determine the one best suited for this problem so that the model can ultimately be incorporated into an echo statistics model. Preparation for HiFAST FNC project. Initial steps in this project were made toward transitioning the results to the HiFAST project. Key elements to be transitioned to the HiFAST project were the depth-dependence of the fish scattering characteristics, statistics of spatial extent of fish schools (variability of fish school dimensions and between-school separation), and statistics of echoes associated with the presence of fish schools in an active midfrequency sonar.

WORK COMPLETED

Four papers intended for refereed journals were worked on. As of this writing, two of the papers have been published in a refereed journal and a third has been submitted to a refereed journal and is currently under revision based on reviewer recommendations. Each of these three papers involves echo statistics associated with patches of scatterers, in general, patches of fish, and clutter features in a Navy sonar. The fourth paper has been drafted (available upon request) which explored statistics of fish school statistics.

In addition to the papers, the initial "building blocks" of fish scattering characteristics were installed into the SST software in preparation for the HiFAST project.

1. Papers published in special issue on clutter in IEEE/JOE (refereed journal; guest editors-- Doug Abraham and Tony Lyons)

Paper #1: Statistics of echoes from fish using a mid-frequency sonar (Stanton and Chu, 2010). This work involved analyzing the echo data collected in a scientific ocean experiment with a short-range downward-looking mid-frequency sonar on another ONR grant (Biology) as described above for various groupings of echo data (involving resolved individual fish and patches of fish-- all data from within a patch, spanning across a single patch edge, and spanning across multiple patches). Conditions under which the data are strongly non-Rayleigh are identified, comparisons are made between theoretical PDF's and data, and the data sets are discriminated through calculating distances between

various theoretical PDF's and data. A key element of this work is connecting parameters of the PDF to physical quantities associated with the data.

Paper #2: General formulation for echo statistics due to finite number of scatterers (or patches of scatterers) randomly distributed in directional sonar beam (Chu and Stanton, 2010). This work connected the results of Ehrenberg, who expressed the echo distribution (as seen through the sonar receiver) in terms of the beampattern PDF and PDF of the scattering amplitude of the scatterer (before beampattern effects), and the results of Barakat, who derived a general expression for the signal PDF due to the summation of a finite number of random variables. Through connecting these results (which includes extending Ehrenberg's results), we developed a new general formulation for the echo PDF (as seen through the sonar receiver) due to an arbitrary number of scatterers or patches of scatterers, each with their own arbitrary echo PDF (before beampattern effects), and each randomly distributed in the sonar beam. The formula is general and is not specific to the fish problem (for example, it could be applied to patches of seafloor scatterers). The paper gives the extension to the Ehrenberg formula, summarizes the Barakat formulation, connects the two in the context of echo statistics of random scatterers in a sonar beam, and gives examples of the solutions for various combinations of important conditions. In addition, the theoretical predictions were numerically validated.

2. Paper submitted to refereed journal involving applying new physics-based formulation for echo statistics from Paper #2 to Navy mid-frequency active sonar data (Stanton et al., submitted). As described above, we have developed a new physics-based model to describe the statistics of echoes from an arbitrary number of scatterers or patches of scatterers, each with their own echo PDF (before beampattern effects), and each randomly located in the directional sonar beam. In parallel to this effort, Jim Gelb applied pure statistics models (e.g., generalized Pareto distribution; no physics) to mid-frequency active Navy sonar data for various types of clutter—bottom-like, compact stationary, and compact non-stationary. We collaborated by applying the new physics-based model from Paper #2 above, to his data. There were generally very good qualitative fits of the theoretical model to the strongly non-Rayleigh tail to most of the mid-frequency data. In order to model the lower amplitudes, the new model was "mixed" with a Rayleigh PDF (Fig. 1). It is assumed that the Rayleigh PDF component of this two-component mixed PDF accounts for background diffuse scattering while the new model accounts for finite numbers of scatterers in the beam. The results showed that the number of clutter highlights inferred varied with clutter type—there were up to about 10 highlights for the bottom-like clutter and one highlight for the compact mobiles (i.e., non-stationary).

3. Comparing competing models of fish school dimension with 3-D data and drafting manuscript for refereed journal. This task involved investigating published models of fish school dimension for future use in the HiFAST project. This involved a combination of learning from the literature and communications with experts in mathematical ecology, as well as analyzing image data concerning dimensions of fish schools collected by

others. In fact, we were given the 3-D images collected from 1,000 fish schools from another investigator for a basis of our investigation.

a. Literature search and communications with experts in mathematical ecology. Two competing theories were investigated, one by Anderson (1981) and the other by Niwa (2003). Both model the dynamics of the fish schools, however with different assumptions leading to dramatically different results. While they predict the same tail of the PDF of the fish school dimension, the functional dependences are different for small fish school dimensions.

b. Comparison of theoretical distributions with school data collected by others. Two sets of data were analyzed: One set was published by Hewitt et al. (1979) in which a horizontal-looking single-beam sonar was used to measure horizontal dimensions of numerous fish schools (providing statistics on along-range dimension of school) off the coast of Southern California. The other data set is unpublished and was provided through a personal communication by Jorge Paramo of the University of Magdalena. His data were collected through use of a downward-looking multibeam sonar towed over the fish to form 3-D images of the schools. Data from about 1,000 schools were provided.

We compared both the Anderson (1981) and Niwa (2003) models to the data (Fig. 2). We determined that both models satisfactorily predicted the tails of the data. However, for small school dimensions, the two models diverged, with the Anderson model following the data. It is difficult to make a definitive conclusion about the accuracy of each model in this latter region since the data tended to have errors for small dimensions. This is not a significant issue regarding the Navy problem, as it would be the larger schools in this context that would be more relevant.

c. Drafted paper describing theoretical predictions of 3-D fish school dimensions. A manuscript has been drafted (available upon request) that describes the intercomparison of the Anderson (1981) and Niwa (2003) models with the 3-D fish school data. The manuscript is intended for a refereed journal.

4. Incorporating fish scattering characteristics into clutter predictions in the SST program for eventual use in the HiFAST project

As part of our anticipated transition of these results into the HiFAST program, we incorporated fish scattering characteristics into predictions of scattering in the SST program in collaboration with Bob Goddard of APL/UW. Two key elements were incorporated: the resonance properties of the fish and their depth dependence. Our results showed that the resonance frequency of the 24-cm Atlantic herring used in the model passed into and then back out of the midfrequency band during a diurnal migration, causing significant variation in the echo during the 30 minute migration (Fig. 3). The predictions demonstrated a 28 dB variation in echo level due to the depth-dependent resonance effects.

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RESULTS

1) Through application of our new physics-based model for echo statistics, we have successfully interpreted Navy active sonar data. This rigorous treatment of the data shows distinct differences in the inferred number of scattering highlights in the different clutter fields—bottom-like, compact stationary, and compact mobiles. 2) Through inter-comparison between two competing theoretical models for fish school dimensions and unique data involving 3-D images of fish schools, we have confirmed the range of validity of the models over dimensions relevant to the Navy problem. 3) Through incorporating the scattering characteristics of fish into the SST, we have demonstrated that for one common sized fish, there can be significant variability (28 dB) in clutter level from fish during their daily migration throughout the water column.

IMPACT/APPLICATIONS

1) Both the scientific (fish) and Navy (three types of clutter features) data have strongly non-Rayleigh tails—an effect that needs to be accounted for in ASW active sonar systems. Our new physics-based model is useful in making predictions to improve the performance of ASW active sonar systems, as it explicitly and rigorously accounts for the physics of the scattering by the clutter feature as well as the sonar parameters (directionality). 2) Through extensive grounding with unique data, we have now identified a model predicting the statistics of fish school size over a wide range of school dimensions. This model will be key in predicting the clutter (and associated echo statistics) from fish schools, such as in the HiFAST program. 3) Through incorporating scattering physics directly into the SST software, we now have a fundamental building block in place for developing high fidelity predictions of clutter due to fish for the HiFAST program.

TRANSITION

In September, 2011, the results of our work on this project were transitioned to the ACB13 SAST (PEO IWS 5A) via the HiFAST FNC program and in collaboration with Dr. Brian La Cour of ARL:UT, and LCDR Ben Jones of NPS.

1)   The statistical models that we developed were used as a metric for the fidelity of the clutter models of patches of fish. Specifically, under this D&I project, we developed models for several important clutter geometries which include a) a beam sweeping across a large patch of scatterers and b) the beam containing an arbitrary number of small patches. Some of the modeling was grounded from mid-frequency measurements we made through funding on another project (ONR Biology). Under the HiFAST program, we modeled the clutter by patches of fish. In order to reduce computation time, many simplifying assumptions were made in the modeling. The fidelity of the simplified models was tested, in part, through use of the new statistics models.

2) A task at the end of this project was also transitioned. This involved incorporating scattering by fish into the SST propagation model for development of the HiFAST reverberation model. Included in that task was modeling the depth-dependence of the fish resonance (which is in the mid-frequency band), modeling shape of the fish patches, and decimating the fish patch into a much smaller number of scatterers (into "scattering centers"), while at the same time maintaining fidelity.

RELATED PROJECTS

This research used scientific data collected by Stanton, Chu, and others in another ONR project (N00014-1-10-0127, Biology) and analysis of Navy data conducted by Dr. Gelb of ARL:UT (ONR, Undersea Signal Processing). Also, the results of this project fed into the HiFAST FNC program which, in turn, were transitioned to the ACB13 SAST this year as described above.

PUBLICATIONS

Chu, D. and T.K. Stanton (2010), "Statistics of echoes from a directional sonar beam insonifying finite numbers of single scatterers and patches of scatterers," *IEEE J. Ocean. Eng.*, **35**: 267-277. [refereed]

Stanton, T.K. and D. Chu (2010), "Non-Rayleigh echoes from resolved individuals and patches of resonant fish at 2-4 kHz," *IEEE J. Ocean. Eng.*, **35**: 152-163. [refereed]

Stanton, T.K., D. Chu, J.M. Gelb, and G.L. Tipple, "Physics-based interpretation of echo statistics of three distinct clutter classes measured with a midfrequency active sonar," submitted to *IEEE J. Ocean. Eng.* and being revised based on reviewer recommendations [refereed]

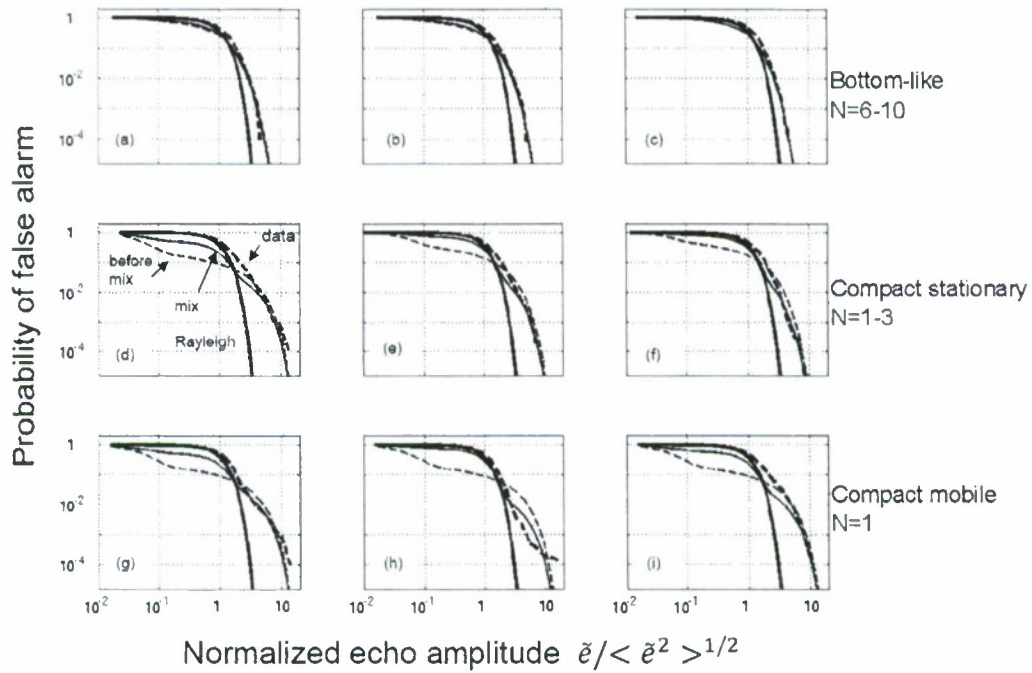# Model: N Rayleigh scatterers mixed with diffuse background

Figure 1. Comparisons of predictions of probability of false alarm (PFA) based on the new physics-based model (Chu and Stanton, 2010) and Navy active sonar data. The data, provided by Dr. Jim Gelb of ARL/UT, are associated with three classes of clutter. There are a different number (N) of scattering features inferred per clutter type. From Stanton et al. (submitted).
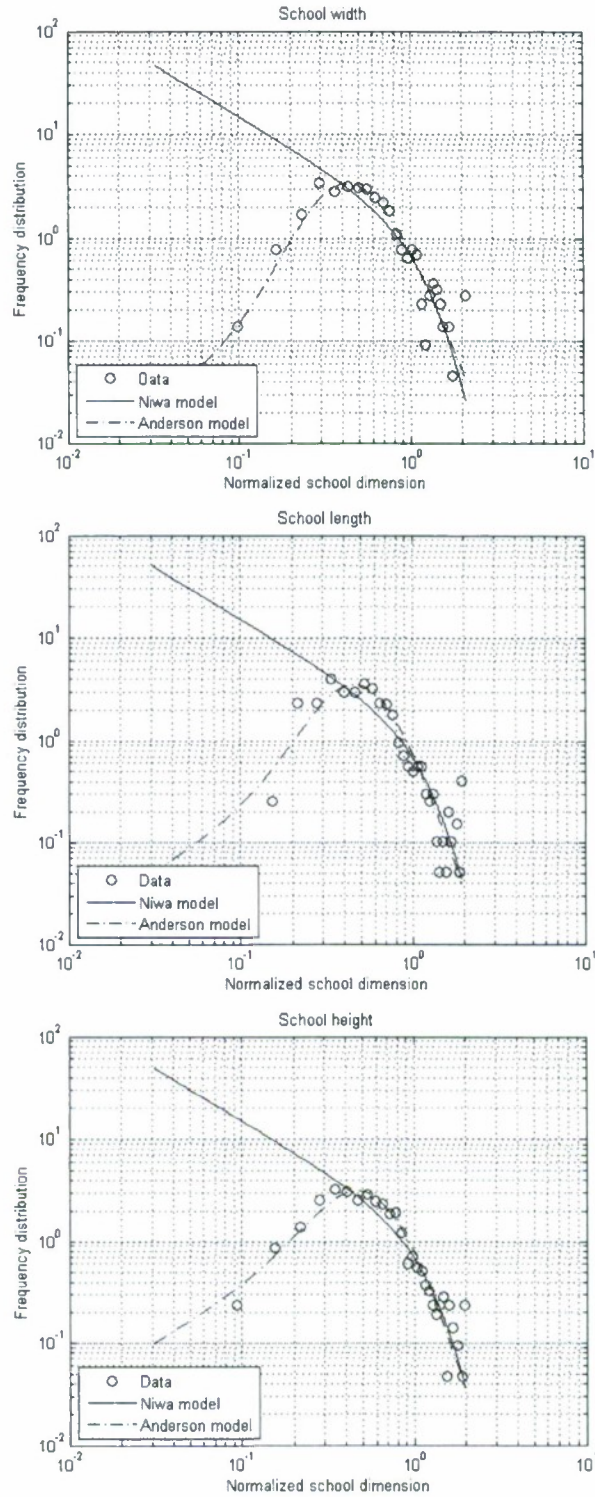
Figure 2. Comparisons between predictions of statistics of school dimensions based on two theories—Anderson (1981) and Niwa (2003)—and data based on unique 3-D images of 1,000 fish schools.
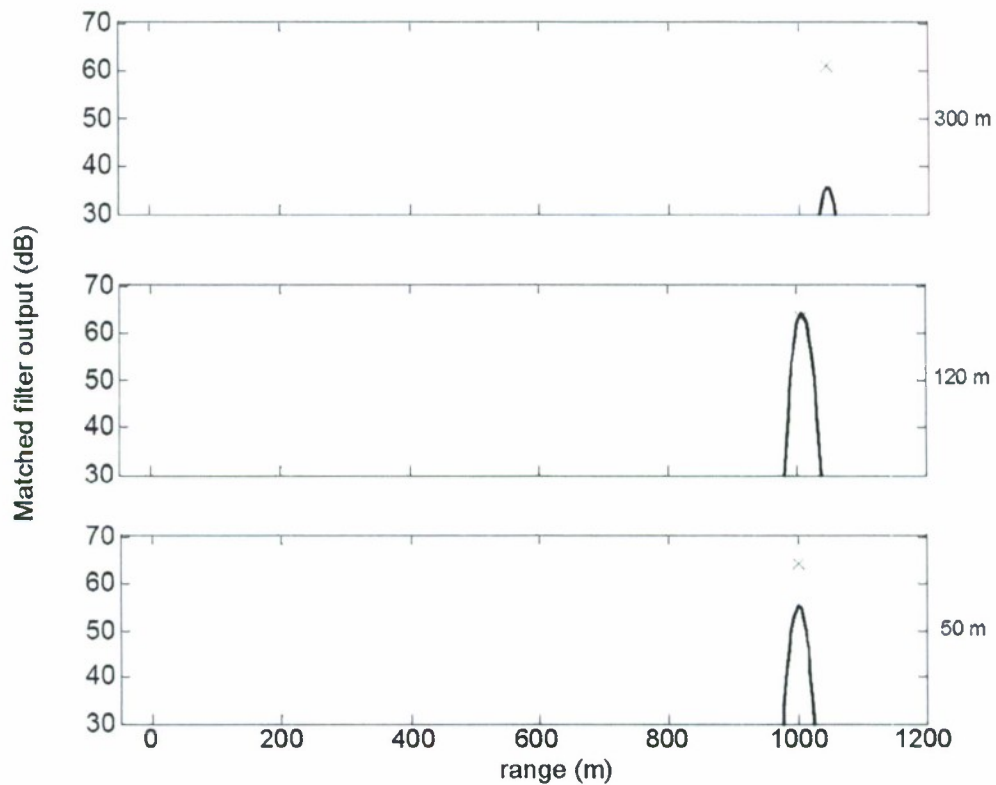
SST – Fish Clutter Predictions

Figure 3. Predictions of echoes from fish in a waveguide using the SST program. Predictions are made for three different depths of fish for a near-surface midfrequency sonar. The resonance frequency coincides with the sonar frequency at an intermediate depth causing the strongest echo at that depth. (From LCDR Ben Jones, NPS—HiFAST collaborator with Stanton).

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