ONR Graduate Traineeship Award in Ocean Acoustics for Ms. Deanelle T. Symonds

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LONG-TERM GOALS

Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical sonar by introducing false alarms in the system. During the Main Acoustic Experiment (MAE) 2003 of the Acoustic Clutter program, densely populated fish shoals were identified to be the dominant cause of shallow water acoustic clutter in the New Jersey Continental Shelf. The mixing of cold and warm water cause nutrient rich upwellings in continental shelf environment, creating favorable conditions for all types of marine life. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it becomes critical to identify, understand, and be able to accurately model the leading order mechanisms which cause bio-clutter in Navy systems in biologically-rich environments such as continental shelf regions.

A remote sensing technique to instantaneously and continuously monitor areal population densities of large fish aggregations over continental-shelf scales has been developed and applied to data acquired during the Main Acoustic Experiment (MAE) 2003 [1-10]. Conventional fish survey methods rely on highly-localized vertical echosounder measurements from slow-moving research vessels to estimate regional fish populations [10-16]. In order to cover the vast ocean volumes that the fish occupy, they typically survey along widely spaced, lawn-mower-like, line transects and, so greatly undersample the environment in time and space, leaving highly aliased and ambiguous abundance records. Acoustical data from these fish finding surveys are commonly coupled with biological sampling from fish trawls in order to estimate densities and abundances of commercially important fish stocks [16]. Vertical and lateral avoidance of conventional survey vessels by the fish also introduce a bias in the fish spatial distribution, leading to additional errors in regional population estimates [17]. Our first long term goal is to apply our remote sensing technique to other biologically-rich environments in order to further investigate and access the extent of which bioclutter affects long range sonar systems. From an ocean resource management perspective, we would also like to monitor the real-time, macro-scale (spanning thousands of square kilometers) areal density distributions of shoaling populations. From these density

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14. ABSTRACT

Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical sonar by introducing false alarms in the system. During the Main Acoustic Experiment (MAE) 2003 of the Acoustic Clutter program, densely populated fish shoals were identified to be the dominant cause of shallow water acoustic clutter in the New Jersey Continental Shelf. The mixing of cold and warm water cause nutrient rich upwellings in continental shelf environment, creating favorable conditions for all types of marine life. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it becomes critical to identify, understand, and be able to accurately model the leading order mechanisms which cause bio-clutter in Navy systems in biologically-rich environments such as continental shelf regions.

15. SUBJECT TERMS

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distributions, we hope to obtain more accurate abundance estimates to be used for more efficient fisheries management.

In addition to accurately enumerating commercially important fish stocks, effective fisheries management also relies on a better understanding of the behavioral dynamics of shoaling populations. Shoaling behavior is directly tied to catchability rates [18,19]. Shoaling fish are amongst the most heavily exploited species in the ocean, as commercial fishing gear is often designed to take advantage of fish natural tendency to organize in large collective units [19,20]. Until now, direct observations of shoaling and schooling behavior were limited to the micro- (cm to meter scale) and meso-scales (tens of meters to kilometer scale) due to technological limitation. Large-scale field observations may elucidate patterns in shoaling behavior that went previously undetected by conventional fish finding methods.

Another goal of this research is to investigate behavior patterns and the organizational structure of large-scale shoaling populations over all spatial scales and to understand physical and ecological mechanisms that cause them to behave and organize in such ways. Understanding of the structure and the mechanisms of shoaling dynamics is important to fisheries management and may be the key to avoid future stock collapse due to over-exploitation [19,20]. From a navy sonar perspective, understanding the dynamics of shoaling populations are also of critical concern to the mitigation of bio-clutter. Often times, compact dense population centers or nuclei within large shoaling populations have spatial extents and undergo motions characteristic of moving man-made targets within a waveguide, such as a slow-moving submarine. By understanding the natural dynamics of marine life, we may more sophisticated algorithms which exploit the natural behavior of shoaling fish in order to better track and discriminate natural targets from man-made targets.

Lastly, “automated species identification remains the ‘Holy Grail’ to acoustic researchers”. [21, p. 356] The third goal of this research is to investigate practical, non-invasive acoustical methods for species identification. This includes designing a field experiment that tests the feasibility and determines the limitations of using long range acoustic remote sensing to locate, map, enumerate, and identify individual classes of marine organisms. We hope to eventually develop a data-calibrated model for automated remote species identification.

OBJECTIVES

The primary objectives of this program are to:

- Apply our full-field, range-dependent, scattering model to the long range scattered field measurements from MAE 2003 to obtain areal density distributions and population estimates.

- Provide a qualitative and quantitative analysis of the relationship between fish shoaling patterns and local environmental conditions

- Provide a qualitative and quantitative analysis of the 2-D horizontal structural organization of a large scale fish populations

- Relate large-scale (tens of kilometer scale) behavioral patterns to classic small-scale (tens of meters to kilometer scale) shoaling/schooling behavioral patterns previously observed in nature and in laboratory studies

APPROACH

We applied our full field, range-dependent, scattering model to the long range acoustic field measurements from MAE 2003 to obtain instantaneous areal population density distributions and estimates of population over continental shelf scales [5-9]. Fish population densities were continuously estimated over continental-shelf scales from the instantaneous wide area acoustic imagery. Images of areal fish population density were generated by compensating for two-way transmission loss in the range-dependent continental-shelf waveguide through parabolic equation modeling, the spatially varying resolution footprint of the long range system, fish target strength, and source power [1,4-9, 22]. The areal population densities obtained using our model are consistent with those obtained from a conventional fish finding sonar simultaneously operated during MAE 2003. Both the long range remote system and fish finding sonar population density estimates depend on the expected scattering cross section of an individual fish, which we find to have a corresponding target-strength of -45 dB *re* 1m in the 390-440Hz band of our experiment. This expected target-strength is based upon tens of thousands of local measurements from the conventional sonar system. This target strength is also consistent with a combination of modeling [4] and empirical evidence gathered by National Marine Fisheries trawl samples obtained in the same location two months earlier as well as in early Springs of 2001 through 2005 [23].

Behavioral patterns of shoaling populations are inferred from qualitative and quantitative analysis of the population density images. The organizational hierarchy in large fish aggregations is revealed and quantified on scales ranging from a hundreds of meters to tens of kilometers from the population density images. Spatial and temporal scales of major population and areal change within large fish shoals are also quantified.

WORK COMPLETED / RESULTS

Fish populations can now be instantaneously detected, located and imaged over thousands of square kilometers in continental-shelf environments. Remarkably, our field measurements have all been made remotely from distances typically greater than 10 km from the shoal boundaries. This is achieved with a remote sensing technology involving underwater-acoustic waveguide propagation that surveys at an areal rate roughly one million times greater than that of conventional fish finding methods. The waveguide technology also makes it possible to continuously monitor fish population dynamics, behavior and abundance with minute to minute updates, producing records unaliased in space and time.

Very large shoals are found to demonstrate far more spatial organization than could previously be observed by highly localized, conventional 1-D horizontal transect methods. All shoals exhibit large internal vacuoles and hourglass patterns previously observed only for fish schools many orders of magnitude smaller in area [7,24]. Our 2-D horizontal imaging also shows that very large shoals exhibit structural contiguity similar to that of smaller scale fish schools (spanning tens to hundreds of meters). Like small fish schools, the shoals are comprised of densely concentrated population centers of various size connected by networks of fish bridges. This observed structural similarity at all spatial scales suggests that the instantaneous population distribution of fish over wide areas follows a consistent fractal or power law process.

Although shoals demonstrate a structurally similar to schools, we find that, over short time scales, they do not exhibit the motion synchrony often associated with schools [24,25]. The interconnected population centers comprising a shoal seem to experience local oscillations independently of each other over minute time scales. Such observations previously went undetected by conventional methods due to spatial and temporal resolution limitations.

We find a consistent daily pattern to shoal behavior that involves considerable horizontal migration, and so differs substantially from the day-night vertical migrations previously observed with line-transect measurements from downward-directed sonar [26,27]. The pattern begins with horizontal consolidation of shoals in the morning hours. The consolidated shoal typically extends for kilometers along the shelf edge. (This geophysical boundary may serve as a potential navigational landmark for populations undergoing distant migrations [28,29].) This is followed by rapid fragmentation and dispersal by mid-afternoon, well before vertical migration begins to occur [26,27]. Fragmentation initiates by faulting at bridges between densely concentrated population centers. These fish bridges do not seem sufficiently strong to withstand the internal or external stresses on the shoal's internal population centers to diverge.

These fragmentation and dispersal episodes are found to occur very rapidly. On May 14, for example, within a roughly 40 minute period more than 10 million fish disperse to below the visible threshold or leave the survey box. These depopulation episodes have peak dispersal rates reaching up to 0.5 million fish/minute. The shoals within the survey area contained less than half the original shoal population. Autocorrelation time scales of major population and areal change in a very large fish shoal is extremely short, only between 5 to 10 minutes. These rapid dispersal rates provide an effective means of predator avoidance since they enable the shoal to effectively disappear from the view of any locally perceived threat. Very large fish shoals would often suddenly disappear from the view of our simultaneously operated conventional line-transect survey system, but never from the view of our remote sensing system based on waveguide technology.

Time series of fish population, the shoal's outer area, as well as its characteristic internal area of coherence can be computed from the areal population density images. We find that the ratio of the shoal's outer area to its internal area of coherence gives an estimate of the number of primary population centers within the shoal or its largest fragment. The fact that this ratio remains relatively constant even after the consolidated shoal undergoes fragmentation and dispersal provides further evidence of structural similarity at all spatial scales. Fluctuations in the shoal's outer scale are relatively small compared to the percentage of area. Inner scale fluctuations are minimized only during periods when the shoal is not undergoing fragmentation episodes. Otherwise rapid variations in inner scale are seen, reflecting a form of internal turbulence that likely leads to fragmentation.

Lastly, both the total population and internal coherence areas tend to attain global maxima just before catastrophic fragmentation and dispersal of the shoal. This coincides with the shoals formation into a classic "hourglass" pattern [24] over a spatial scale many orders of magnitude larger than has likely ever been observed in nature or the laboratory setting before. In hourglass patterns, migration from one wing to the other has often been observed when the depopulating wing is under attack by predators [24]. While we have no current evidence of such an attack on the remotely imaged shoal, we do directly observe similar behavior from the areal density images. For example, we've often observed massing of population in the northern wing of the hourglass, with a simultaneous depopulation in the southern wing in our areal density images.

IMPACT/APPLICATIONS

- The findings are significant in that we are now able to instantaneously observe and continuously monitor the detailed behavior and horizontal 2-D organizational structure of large scale shoaling populations.

- Typical realizations of the instantaneous horizontal structure of very large fish shoals during MAE 2003 are the largest massing of higher organisms ever instantaneously imaged in nature.

- Very large shoals are found to demonstrate far more spatial horizontal organization than could previously be observed by highly localized, conventional 1-D horizontal transect methods.

- The structural similarity observed at all spatial scales suggests that the instantaneous population distribution of fish over wide areas follows a consistent fractal or power law process. Quantitative knowledge of this power law will allow for more accurate statistical predictions of the spatial distribution of fish populations.

- From a navy sonar perspective, the ability to monitor fish shoal dynamics instantaneously and continuously over wide areas will tremendously influence the development of target tracking and discrimination algorithms and technology. For example, some of the isolated densely concentrated population centers within a shoal can remain intact and have a compact uniform morphology over long periods of time and will have dynamic properties similar to that of a moving target in the waveguide. By understanding the natural dynamics of shoaling fish, we may develop adaptive algorithms or technology to track and discriminate these natural targets from man-made targets.

- By continuously monitoring the fish populations over wide areas, we may also be able to predict cyclic or rhythmic patterns in bioclutter from observed behaviour patterns of fish. For example, there may be a high diurnal or seasonal dependence of clutter depending on changing distributions, densities, and spatial migrations of different species throughout the day or year. There may also be a frequency and species dependence of bioclutter, depending on the type of fish, the existence of a swim bladder, and the swim bladder size.

- By monitoring properties of shoals and schools, such as size, density, and population distributions, we may better understand and quantify how variable distributions and densities of biological inhomogenieties, such as different fish species or fish food sources, affect the acoustical properties of the waveguide in order to develop theoretical scattering models to describe sound propagating through a fluctuating, “fishy” medium.

- The long range acoustic sensing technique used during MAE03 has the potential to become an invaluable conservation tool by which government regulatory agencies could use to rapidly image and enumerate large scale fish populations over thousands of square kilometers to effectively monitor and manage the national fish stock.

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