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RESEARCH ARTICLE

INFLUENCE OF INTERNAL WAVES ON UNDERWATER ACOUSTIC PROPAGATION

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ABSTRACT

The harmonic excitation is taken imperfect, i.e., with a random phase modulation due to Gaussian white noise, accounting for both chaotic and stochastic behavior. Simulated turbulence is represented using the potential theory line vortex approach. Simulations are conducted for long range propagation, 1000km, containing internal wave fields with added deterministic effects and are compared to those fields with non-deterministic properties. These results show that long range acoustic propagation has a very strong dependence on the intensity of deterministic fluctuations. Numerical analysis for short range propagation, 10km, was constructed for sound passage through the following perturbation scenarios: simulated turbulence, an internal wave field, and a field of internal waves and simulated turbulence combined.

INTRODUCTION

The ocean is a random medium having both deterministic and nondeterministic characteristics. This behavior often leads to difficulty in performing such underwater applications as telemetry and tomography. These methods involve sound wave propagation as a means to study and monitor the ocean medium or serve as a means of underwater communication.

Review of Chaotic and Stochastic Internal Wave Models

The behavior of the pulse during its transmission is also a complex issue. Recent theoretical and experimental studies by Simmon et al. (1999), have suggested that the breakdown in identifying isolated and resolved signal arrivals at long ranges is due to ray chaos induced by a range-dependent ocean structure. This chaotic behavior has been investigated in numerous works ((Smith, Brown, and Tappert, 1992); (Duda and Bowlin, 1994); (Colosi, Flatte, and Bracher, 1994); (Zaslavsky and Abullaev, 1997); (Simmen and Flatte, 1999); (Wiercigroch, Badiey, Simmen, and Cheng, 1999)). In his recent work, Wiercigroch *et al.* (1999), studied the non-linear dynamic behavior of basic ray equations in the presence of a wave-like forcing assuming a single-mode sound speed perturbation is superimposed onto a generic range independent sound speed profile, Munk's canonical sound speed profile (Munk, 1974). This model vastly simplifies nature by only accounting for the chaotic behavior caused by internal waves, and ignoring the randomness of the process. Other researchers suggest that the motion of sound trajectories in deep ocean environments exhibits stochastic behavior, which can be attributed to internal waves (Brown and Viechnicki, 1998). In their recent work, Colosi and Brown (1998) developed a method to construct statistically realistic random realizations of internal wave induced sound speed perturbation fields, despite its simplicity and efficiency, the method has certain limitations. It is the intension of this work to demonstrate that the consideration of both chaotic behavior and stochastic influences produce more realistic predictions for underwater wave propagation.

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Objectives and Approach

The primary objective of this research is to develop a predictive methodology for received signal variation as a function of ocean perturbations that occur during short and long range propagation. The motivations for the work presented in this thesis are the limitations of underwater acoustic propagation. The classification of ocean environments will provide information that will be useful in enhancing the processing techniques for transmitted signals. The approach here is twofold. The first is to consider internal waves only, since it is typical that these perturbations dominate turbulent effects at the sound channel axis during long range propagation (Colosi, Flatte, and Bracher, 1994). Our theoretical development will consider both the chaotic and stochastic effects of internal waves; this dual contribution has not been considered in prior acoustic propagation models. The eikonal equation is considered in the form of a second order, nonlinear ordinary differential equation with internal waves. The internal waves are considered to have random phase or amplitude modulation in the form of zero-mean Gaussian white noise. Bifurcation analysis can illustrate that consideration of only chaotic behavior somewhat simplifies the real problem, where the stochastic behavior may have a substantial input, thereby providing a more realistic characterization of acoustic arrivals.

The second portion of this work is to expand the model to consider other perturbations affecting ray behavior during ocean sound transmission typical to short range propagation. The improved computational ray tracing model simulates three typical turbulent states that can occur in the ocean's main thermocline along the sound channel axis. These scenarios include:

Sound passage through simulated turbulence
Sound passage through internal gravity waves

Sound passage through a field containing both internal gravity waves and simulated turbulence combined. Each vortex in the eddy field is treated as a line vortex based on potential theory assumptions. For each perturbation scenario the developed acoustical propagation model: Illustrates the multi-path structure induced by the sound speed profile through presentation of ray tracing diagrams for varying initial conditions. Estimates signal delay and arrival behavior induced by the turbulent medium by predicting arrival times, arrival depth, and velocity fluctuations for a geophysical time series. Presents energy-frequency spectra of the fluctuating mean travel velocity based on predicted arrival times.These simulations provide the necessary information for the classification of perturbation scenarios in a multi-path underwater environment. This analysis is useful in predicting impulse response as well as for providing the necessary data for improvement of filtering and smoothing techniques. It is the intention of this research to provide the ground work for enhancing transmission capabilities as well as to provide some analysis of typical ocean turbulent flows and its impact on high-frequency propagation.

Sound Velocity in Water

The sound speed in the ocean is an increasing function of temperature, salinity, pressure, and depth. The following is an empirical function for sound velocity, c, in terms of three independent variables: temperature - *T \C),* salinity - *S (parts*1000), depth-*z* (m), (Brekhovskikh, 1982).*c* = 1449.2 + 4.6r-0.055r^2 +0.00029r^3 +(1.34-0.0ir)(S -35) + 0.016z (2-1)

Oceanographers perform CTD (Conductivity, Temperature, and Depth) scans of the ocean to determine the sound speed over a region. Figure 1 shows a plot of three sound speed profiles calculated using CTD data obtained from the National Oceanographic and Atmospheric Administration, Table 1 lists the date and location of each cast.

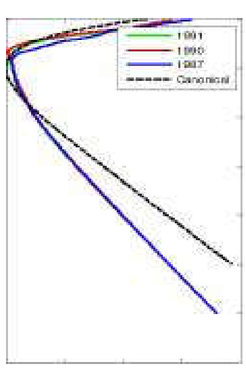

Fig. 1: Sound Speed Profiles based on Pacific Ocean CTD scans (NOAA/EPIC, 2005)

Table 1: Date and location of CTD casts used for Figure 1 (NOAA/EPIC, 2005)

Date of CTD cast		Longitude Latitude
04 August 1987	24°0.5'iV	165°0.3£
24 July 1990	22° 47.1 'N	158°0.6'W
09 July 1991	22°45.0'iV	158W

The ocean is considered a horizontally stratified medium, having several layers; the upper most are depicted in Figure 2, which indicates the regions of variability based on the sound speed profile. Sound speed increases linearly toward the ocean floor and increases exponentially toward the ocean surface. The coordinate system is two-dimensional, referencing the (r, z) plane, where *r* is range and *z* is depth. The properties of the water nearest to the surface result from mixing due to surface winds and wave activity at the ocean-air interface. This layer holds for varying temperature, except during severe environmental conditions. The next layer is the thermocline. The warming of the sea surface by the sun creates a temperature gradient, the temperature decreases with depth and thereby so does the sound speed. Below the thermocline lies the deep isothermal layer, in this layer, there is less fluctuation in temperature, and the pressure becomes greater, leading to an increase in sound speed. Between the mixed layer and the deep isothermal region, there is a sound speed minimum at a certain depth, which varies for different geographic regions. This depth is referred to as the underwater sound channel axis. For example, in the Polar Regions the water is coldest near the surface and hence the sound speed minimum is at the ocean-air or ocean-ice interface. A typical depth of the axis in other regions of the world, is 1000-1500m, in the tropical zone it falls to 2000m, but rises closer to the surface at higher latitudes.

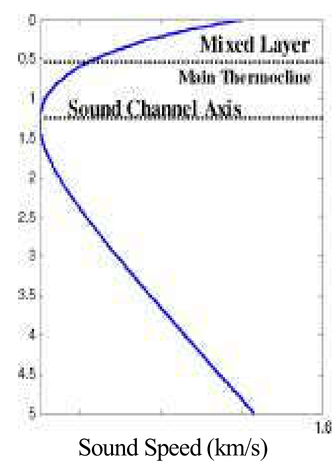

Fig. 2: Sound Speed profile with regions of instability

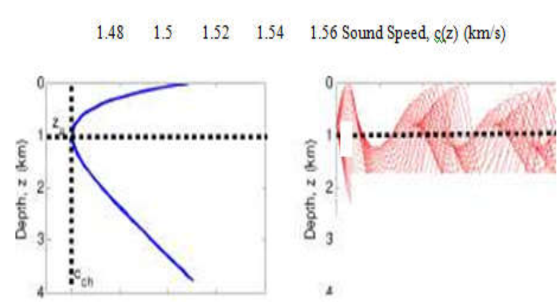

Figure 3: Munk Sound Speed Profile and resulting Ray Path behavior

The sound channel is one particular case of a natural waveguide for the sound waves transmitted along it, analogous to the acoustic waveguide in the atmosphere. Sound waves tend to bend toward regions of lower sound speeds, illustrated in Figure 3, where $z = z_a$ shows the boundaries of the sound channel and $c = c_{ch}$ is the sound speed at the sound channel axis. Interest lies in modeling sound behavior generated by a source and received by a hydrophone. Pulses emitted at small or moderate angles (with respect to the horizontal) from a spherical sound source placed on or near the sound channel axis will be redirected to the sound channel axis repeatedly, and their energy will remain trapped in the sound channel. These pulses propagate without reaching the bottom or surface, and do not undergo scattering or substantive absorption. This is the ideal case for the prior mentioned applications. Ray paths typical to a ray traveling through an ocean with a canonical sound speed profile are depicted in the ray trace diagram seen in Figure 3, launch angles range from $-15° < \varphi(0) < 15°$. This canonical sound speed profile was developed by Munk in 1974 to represent an idealized sound channel (Munk, 1974).

SUMMARY AND DISCUSSION

The ocean acoustic channel creates strong amplitude and phase fluctuations in acoustic transmissions (long range and short range) used for underwater communications. These fluctuations can be induced by internal waves, turbulence, temperature gradients, density stratification or by other related phenomena that cause local perturbations in the sound speed. Received signal fluctuations arise from these medium fluctuations and cause the signal to oftentimes become unreadable. Underwater acoustic communications systems rely heavily on having prior knowledge of the underwater acoustic environment. The ocean is a stratified medium containing several layers. The layer of interest is the thermocline, which hosts a large temperature gradient and thereby a region where the sound speed is at a minimum, the sound channel axis. The sound channel axis acts as a waveguide, sound speed increases linearly toward the ocean floor and increases exponentially toward the ocean surface. The ocean's sound speed is a function of depth, salinity, and temperature. It is represented by the canonical profile developed by Munk (1974), which accounts for the mentioned variability.

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