Acoustic Sensor Array for Determination of Undersea Acoustic Signatures

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***Abstract*— Identifying undersea objects and their locations at any time is a growing research area for topological mapping applications. The capability to classify, characterize, and identify ocean anomalies would enable a more precise tracking capability and a more reliable communications system. The objective of this study is to present a spatial and temporal acoustic structure that will be able to both track and identify ocean anomalies as well as to characterize the transmission channel. This consists of using a multiple sensor spatial array with a multi-sensor correlation analysis capability. Both spatial and temporal acoustic signals are received from transmitting source. The Pearson product moment correlation is used to correlate the received acoustic signal in the form of both transmission loss and received phase temporally at a spatially distributed sensor array. Each originating source of an acoustic signal will have various distinguishing unique characteristics that are referred to as acoustic signatures. This combination of a spatial and temporal multi-sensor array together with the Pearson product moment correlation is proposed as a new analysis method and it is combined with the Dempster-Shafer Theory to compute and arrive at a degree of belief. The proposed acoustic architecture will have the ability to ascertain and distinguish between acoustic signatures.**

I. INTRODUCTION

The underwater acoustic signature algorithm incorporates a combination of temporal and spatial methods of extracting acoustic signatures from a passively emitting underwater source. The underwater channel is modeled with the Bellhop model, which is a Gaussian beam tracing model based on the concepts of ray theory used to solve the wave equation. The Pearson correlation method is utilized to correlate the outputs provided by the Bellhop method, including the amplitude loss, phase variation, and source and receiver spatial variations for a given set of acoustic input characteristics into the channel from the source. The combination of the various results of the correlation analysis (provided by the Pearson correlation algorithm) is then combined using the Dempster-Shafer Algorithm in order to provide a new and robust method of classifying and identifying the type of source emitting the acoustic signatures. This analysis also provides information about the channel itself in terms of topological characteristics. Figure 1 shows the breakdown of the various parts of the algorithm.

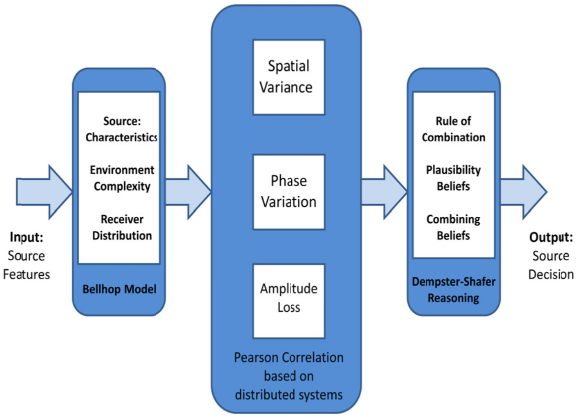

Figure 1. Underwater Acoustic Source Identification

II. BELLHOP ACOUSTIC PROPAGATION MODEL

Bellhop is a Gaussian beam tracing program. It used in this study to simulate transmission loss from an acoustic source in an ocean environment. Bellhop is used in this instance because it has proven to be a very accurate model for a wide acoustic frequency range. The Bellhop model, as defined in the AcTUPℓ, program can generate both Gaussian and Geometric beam types. The option used in this study is of Gaussian beam types. The Bellhop program was developed by Porter and Buckner at the Space and Naval Warfare System Center in San Diego in 1987 [1].

The simulation used in this study incorporates the Bellhop acoustic propagation model in an underwater environment in order to provide raw acoustic data for the development of an algorithm to identify, classify, and provide the features of underwater objects emitting their own unique acoustic signature [2]. This would facilitate many applications such as enabling a more precise tracking capability as well as a communications system to perform with better error control and reliable message transmission. The framework of the simulation allows investigation of both spatial and temporal acoustic structures to develop a tool that will provide the ability to discern an acoustic signature. This signature can be used to identify the source of the acoustic emission and also the location of both the emitting source and other spatial objects in the acoustic path that would affect temporally and spatially the received acoustic signatures.

The main environmental inputs in the Bellhop simulation include a range-dependent Sound Speed Profile (SSP), water depth (*z*) and water density. The program allows for the consistency of the sea floor (such as sound speed, attenuation coefficient, and density) to be added to measure the reflection from the bottom. It also allows the definition of different sediment layers having their own unique acoustic

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characteristics. Receiver arrays of varying distances and depths can also be defined to add temporal and spatial flexibility. Acoustic system inputs are frequency (*f*), source depth (z_S) and receiver depths (z_R).

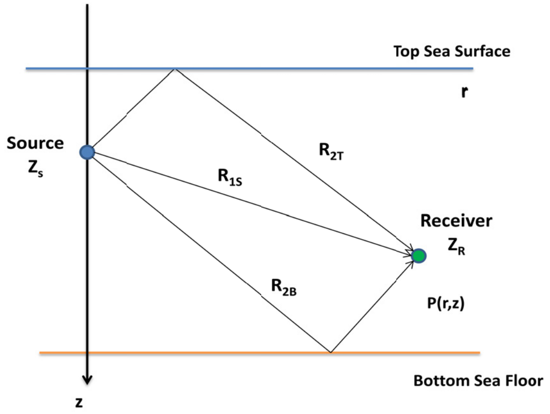

Figure 2. Propagation Environment

The AcTUPℓ model is modeled in a 2-dimensional space. The propagation of the acoustic waves is computed for a 2-dimensional vertical slice of the medium. The assumption is that this result applies for all bearings. These assumptions allow a reduction in the computational times.

Bellhop uses Gaussian beam tracing to produce the ray-trace and impulse response plots [3],[4]. Gaussian beam tracing uses standard ray tracing to describe what is referred to as a central ray. The central ray is the center of the acoustic wave as it diverges. The center point or ray is typically the area of least distortion. Distortion will increase the further away from the central ray one is. Gaussian beam tracing is a simulation of wave propagation where a beam is formed whose intensity decays normal to the central ray with a Gaussian distribution. Beam tracing is computationally more efficient while being mathematically equivalent to standard ray tracing.

Bellhop is able to trace a user-defined fan of rays emitted from a sound source whose coordinates and frequency are specified by the user. It also calculates the amplitude and arrival time of an impulse signal arriving at the receiver via each ray path. Bellhop can also compute the intensity of the sound field at the receiver by finding only the rays that reach the receiver. These rays are called eigenrays. The main input file to Bellhop is called the environment file. The environment file is a simple text file given in a structured format specifying the details of the environment, the source and receiver characteristics, and the type of analysis to be performed. The environment information includes the sound-speed profile, the depth of the channel, the channel bottom composition, and surface boundary definitions. The source and receiver characteristics include the transmission frequency, the source and receiver locations, the angle limits for the fan of beams and the number of beams used. The type of analysis specified dictates the output of the algorithm in the form of a ray file, an eigenray file, an amplitude delay file, or any of three different types of transmission loss files (coherent, incoherent and semi-coherent). Information in the output ray file can produce a plot showing the paths traveled by all the rays specified in the environment file. The plot has depth on the vertical axis and range on the horizontal axis. Bellhop can selectively plot the paths traveled by only those rays that reach the receivers.

The Bellhop model can also create an amplitude-delay file, which is a text file stating transmission frequency, channel depth, source and receiver geometry and number of eigenrays. Also included is information about each eigenray such as amplitude, time delay, phase shift at the receiver, and the number of surface and bottom bounces experienced by the eigenray. The phase shift calculated in the amplitude-delay file is used to generate raw phase variation files for each scenario of phase angle, source depth, receiver depth, and transmission frequency. An algorithm using the information in this file can be used to plot the impulse response. The impulse response is defined as the output of the receiver to a very brief signal from the source, called an impulse. The plot has the dimensionless amplitude at the receiver in the vertical axis and the time delay in seconds in the horizontal axis. The impulse response plot shows the time dispersion of an initial impulse at the source into multiple impulses at the receiver. This time dispersion is caused by the different path lengths and travel times associated with each ray. An important implication of this multipath time dispersion of signal energy is the possibility of intersymbol interference for acoustic communications.

III. UNDERSEA BELLHOP MODEL

Bellhop uses the concept of ray theory to solve the wave equation. The wave equation is a partial differential equation describing the motion of a wave in a medium. The acoustic wave equation is a linear approximation retaining only first-order terms of the wave equation. The propagation of sound in an elastic medium (such as seawater) is described mathematically by solving the acoustic wave equation while applying the appropriate boundary and medium conditions.

The model used in this study is a two dimensional view of the undersea environment. The acoustic source is a single point set as a point of reference at a depth of 50 meters. The acoustic point source will radiate out a pulsed acoustic wave at an angle θ both above and below a horizontal reference line. The transmitted frequencies include the following frequencies: 10 Hz, 20 Hz, 25 Hz, 50 Hz, 100 Hz, 200 Hz, 500 Hz, 1 KHz, 5 KHz, and 10 KHz. The receiver consists of an array of individual receivers positioned in a rectangular array consisting of 30 receiver levels deep and 200 receiver positions wide. For each given receiver position, there are 30 individual acoustic sensors positioned every 5 meters starting at 5 meters deep from the surface of the ocean to 150 meters at the bottom of the ocean. The receiver sensor configuration consisted of 200 acoustic sensors spaced linearly from a distance of 100 meters to 1000 meters from the acoustic point source.

The source point, receiver sensor array, as well as the environmental aspects such as sound pressure, reflective and refractive results are all assumed to be in the same z-plane in the model. The layout of the model is shown below.

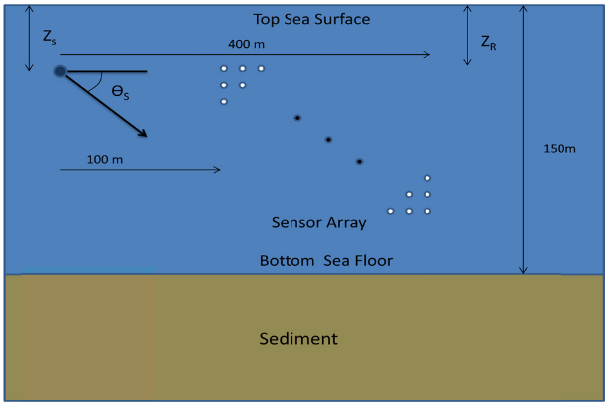

Figure 3. Simulation Environment

The principal layer is the sea water layer with a uniform depth of 150m. Below that is the sediment layer.

IV. RESULTS

The parameters used in this study consist of a bundle of 50 beams with a Gaussian beam structure. The simulation outputs both amplitude values and time delay outputs which are used to serve as the raw inputs for the transmission loss and phase variation which will be used in the Pearson correlation coefficient calculations. The Pearson product moment correlation coefficient is calculated for the amplitude, phase and frequency received at the receiver array as a result of the two different transmitted acoustic waves.

The corresponding Pearson product moment correlation coefficient is calculated for the transmission loss and phase variation of the two different received acoustic signals as a function of the 30 different depths of the receiver array. This will be used to characterize the correlation of the two different transmitted waves as a function of the following different characteristics of the acoustic waves represented by *Transmission Angle, Source Depth, Ocean depth, and Receiver Depth.*

Figure 4 shows the Bellhop transmission loss calculated for two different sets of received acoustic signals originating from a 500 Hz, 50 meter deep acoustic source point at a 60° transmission angle, and a 500 Hz, 50 meter deep acoustic source point at a 75° transmission angle.

The transmission loss results show a virtual identical similarity in the behavior at a range of 400m and greater. The comparison of the transmission loss at a range of less than 400m is shown to be distinctly different between the results from transmission angles of 60° and 75°. This is due to the fact that at closer ranges, the multipath effects would be more unique and specific depending on the transmission angle. As the range increases, the amplitude of the transmitted waves and respectively the indirect and direct wave fronts would diminish and the corresponding unique signat ure characteristics would become less pronounced. The variation in the transmission loss intensity at all range values is shown to vary between 10 dB and 20 dB as the range changes. This is due to the phase variation and multipath effects resulting from wave fronts converging at points from different paths. The phase variation effects on each of the different paths would then have a constructive or destructive overall effect. The fact that the depth of the water is 150m also contributes to this effect. If the water depth was much deeper, the multipath effects interacting with each other would have less of an effect and the graph would have less flunctation in the transmission loss value. Effectively, the graph would be smoother and would have less variation.

Table I shows the results of the Pearson correlation analysis for the following source depth and receiver depth combinations: 40° (transmission angle)/50 meter (receiver depth) and 60° (transmission angle)/50 meter (receiver depth). The assumption here is that the transmission losses and phase variations both have a Gaussian distribution. This data is used to calculate the prior probability distribution for the transmission loss, PP_{TL}, and phase variation. PP_{PV}. As the results show, the prior probability distribution is weighted very heavily towards the deeper depths since the values of the transmission losses and phase variation mean values for the shallower source depths are very close to each other. In fact, the single standard deviation intervals intersect for adjacent source depth values for source depths from 50m, 55m, 65, and 75m. The phase variation values are spaced more linearly from each other in terms of the mean of the phase variations.

These values form the basis for using the Dempster-Shafer algorithm to calculate the degree of belief that the source of the acoustic transmissions originated from a particular depth and angle of transmission or particular finite set of depths or angles or transmission. These can then be used to categorize the identity of a specific source (i.e. whale, submarine, surface ship, etc.) that emitted the acoustic signature.

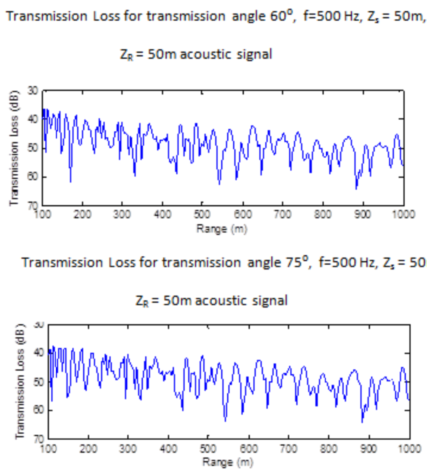

Figure 4. Transmission Loss calculated using Bellhop Model

Table I. Transmission Loss and Phase Variation Prior Probabilities

Probability of Source Depth – Transmission Loss and Phase							
Source Depth(m)	Transmission Angle	Trans Loss (mean)	Trans Loss (StDev)	Phase (mean)	Phase (StDev)	PP_{TL}	PP_{PV}
50	60°-40°	**0.7859**	**0.003**	**0.7215**	**0.0084**	**1.58E-18**	**0.12555776**
55	60°-40°	**0.785**	**0.0043**	**0.7353**	**0.0047**	**1.62E-09**	**0.0001657**
65	60°-40°	**0.7772**	**0.004**	**0.7288**	**0.0062**	**4.53E-06**	**0.02279149**
75	60°-40°	**0.7724**	**0.0034**	**0.712**	**0.0059**	**7.03E-05**	**0.26696334**
100	60°-40°	**0.7009**	**0.039**	**0.682**	**0.006**	**0.495526**	**0.29258192**
125	60°-40°	**0.5775**	**0.1097**	**0.6861**	**0.0119**	**0.504399**	**0.2919398**

The calculated values for transmission loss and for phase variation were made at a distance of 400m from the source. Table I shows the computed values using the Pearson correlation coefficient assuming transmission angles of 40^{o} and 60^{o} for the source. The associated prior probability distributions are shown for source depth range of 50m to 125m and computed for the transmission loss and the phase variation. The results show that there is a 49.55% probability that the source believed to be at a depth of 100m is accurate and a 50.4% probability that the source believed to be at a depth of 125m is accurate when using the calculated transmission loss measurements. When using phase variation measurements, there is a 26.6% probability that the source believed to be at a 75m depth is accurate and a 29.25% probability that the source believed to be at a 100m depth is accurate.

V. UNCERTAINTY CALCULATION

The Dempster-Shafer Algorithm is the method of combining evidence from multiple different sources of evidence to calculate a degree of belief regarding that evidence. The uncertainty of the evidence is a major consideration in the tracking and identification of targets. Dempster-Shafer theory is a concept that can handle the combination of the concept of probability with the conception of sets of similar evidence.

In Table I, the prior probabilities are represented by the two variables PP_{TL} and PP_{PV} . These variables represent the probabilities for given received values for the transmission loss and phase variation that the received signal originated from either one of the following source depths, 50m, 55m, 65m, 75m, 100m, or 125m. These probabilities were calculated from results of the Bellhop model simulation. A Gaussian distribution was assumed for the probability distribution with the standard deviations given for the transmission loss and phase variation. The BoE, Body of Evidence, for the Dempster Shafer model, can be defined using the following Field of Discernment, $\Theta = \{a, b, c, d, e, f, g, h, i, j, k, l\}$. There are 12 elements of the Field of Discernment representing the six transmission loss measurements for each of the source depth and the six phase variation measurements for each of the source depths.

Several theorems are used in a fusion process using a conditional approach to the Dempster Shafer Algorithm [5]. These are the Condition Core (CCT) Theorem, basic equations of Dempster Shafer Theory, [6] and the Fagin - Halpern Conditionals. [7]. These will be used to convert the initial event probability mass, m(B), to a conditional probability mass, m(B/A). The conditioning proposition is given by $A = \{b, c, d, e, f, g, u, v, w, x, y, z\}$. Each member of the proposition A is an element of either the PP_{TL} or PP_{PV} for one of the source transmission angles. The core $F = \{au, bv, dx, eyb, fzc, \Theta\}$. The probability $m(B) = \{.27, .27, .09, .04, .09, .01, .23\}$ for each $B \epsilon\ F$. For example, $m(au) = .27$. The conditional core corresponding to the conditional proposition of A is then calculated and given in the Table II. The results shown in Table II for the conditioning core with respect to the defined proposition of $A = \{b, c, d, r, f, u, v, w, x, y, z\}$ show a noticeable conditional probability mass result.

Table II. Conditioning Core for the Proposition A

B	m(B/A)	B	m(B/A)
bvu	.06	eybu	.43
cwu	.06	fzcu	.46
dxu	.12		

The conditioning proposition A was chosen eliminating the element “a” since by itself the probability mass of “a” by itself is significantly less than all the other elements. Based on this conditioning proposition, a useful and believable conditional mass is calculated as a result. The results show that the probability mass of an element consisting of “fzbu” has a value of .46 assuming the core value of A. The probability mass of the element “eybu” has a probability of .43 given the core value of A.

VI. CONCLUSIONS

This study shows a promising algorithm with the ability to reliably characterize, identify and classify ocean anomalies as well as characterize the transmission channel that the acoustic signatures of the anomalies propagate through. The spatial and temporal acoustic analysis has proven to provide a reliable means together with the Dempster Shafer algorithm for analyzing both the spatially and temporally received and analyzed acoustic signals. These signals from both a direct and indirect perspective provide promising characterization, identification and classification results. Further work is needed to define a set of possible conditional cores for use with the Dempster Shafer algorithm to provide more accurate characterization results. This may be done by incorporating additional information such as Doppler shift analysis and the number of received wave fronts for a given time interval to add as possible additional sensor data.

REFERENCES

[1] Michael B. Porter and Homer P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields", Naval Research Laboratory, Naval Ocean Systems Center.

[2] Amos L Maggi & Alec J Duncan, "Acoustic Toolbox User-Interface and Post Processor", Centre for Marine Science & Technology.

[3] Michael B. Porter and Yong-Chun Liu, “Finite-Element Ray Tracing”, Dept of Mathematics and Center for Applied Mathematics and Stats., New Jersey Institute of Technology, 1994.

[4] Orlando Camargo Rodriguez, “General Description of the BELLHOP ray tracing program”, Universidade do Algarve, Version 1, 2008.

[5] Thanuka L. Wickramarathne, Kamal Premaratne, Manohar N. Murthi, "Focal Elements Generated by the Dempster-Shafer Theoretic Conditionals: A Complete Characterization", Department of Electrical and Computer Engineering.

[6] G. Shafer, "A Mathematical Theory of Evidence", Princeton, NJ: Princeton University Press, 1976.

[7] R. Fagin and J. Y. Halpern, "A new approach to updating beliefs," in Proc. Conference on Uncertainty in Artificial Intelligence(UAI'91), P.P. Bonissone, M. Henrion, L.N. Kanal, and J.F. Lemmer, Eds. New York, NY: Elsevier Science, 1991.