HIGH FREQUENCY ACOUSTIC IMAGING IN THE OCEAN

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ABSTRACT

The use of acoustical techniques in oceanography is well known. Traditional applications have concentrated on long range, low frequency propagation. More recently, due a convergence of both technology and national interests, consideration of the possibilities for creating high frequency, real time, multi-dimensional imaging systems (2 and 3-D) has emerged. Unfortunately, due to a lack of experimental investigation, the propagation issues related to these frequencies are relatively unknown. Our group in underwater acoustic imaging applied to ocean exploration and oceanography has been taking high frequency acoustic pictures in the ocean for almost a decade. Our first experiences were in using the traditional types of ocean going sonars such as side scans. More recently we have been developing a 3-dimensional multibeam imaging system for tracking small animals in the sea. As part of this effort we have been looking at both the spatial and temporal correlation scales for the propagation of high frequency sound.

1. INTRODUCTION

The use of high frequency ($\geq 20kHz$) sound for imaging in the ocean is an area which is receiving increased attention. This is due partly to the ready availability of fast digital hardware for beamforming in the near field and also in part to the continued exploration of the oceans to satisfy both civilian and military goals. Examples of the applications of such sonars include robotic vision systems, bottom survey including mine hunting operations and biology, as well as looking at the abundance of marine life that exists in the water column. Even though the propagation of sound in the ocean is slow ($1500m/s$), compared to the speed of light, large aperture devices which use large time bandwidth projects have the most potential to optimize various measures of performance. For one example of the use of large time bandwidth products to obtain more rapid sonar images see [8]. As such, in all conceivable situations, higher resolution in both space and time offer advantages for improving the performance of high frequency imaging systems.

With respect to these issues, two types of fundamental measurements which are important for designing sonar imaging systems are the spatial and temporal coherence of the medium. Intuitively, the spatial coherence of the ocean sets the limit on how large an aperture might be used for image formation. Temporal coherence sets the limit on how long a duration temporal waveform might be used. In addition, if these quantities vary systematically in either space or time, knowledge of the general form and variability of these quantities could be used to devise signal processing schemes which can "accommodate" these fluctuations to extend the resolution (in range or azimuth) over simple schemes which do not.

Despite the importance of these coherence functions in designing and utilizing high frequency sonar systems, there has been relatively little work done in experimentally measuring them. In the con-

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text of assessing the possibilities for using high frequency synthetic aperture sonars, the phase stability was measured at a frequency of 100 kHz [2]. Here, the phase instability of the medium (a function of both depth and tidal cycle) was as large as .31 radians over a 2-min. interval. In another study, Gough et al [7] measured excellent phase stability, only limited by their instrumentation, at frequencies of 15-30 kHz.

More commonly, experimental measurements of temporal variability have been made of sound after reflection from the ocean floor. In this case, the measured perturbations that are measured are the result of both sound propagation through the water and the variability that is superimposed by the bottom. Nicholson and Jaffe [10] characterized the variability in high frequency bottom backscatter at 100 kHz from a pier in Woods Hole, Mass. and found significant fractional variability. More recently, Stanic et al. [12] have computed histogram statistics for acoustic backscatter from a number of different types of ocean bottoms as a function of frequency ($20-180kHz$) grazing angle, and beamwidths. In all cases substantial variability was noted.

In understanding the origins of sound variability in the ocean there is a rich literature which has addressed the propagation of sound at low frequency through large scale oceanographic structures [4]. At higher frequencies one needs to think about much shorter distances (due in part to attenuation) and structures that have higher spatial frequencies (due principally to spatial scales which are on the same order as the wavelength of the sound). Broadly, the loss of both spatial and temporal coherence of sound can be the result of volume inhomogeneities or velocity inhomogeneities. In the case of the former, changes in salinity and temperature microstructure and considered to be the most important. Goodman et al. [5], [6] investigated how, in the weak scattering regime, thermal microstructure can give rise to a "diffraction pattern" of the temperature micro-structure. The paper also proposes a technique for temperature inversion which has yet to be attempted. Another group [3] has used the variability in acoustic phase, measured across a narrow channel, to infer agreement with a turbulent spectral model. In both of these situations, the primary motivation for the use of the sonar is as a remote sensing tool with the potential for mapping a physical variable of interest (temperature microstructure, turbulent velocity spectra).

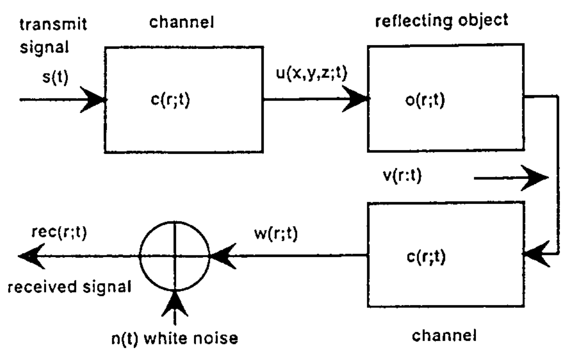

Figure 1: System Flow Chart

Our own research in high frequency sound propagation has been aimed at understanding both the sources and consequences of sound variability. One set of experiments, to be described here, was designed to parse out the variability in bottom backscatter vs. volume variability by inserting a reflecting cube in the sonar beam and comparing the variability in the response with that from a neighboring bottom. The following sections describe both the model and the results of our experiments.

2. LINEAR SYSTEM MODEL

An active sonar system can be modelled using a linear systems theory framework. If the channel and the object are linear time-varying systems, the following equations describe the input-output relations between various system blocks as illustrated in Figure 1.

As illustrated,

$$u(\vec{r};t) \quad = \quad \int c(\vec{r};t,\tau)s(\tau)\,d\tau \qquad (1)$$

$$v(\vec{r};t) = \int o(\vec{r};t,\tau)u(\vec{r};t,\tau)\,d\tau \quad (2)$$

$$w(\vec{r};t) = \int c(\vec{r};t,\tau)v(\vec{r};t,\tau)\,d\tau \quad (3)$$

$$rec(\vec{r};t) = w(\vec{r};t) + n(t) \quad (4)$$

Here, $\vec{r} = x, y, z$ are the spatial coordinates, t the time, $s(t)$ the transmitted signal, $c(\vec{r};t)$ the channel impulse response, and $o(\vec{r};t)$ the insonified object's impulse response. $n(t)$ is additive white Gaussian noise from the system electronics and $rec(\vec{r};t)$ is the received signal. The statistics of the additive white Gaussian noise is assumed to be known. Although channel response $c(\vec{r};t)$ and the object response $o(\vec{r};t)$ are space-time random processes, since the temporal statistics is the issue of current interest, the spatial coordinates will not be indicated henceforth.

If the channel impulse response does not change over the duration of the signal it can be considered a linear time-invariant system and the channel output is a convolution of its impulse response with its input. Similarly, the object impulse response can also be considered linear time-invariant if it does not change over the duration of the signal. In this case equation (2) leads to a physical interpretation of the object as a continuum of non-moving scintillating scatters with $o(t,\tau)$ representing the modulation produced by elemental scatterers [1]. Thus equation (4) can be written as

$$r = c * \{o * (c * s)\} + n \quad (5)$$

where the $*$ represents convolution.

Inspection of the received signals from the known reflector (to be considered below) show that the channel can be considered slowly fading with the magnitude or attenuation, phase shift remaining constant over one pulse period. In fact, it is reasonable to assume that the channel impulse response remains constant over the time it takes for the pulse to travel to the target and back, since the distances involved are short at high frequencies. In other words, the coherence time of the channel is much greater than the round trip time for the signal. We also assume that the signal bandwidth is much less than the coherence bandwidth of the channel, which makes the channel frequency non-selective [11].

Thus equation (5) can be written as

$$r = c^2\{o * s\} + n \quad (6)$$

because c does not change over the duration of the signal rec, received from one ping.

An exact characterization of the bottom and the channel can be obtained from their multi dimensional probability density functions. However, a more practical approach is to get a second order statistical characterization, represented by correlation functions. One such quantity of interest is the coefficient of variation or the scintillation index of a random variable x [13]. It is defined as

$$\mu = \frac{\sqrt{E[x^2] - (E[x])^2}}{E[x]} \quad (7)$$

3. EXPERIMENTS

In order to examine the variability of the reflected sound due to propagation effects alone and also due to reflection from the botom an experiment was conducted with our existing multibeam sonar imaging system [9]. The system consists of two sets of 8 transducers and operates at a frequency of 450 kHz to produce a three dimensional image of 8 beams by 8 beams by up to 2048 range bins. Figure 2 shows a diagram of the system configuration for the experiment. As can be seen, a corner cube reflector was positioned in the field of view of the sonar. This represents a target which does not vary in time. In comparison to this, a section of the bottom was imaged at the same time and the coefficient of variation was compared for the cube reflector and the bottom to determine the major sources of the variability.

Figure 3 shows an image of both the average value of the intensity of the reflected waveform as well as the coefficient of variation of the intensity as a function of beam (horizontal 1-8) and range (1-1024). The horizontally extended target is due to the side lobes of the beams. As evidenced from the figure the degree of variability from the target was approximately 5 % whereas that of the bottom was much higher, on the order of 10-30 %. This indicates that for this experiment, the major source

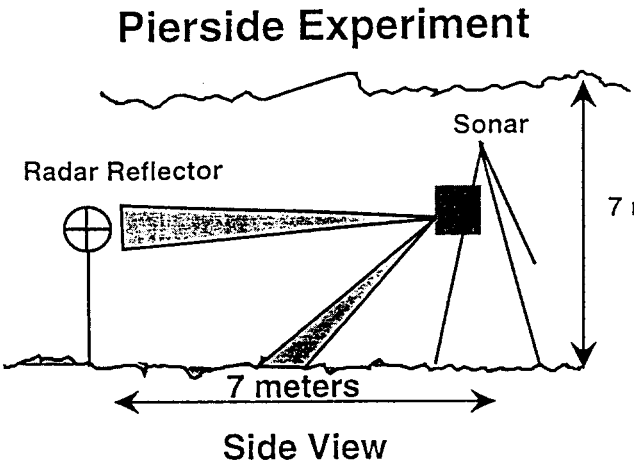

Figure 2: Experimental Configuration

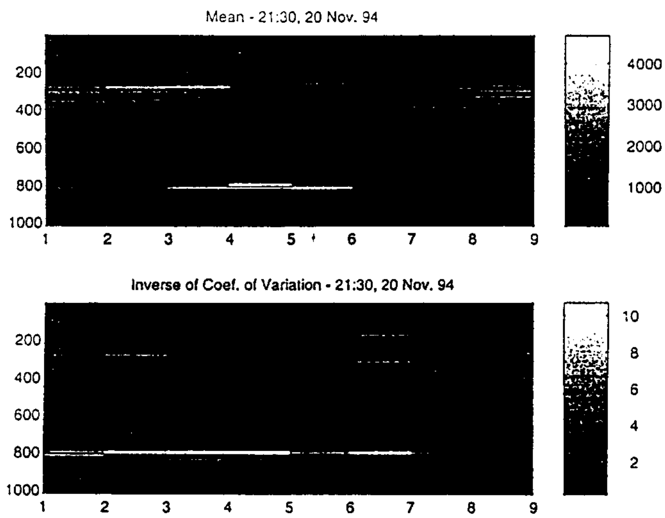

Figure 3: Experimental Results

of variability is the water column itself. Further experiments to measure temporal and spatial coherence are presently underway in our group.

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