Acoustic Propagation Considerations for Underwater Acoustic Communications Network Development *

James Preisig
jpreisig@whoi.edu
Department of Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Woods Hole, MA, USA

The underwater environment is widely regarded as one of the most difficult communication channels. Underwater acoustic communications systems are challenged by the characteristics of acoustic propagation through the underwater environment. There are a wide range of physical processes that impact underwater acoustic communications and the relative importance of these processes are different in different environments. In this paper some relevant propagation phenomena are described in the context of how they impact the development and/or performance of underwater acoustic communications networks. The speed of sound and channel latency, absorption and spreading losses, waveguide effects and multipath, surface scattering, bubbles, and ambient noise are all briefly discussed.

I. Introduction

The ocean is a temporally and spatially varying propagation environment whose characteristics pose significant challenges to the development of effective underwater wireless communications systems. The high rate of absorption of electromagnetic signals in sea water has limited the development of electromagnetic communications systems to a few specialized systems. Similarly, optical signals are also rapidly absorbed in sea water and have the added disadvantage of scattering by suspended particles and high levels of ambient light in the upper part of the water column. As a result, the development of underwater optical communications systems has also been limited to a few applications. Thus, acoustic signaling is the primary form of wireless underwater communications.

Despite its favorable characteristics relative to electromagnetic and optical propagation in the underwater environment, the physics of acoustic propagation severely tax underwater acoustic communications systems. Effective single model representations of the salient propagation characteristics of the underwater environment have been elusive. There is no ”typical” underwater acoustic environment, so no ”typical” underwater acoustic communications channel exists. In different environments, different physical processes pose the most significant hurdles to reliable communications resulting in varying challenges to a system. Thus, a system that is designed for and works effectively in one environment (e.g., a shallow water environment) may fail completely in another environment (e.g., a deep water environment). The design of reliable general purpose systems that work effectively across a broad spectrum of environments remains difficult.

While most work to date has focused on developing physical layer algorithms that can tolerate the characteristics of the underwater acoustic channel, there is an increasing awareness that many of these characteristics impact algorithm development and performance at higher network layers as well. This paper begins with a discussion of properties of acoustic propagation through sea water that are common to all environments. It then addresses waveguide and multipath effects, surface scattering, the impact of bubbles, and ambient noise. In each section, an attempt is made to describe how the acoustic propagation characteristics may impact the development and performance of underwater acoustic communications networks.

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II. Properties of Acoustic Propagation Through Seawater

When compared to electromagnetic propagation through the atmosphere, acoustic propagation through the sea water is characterized by significant frequency dependent attenuation and a relatively slow speed of propagation. These characteristics are present in all ocean environments.

Spreading loss, absorption loss, and scattering loss are the three primary mechanisms which attenuate underwater acoustic signals. Spreading and absorption loss are discussed here. Surface scattering loss is discussed in Section IV. Spreading losses are due to the expansion of the fixed amount of transmitted energy over a larger surface area as the signal propagates away from the its source. At relatively short ranges, the increasing surface area is represented by the surface of a sphere so signal energy decay due to spreading loss is at a rate of R^{-2} where R is the range from the source.

However, the ocean is bounded from above by the surface and, at the frequencies and ranges typically of interest for acoustic communications, it is effectively bounded from below by the sea floor. Thus, at some range from the source, the acoustic signal can no longer spread vertically and the nature of spreading changes from spherical to cylindrical spreading. This transition typically occurs at ranges much greater than the water depth. [1]. In the cylindrical spreading region, signal energy decay due to spreading loss is at a rate of R^{-1}. Figure 1 shows the spherical spreading loss out to a range of 2000 meters.

A second mechanism of signal loss results from the conversion of the energy in the propagating signal into heat. This mechanism is referred to as absorption loss. In sea water, the absorption loss of acoustic signals is strongly frequency dependent and increases with increasing frequency [2]. Signal energy decay due to absorption loss is proportional to $\exp^{-\alpha(f)\,R}$ where $\alpha(f)$ is an increasing function of frequency. Figure 1 shows absorption losses at 4 frequencies that span the acoustic frequency bands typically used for communications systems. This data was generated for values of ocean temperature and salinity typically found in temperate climates and were calculated using the expressions in [2].

Two characteristics of spreading and absorption loss are worth noting. First, at short ranges the spherical spreading loss dominates the absorption loss. Second, even at short ranges (e.g., approximately 400 meters) the absorption loss at 100 kHz exceeds that at 25 kHz by close to 15 dB. The practical impact of

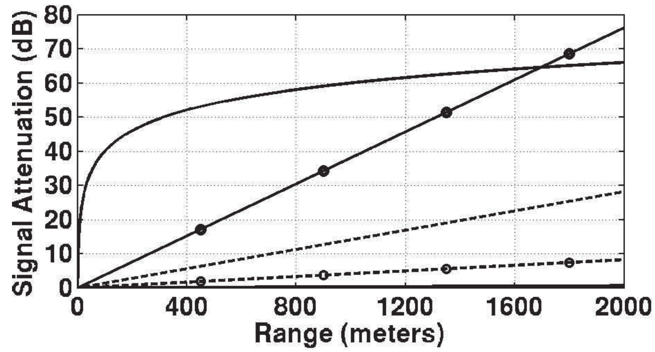

Figure 1: Acoustic signal attenuation as a function of range in sea water expressed in dB relative to the attenuation at a distance of 1 meter from the source. The upper solid line shows spherical spreading loss. The four other lines show absorption losses under typical sea water conditions at 5 kHz (the solid line that is indistinguishable from the 0 dB attenuation line), 25 kHz (the dashed line with circles), 50 kHz (the dashed line), and 100 kHz (the solid line with circles).

the frequency dependence of absorption loss is that the communications channel is effectively bandlimited and available bandwidth is a decreasing function of range. This characteristic can significantly impact choice of modulation and multi-access techniques as well as the problem of optimizing network topology. See [3] for an analysis of the impact of this frequency dependent absorption on network topology and capacity.

The relatively slow speed of propagation of sound through sea water ($c \approx 1500$ m/s) is also a factor that differentiates it from electromagnetic propagation ($c \approx 300,000,000$ m/s). The slow speed of propagation impacts communications system performance in a number of ways. First, as data discussed in Section IV demonstrates, channel coherence times can be on the order of 40 milliseconds and the "quality" of a single hop link can change significantly in a second or so. Thus, for source to receiver separations of more than about 100 meters in such dynamic environments, channel state information fed back from a receiver to a transmitter may be outdated before it is received at and exploited by the transmitter.

Another impact of the potentially high channel latency is the penalty that is incurred by any MAC or message acknowledgment technique that requires significant handshaking between source and receiver or requires time slots to guard against collisions between messages.

Finally, the relatively slow speed of propagation results in high Doppler spreads or shifts of received signals resulting from propagation path length fluctuations due to platform motion or scattering off of the moving sea surface. The Doppler shift (f_d) of a received signal is given by $f_d \approx f_o v/c$ where f_o is the original frequency of the signal and v is the rate of change of the propagation path length (e.g, the platform velocity). Thus, even at the modest values of $v = 2$ m/s and $f_o = 25$ kHz, the Doppler shift of a signal would be approximately 33 Hz. Similar Doppler spreads have been reported (for example, see data in [6]) resulting from a difference in rates of fluctuations of the lengths of two propagation paths. These Doppler spreads and shifts result in a reduction in the coherence time or apparent increase in the rate of channel fluctuation. This complicates the problem of channel tracking at a receiver and further exacerbates the problems discussed previously regarding the feedback of channel state information from a receiver to a transmitter.

III. Waveguide Propagation, Multipath, and Shadow Zones

In most environments and at the frequencies of interest for communications signals, the ocean can be modeled as a waveguide with a reflecting surface and ocean bottom and a spatially variant sound speed in the water column. The reflections of acoustic signals from the sea surface and bottom and the refraction of signals by the spatially varying sound speed in the water column results in multiple propagation paths from each source to receiver. This multipath results in a delay spread in the often time-varying impulse response of the communications channel leading to intersymbol interference at the receiver.

The delay spread of this impulse response can be significant at times. Delay spreads of up to 100 ms are mentioned in [4] and delay spreads of up to 80 ms are shown in [5]. With symbol rates of up to 5000 symbols/second common in modern phase coherent systems, these delay spreads result in intersymbol interference that can extend for hundreds of symbols. For high rate phase coherent systems, the receiver must either explicitly or implicitly track this impulse response in order to successfully estimate the data sequence that has been transmitted through the channel. The ability of the receiver to do this depends upon the delay spread and rate of fluctuation of the channel impulse response and is a primary factor in determining the capability of the channel to support such communications.

The temporal fluctuations in the channel impulse response can be driven by both time variations in the propagation environment and motion of the transmitting or receiving platforms. Environmental variation can give rise to rapid temporal fluctuations in the channel (e.g., Doppler spreads in the channel scattering function of up to about 25 Hz are shown in [6].) resulting in the challenge of estimating the parameters of a rapidly fluctuating system (i.e, the channel impulse response) with an apparently large number of independent parameters (i.e., samples of the impulse response). The scattering of the signals off of the sea surface gives rise to the most rapid fluctuations and are covered in more detail in Section IV. However, the spatial and temporal variations of the sound speed in the water also impact communications system performance.

The refraction of signals by the sound speed fluctuation not only gives rise to multipath but can also result in the formation of ”shadow zones” [2]. These are areas where there is little propagating signal energy. Thus it could be difficult to communicate with a receiver located in a shadow zone. Figure 2 shows traces of propagation paths through an environment with a typical deep water sound speed structure. Note that there are regions where either the propagation paths are widely separated or non-existent. In these areas, received signal energy would be low. While the depths (1000s of meters) and ranges (10s of kilometers) in this figure exceed those typically found in underwater acoustic communications networks, it is a good illustration of the principle of the formation of shadow zones.

The same shadow zone phenomenon is found in shallow water (order 100 meter depth) and at shorter ranges (order 3 km). In these environments, the vertical movement of masses of water results in vertical movement of the sound speed structure of the water column. This gives rise to variations in the location of shadow zones, even for the case of a stationary source and receiver, and has been studied in [7]. In that work, variations in received SNRs by as much as 10 dB on time scales of several hours were observed and shown to dramatically impact communications system performance. The temporal fluctuation in the location of regions of low received signal levels impacts the planning of network topologies and adjustment of message routing as the quality of the channel between source/receiver pairs slowly changes.

The refraction of sound can also lead to channel impulse responses that are non-minimum phase. That is, responses for which the first arrival is not the strongest. If not properly accounted for, such behav-

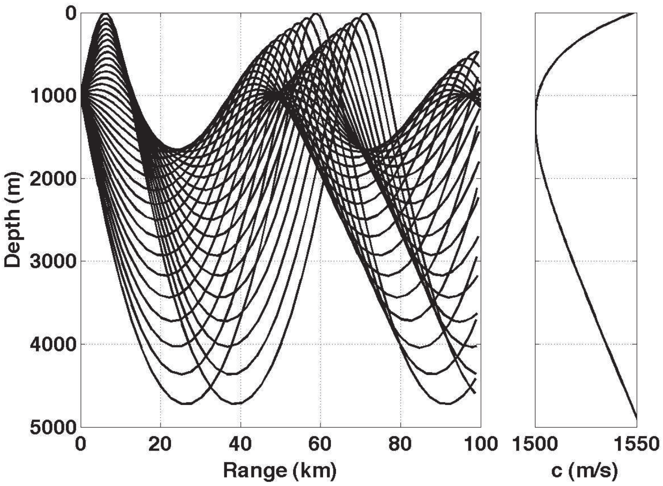

Figure 2: Ray paths for a deep water environment resulting in the formation of shadow zones. The right panel shows the sound speed profile (i.e., the speed of sound propagation as a function of depth) for which the ray paths were calculated. The left panel shows the ray paths radiating from the source. The source is located at a depth of 1000 meters and range of 0 km.

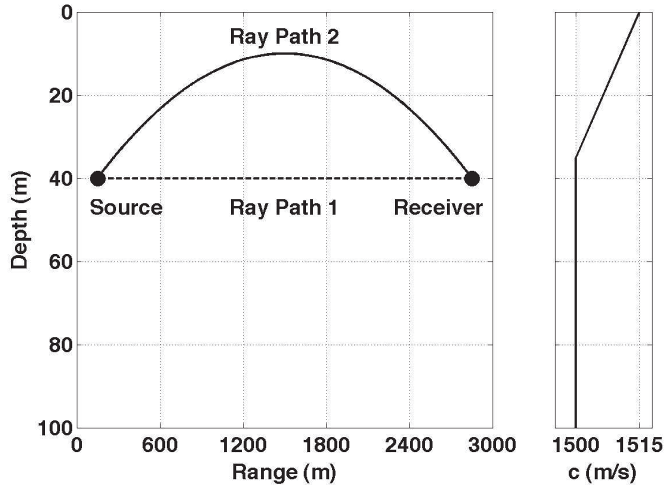

Figure 3: Schematic illustration of generation of a non-minimum phase impulse response due to refraction of acoustic propagation (ray) paths. The right panel shows a sound speed profile while the left panel shows two corresponding ray paths between the source and receiver.

ior can adversely impact signal alignment and synchronization algorithms. The physics underlying this phenomenon are illustrated schematically in Figure 3. Ray Path 1 propagates in a straight line since it is in the part of the water column that has a constant sound speed. On the other hand, Ray Path 2 refracts downward as it passes through the upper part of the water column. Therefore, it follows an arc from the source to the receiver. Since the length of Ray Path 2 is greater than that of Ray Path 1, the signal propagating along Ray Path 2 will incur more spreading and absorption loss than the signal propagating along Ray Path 1. However, the speed of propagation along Ray Path 2 is greater than that along Ray Path 1. In some environments, the difference in sound speed along the paths is large enough so that the propagation delay along Ray Path 2 is shorter than that along Ray Path 1. In this case, the first arrival will have a lower amplitude than the later arrival and the channel impulse response will have a non-minimum phase characteristic. The focusing of acoustic signals that scatter off of the ocean surface can also give rise to non-minimum phase impulse responses as discussed in Section IV.

Figure 4 shows such a channel impulse response estimated from data collected during an experiment in Monterey Bay in August 2006. The source to receiver distance was 3.2 kilometers and the water depth was approximately 100 meters. The sound speed profile in the area was downwardly refracting yielding the impulse response shown. There are two very small arrivals at relative delays of 0 and 5 ms, larger arrivals at relative delays of 17.5 and 27.5 ms, and the largest arrival at a relative delay of 20 ms.

IV. Surface Scattering

Reliable communications in the presence of the scattering of some of the transmitted signal by the moving sea surface presents one of the most challenging communications scenarios. The rough sea surface gives rise to a spreading in delay of each surface bounce path, can reduce the spatial correlation of scattered signals, and can result in very high intensity and rapidly fluctuating arrivals in the channel impulse response.

When the sea surface is calm, each surface scattered path results in an arrival in the impulse response that is both fairly stable in amplitude and localized in delay. In such cases, the impulse response of the channel is often sparse (i.e., has significant arrivals at only a few locations in delay). As the surface becomes more dynamic and roughens, the arrivals not only begin fluctuating in time but also become spread in delay. This results in the need to track a more rapidly varying and less sparse impulse response. A number of works have explored the dependance of the delay spreading of each surface scattered arrival on environmental conditions. In one reported set of experiments [8], the characteristic time spread for a single surface scattered path ranges from 0.2 ms at an acoustic fre-

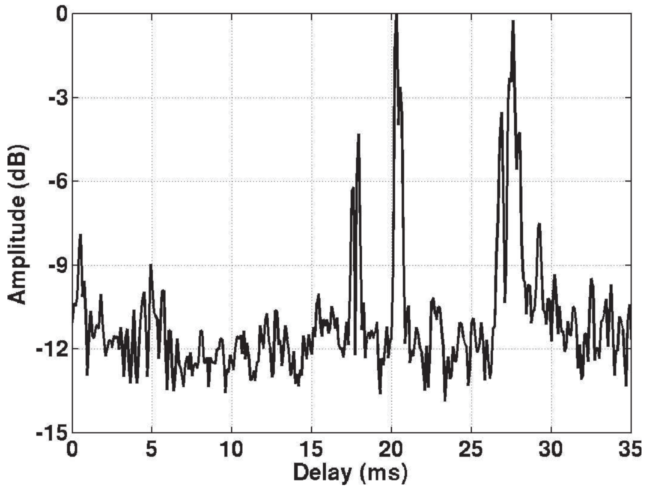

Figure 4: Estimate of the acoustic channel impulse response from data collected in Monterey Bay in 2006. Source to receiver range was 3.2 km and water depth was approximately 100 m.

quency of 30 kHz, wind speed of 0.8 m/s (1.55 knots), range of 669 meters, and grazing angle of 14.6^o to 2.33 ms at an acoustic frequency of 40 kHz, wind speed of 5.0 m/s, range of 740 meters, and grazing angle of 17^o. In general, the time spread of each surface scattered arrival is an increasing function of range, frequency and wind speed.

The spatial coherence of received signals is of concern in systems using MIMO type techniques to increase link data rates. A primary determinant of this coherence is the characteristic of the surface scattering In one experiment conducted using frequencies and geometries of interest for acoustic communications systems, the correlation scales of a surface scattered acoustic signal at a frequency of 20 kHz ($\lambda = 0.075$ meters) were estimated to be 0.25 meters ($> 3\lambda$) in the vertical and approximately 1.5 meters (20λ) in the horizontal. The horizontal source to receiver separation for this test was 497 meters and the measured wind speed was 7.0 m/s [9].

While the preceding cited works generate a statistical description of the surface scattering process, recent work utilizing an analysis of the scattering from individual surface waves has lent new insights into extremal scattering events that can cause fairly abrupt failures of communications links [10]. Referred to as ”surface wave focusing”, the events result in very high intensity (sometimes 3 to 5 dB higher than the direct, unreflected arrival) and rapidly fluctuating arrivals. Surface wave focusing results from the fact that waves moving over the sea surface can act as downwardly facing curved mirrors that reflect the sound down into the water column and focus it at predictable locations.

Figure 5[1] shows data from the experiment described in [10] in which the source and receiver were separated by approximately 40 meters and a surface wave focusing event occurs at a time of approximately 20 seconds. The ability of a channel estimation algorithm to accurately estimate the channel impulse response is significantly decreased as the large surface wave passes between the source and receiver creating focused arrivals. Recent research has shown that significant performance improvements in physical layer performance can be made by properly accounting for the characteristics of the scattering functions of these arrivals. [11].

Surface wave focusing has been observed in the experiment described in [6] at source to receiver ranges out to 500 meters in shallow water (15 meter water depth). Data from the same experiment collected at a source to receiver distance of 1000 meters also shows evidence of surface wave focusing and highlights one of the challenges that it poses. Figure 6 shows a sequence of channel estimates in which a surface scattered arrival intensifies and then decays over a dynamic range of close to 10 dB in a span of 0.25 seconds. Proper channel synchronization and estimation can both be compromised by such channel fluctuations.

The role of surface scattering in determining communications link quality can also result in the link quality having a periodic characteristic when the surface waves are nearly periodic [6]. Figure 7[2] shows the bit error rates achieved by channel estimate based decision feedback equalizers (CE-DFE) operating on signals collected on one and four receiver hydrophones. The source to receiver range in this case was approximately 250 meters, the water depth was 15 meters, and the significant wave height of the surface wave field was 3 meters. Knowledge of or the ability to reasonably predict the periodic nature of the quality of a particular communications link would be instrumental in improving transmit scheduling, selecting error correction coding and interleaving strategies, and improving message routing in underwater acoustic communications networks.

V. Bubbles

Bubbles generated by breaking waves at the sea surface can have a major influence on high frequency

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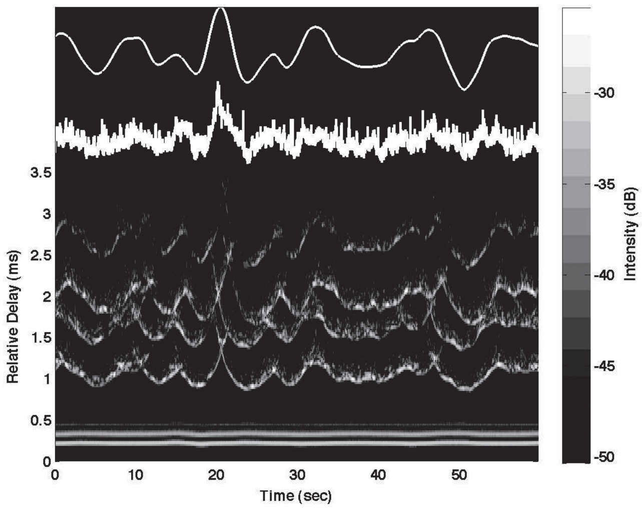

Figure 5: Surface wave height, signal estimation residual error, and intensity of estimated time-varying channel impulse response. The horizontal lines at the bottom represent the overlapping direct arrival and first bottom bounce. The time-varying arrivals, in order from bottom to top, are the first surface bounce, the surface-bottom bounce, the bottom-surface bounce, and the bottom-surface-bottom bounce. The smooth white line at the top of the figure shows the measured surface wave height near the specular reflection point of the first surface scattered path. The trough to peak excursion on this plot is 1.21 meters. The jagged white line immediately below the surface wave height line is a plot of the magnitude of signal estimation residual error realized by the algorithm used to estimate the channel impulse response. This plot is in dB and the minimum to maximum error excursion is 10.74 dB. The signal estimation residual error is a good indicator of the ability of the estimation algorithm to accurately track the channel impulse response. A high signal estimation residual error indicates that the algorithm is not effectively estimating the channel impulse response.

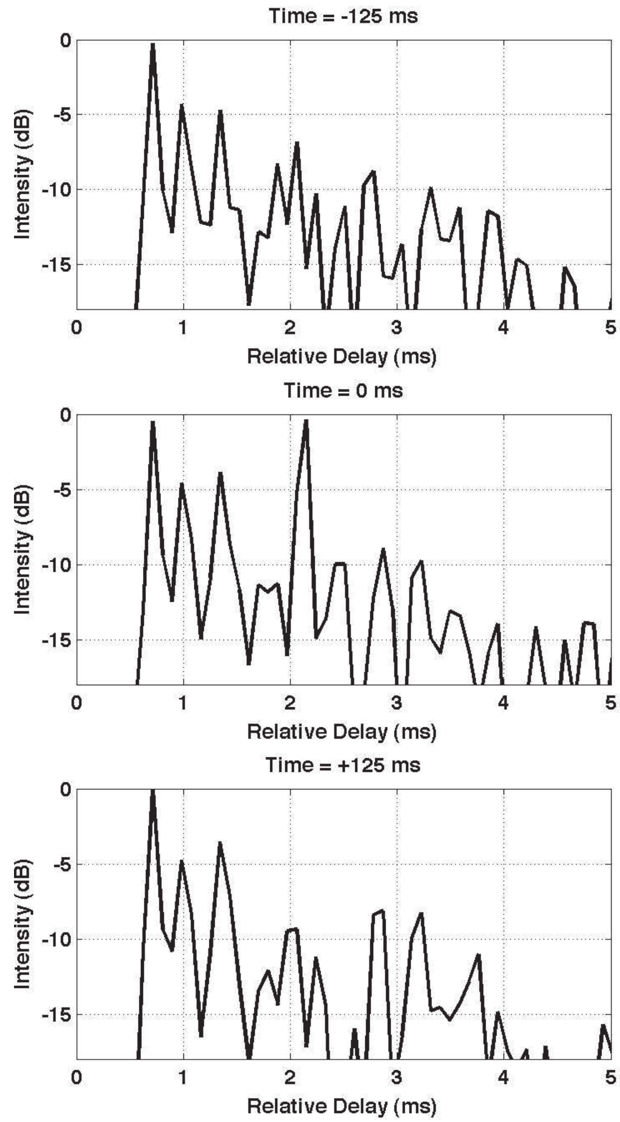

Figure 6: The first 5 ms of the estimated channel impulse response from data collected at a source to receiver range of 1000 meters in 15 meters of water. The three estimates were made using data collected at 125 ms intervals. The intensity of all three estimates was normalized using the same factor so that the largest arrival has an intensity of approximately 0 dB. The first arrival is a stable direct path that maintains a normalized intensity of approximately 0 dB over the period. The surface scattered arrival which arrives at approximately 2 ms in delay shows a rapid intensity fluctuation characteristic of a surface focused arrival. In the top panel (Time = -125 ms), the intensity of the arrival is approximately -7 dB. In the middle panel (Time = -0 ms), the intensity is approximately 0 dB. In the bottom panel (Time = -125 ms), the intensity is approximately -9 dB.

acoustic propagation in both the open ocean and near shore regions. Layers of bubbles near the surface can result in a significant attenuation of surface scattered signals. In one experiment, the impact of scattering off of the surface bubble layer was estimated to be an attenuation of the surface scattered signal by 3 dB per surface bounce. The acoustic frequency for this work was 30 kHz. [8] More recent work [12] has quantified the relationship between bubble density and scattering losses in a single surface bounce. For bubble densities characteristic of wind speeds up to around 6 m/s no bubble induced losses were reported. Above this level, bubble induced losses increased as a function of wind speed with almost total signal loss (approximately 20 dB loss per surface bounce) at wind speeds of approximately 10 m/s.

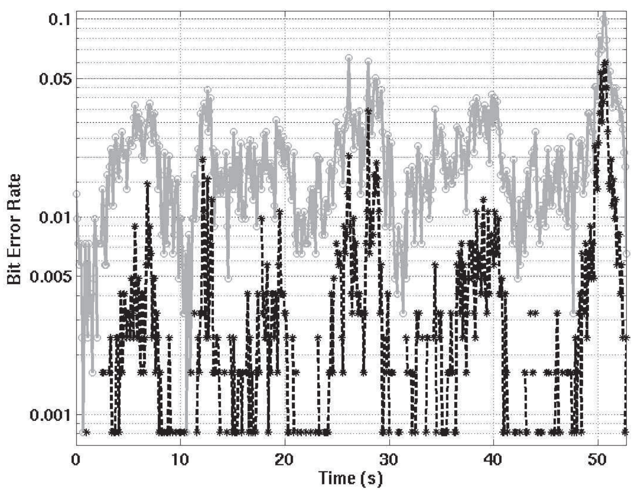

Figure 7: Bit error rate for the processing of a received signal by one (solid gray line with circles) and four (dashed black line with asterisks) channel equalizers (CE-DFEs). These bit error rates were calculated over 1230 symbol intervals corresponding to a time interval of 0.1102 seconds. Thus, the minimum error rate shown is 0.00081, which corresponds to one demodulation error in a single averaging block. Points in time where successive marks (asterisks for the four channel data) are not connected by lines indicate periods where there were no demodulation errors in a block. The data for both equalizers show periodic increases in bit error rate on a time scale that is commensurate with the dominant surface wave period during the time that the signals were transmitted.

Bubble clouds injected down into the water column also significantly attenuate propagating signals with rates as high at 26 dB/m being reported [13]. The injection of bubbles by a breaking wave in shallow water can result in a sudden channel outage. Figures 8 and 9 show examples of the rapid increase in signal attenuation that can occur. Figure 8 shows an extended and complete channel blockage (approximately 50 dB of additional signal attenuation) that is characteristic of a breaking wave and complete penetration of the water column by a bubble cloud. Figure 9 shows a more modest outage in both the level of attenuation and the duration of the outage.

VI. Ambient Noise

There are several important natural sources of ambient noise in the ocean at frequencies of interest for acoustic communications. These include breaking waves and bubbles, biological sources, and rain. Ambient noise has been studied extensively with a common theme that the power spectral density of the noise decreases with increasing frequency. References [1] and [14] both discuss a number of the sources of noise while [15] focuses on bubbles. Bubbles are one primary source of ambient noise in the open ocean in the 3 to 30 kHz band. [15] reports that the power spectral density of the noise rolls off at approximately 5 dB per octave and that noise levels increase with wind speed until a point where they begin to decrease due to absorption by the surface layer of bubbles. The frequency dependence of the ambient noise should be one of the factors considered when selecting frequency bands for underwater acoustic communications systems.

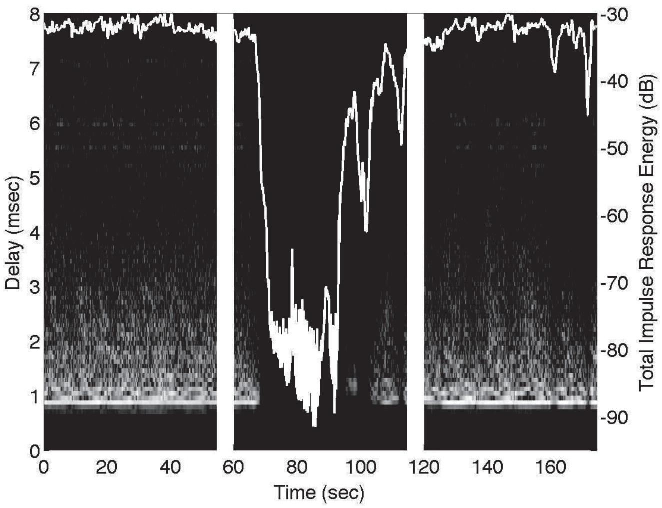

Figure 8: Estimate of magnitude of the time-varying channel impulse response as a function of time and delay and the corresponging total impulse response energy (white line - scale in dB shown on the right axis) shown as a function of time. The gray scale is in dB and spans a range of 30 dB with black at the low end of the scale and white at the high end of the scale. The receiver at which this data was gathered was located in the surf zone and the source was located 144 meters seaward of the receiver.

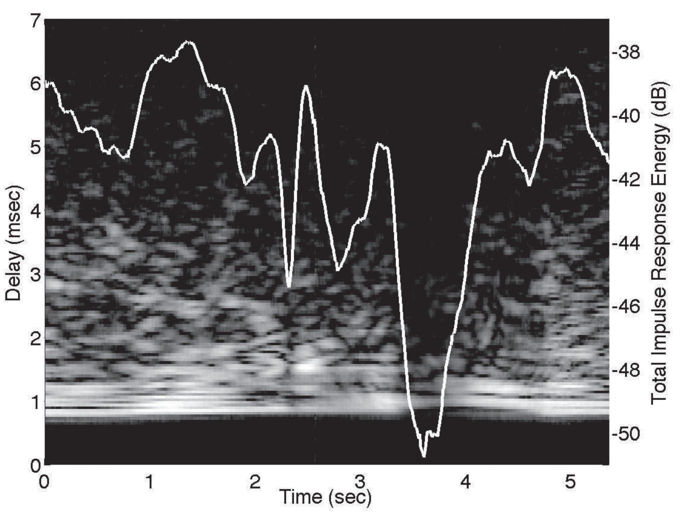

Figure 9: Estimate of magnitude of the time-varying channel impulse response as a function of time and delay and the corresponging total impulse response energy (white line - scale in dB shown on the right axis) shown as a function of time. The source-receiver geometry and gray scale range are the same as for Figure 8. Note that the later arrivals (greater delay) are attenuated the most during the outage. These arrivals propagate at steeper angles with respect to the horizontal and are more prone to blockage by bubble clouds near the sea surface.

VII. Conclusions

There is no single channel model that captures the relevant acoustic propagation characteristics in all underwater environments. Thus, the successful development of underwater acoustic communications networks will greatly benefit from an understanding of the roles of the different characteristics in different environments of interest. Signal attenuation and propagation speed, the ocean waveguide and time-varying multipath, surface scattering, bubbles, and ambient noise can all impact the development, performance, and analysis of physical layer, MAC, routing, and coding techniques.

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