UNDERWATER SOUND PROPAGATION AND
ACOUSTIC COMMUNICATION IN
A TIME-VARYING SHALLOW ESTUARINE ENVIRONMENT

by

Zhenguang Zou

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Oceanography

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ABSTRACT

Estuaries are water regions that connect rivers and oceans, which are very important due to heavy traffic, fishery and other coastal engineering activities. Underwater acoustic technology offers a series of effective applications and technical supports for real-time monitoring and long-term preservation of the nature environment and ecosystem in these regions. However, estuaries are shallow waters with complicated temporal and spatial environmental variability, involving a variety of physical oceanographic processes, such as tidal water mixing and ocean winds/waves, which can significantly influence the underwater sound propagation and moreover, underwater acoustic communications. In order to perform reliably and effectively in such complex time-varying shallow-water ocean environments, next-generation underwater acoustic communication systems need an all new design based on the environmental variability of the physical ocean, which takes the environmental physics and time-varying variability into account and is able to adapt and switch to the optimal mode as the environment evolves. Therefore, a deep, comprehensive and thorough understanding of the link between the time-varying ocean environment, underwater acoustic channel, and underwater acoustic communication systems is highly required.

This dissertation investigated the relationship between the shallow-water, time-varying environment of estuaries, the underwater sound propagation and underwater acoustic communications, which can help the design of underwater acoustic systems so that they can adapt the time-varying environment with wiser parameter configurations. In this dissertation, field data analysis, joint numerical modeling, together with a controllable laboratory experiment were used to study acoustic channel variability of a shallow estuary and its influence on the performance of underwater acoustic communications. This dissertation included four aspects: (a) Effect of water-column
variation due to the tidal dynamics in an estuary on the underwater acoustic direct path; (b) Effect of time-varying surface roughness due to the wind-driven waves on underwater acoustic surface paths; (c) Numerically modeling the effect of time-varying wind-driven shallow-water waves on coherent underwater acoustic communications using a combined model; (d) Conducting a controllable laboratory experiment to investigate the time-varying wind-driven water waves on the performance of coherent and non-coherent underwater acoustic communications.

The first two aspects focused on the link between the time-varying environment of an estuary and the underwater acoustic wave propagation. With field data analysis and joint numerical modeling, the time-varying variability of acoustic direct paths and surface-bounced paths from a high-frequency acoustic experiment conducted in the Delaware Bay estuary was explored. On one hand, periodical acoustic direct path fading was found in the tidal-straining Delaware Bay estuary, with the fading period as same as the semi-diurnal tide. Based on physical oceanography and ocean acoustics, the mechanism that causes the direct path fading and its link to the water dynamics of an estuary was investigated. On the other hand, the relationship between the acoustic surface paths and the surface wind speed was investigated, and the wind-influenced shallow-water time-varying channel was studied using field data analysis and a joint model combining physical oceanography and ocean acoustics. The joint numerical model, including a wind-wave model, a surface generation algorithm and a parabolic equation acoustic model, reproduced the relationship between the wind speed and surface reflection signals.

The last two aspects applied the knowledge of underwater sound propagation in shallow estuaries into analyzing the performance of underwater acoustic communication systems, i.e., investigating how the fast fluctuation of a shallow-water environment (wind-driven waves) influences different fundamental modulation schemes for underwater acoustic communications. To better analyze the effect of environmental variability of the physical ocean on underwater acoustic communications, the surface condition was set as the only variation in the numerical modeling and the controllable laboratory
experiment. On one hand, a combined model including physical oceanography, ocean acoustics, and underwater acoustic communication was used to study the time-varying underwater acoustic channel under different wind speeds, and the performance of the coherent acoustic communication (QPSK) system. On the other hand, a controllable laboratory experiment was conducted to investigate bit-error-rate (BER) performance of the MFSK (representing the non-coherent acoustic communication) and the QPSK (representing the coherent acoustic communication) acoustic modulations.

The main conclusions of the dissertation are as follows. For the time-varying variability of underwater acoustic channel: (a) Due to the tidal-straining water dynamics of an estuary, periodical water column exchange between the seawater and the freshwater, up-refracting sound speed profile is more likely to form by the end of ebb tide, which redirects sound signal away from the deep receivers and creates shadow zone for the sound direct path; (b) In an open estuary, the acoustic pressure of surface-bounced paths decreases with increased wind speed, as a result of increased acoustic scattering due to the wind-driven surface roughness. For underwater acoustic communications: (c) Coherent acoustic communications are sensitive to the fast time-varying variability, and performance decrease significantly with increased wind speed, as a result of increased channel variability and decreased temporal coherence; (d) Non-coherent acoustic communications are less sensitive to the channel variability, and the reduced multipath signals due to wind-wave surface may improve the system performance.

The key novelties of this dissertation include: (a) Using a joint model involving physical oceanography and ocean acoustics to study the effect of time-varying estuarine environment (water-column variations and wind-driven surface waves) on underwater sound propagation and the underwater acoustic channels. (b) Using an integrated model involving physical oceanography, ocean acoustics, and underwater acoustic communications to study the effect of time-varying estuarine environment (wind-driven surface waves) on underwater acoustic communications. (c) Using field experimental
data, numerical modeling and controllable laboratory experiment to study the underwater sound propagation and underwater acoustic communications in a time-varying ocean environment.
Chapter 1

INTRODUCTION

Sounds are one of the most effective forms that can travel effectively over a long distance in the ocean with a relatively small attenuation, much smaller than electromagnetic waves [1]. As a qualified candidate for underwater wireless applications, acoustic waves enable many practical underwater acoustic technologies such as underwater sonar detection [2], acoustic communication [3], and acoustic inversion [4] for ocean exploration. Due to the wide applications in military, scientific and civil engineering areas over the years, the underwater acoustic communication has received increasing interests and attentions and become a research hotspot. Because all underwater acoustic technologies use the propagation of acoustic waves in a water medium, the variation of the physical ocean environment can significantly influence sound propagation under the water and further, underwater acoustic communications. Thus, a better understanding of the relationship between the physical oceanography, ocean acoustics and underwater acoustic communications is greatly beneficial for improving the design of next-generation underwater acoustic communication systems.

The booming of the study on underwater sound propagation began at the World War II, for military purposes as the key driving force at the time [2]. Since active sonar systems are mono-static, and use single-frequency continuous wave (CW) as the sound source [2], early studies usually viewed underwater sound propagation problems based on a sonar perspective, i.e., in terms of transmission loss, target strength, attenuation coefficient, reverberation, etc [2, 5, 6]. Later, with increasing demand for underwater acoustic communications, the perspective of underwater sound propagation has been greatly extended, shifting to the underwater acoustic communication channels. Unlike traditional sonars, acoustic communication systems are in a bistatic configuration,
and use broadband signals [7]. Therefore, underwater sound propagation research for acoustic communication systems focuses on the characteristics of underwater acoustic channels, i.e., in terms of multipath structure. Due to the high variability of nature ocean environments, understanding the complicated underwater acoustic channel has become an important topic for underwater acoustic communication research.

Previous studies have revealed two key challenges for the effective and reliable acoustic communications under the water – the multipath structure of underwater acoustic channels and the acoustic variability due to time-varying ocean environments. On one hand, due to the existence of two nature boundaries (an air-water interface and a seafloor) reflection and scattering of sound occurred at these two boundaries can create more than one acoustic paths between the transmitter and receiver [8]. This multipath effect creates later acoustic arrivals after the direct path, leading to the amplitude variation of received sound signals, which further transfers into the spatial, temporal and frequency domains of acoustic waves, causing problems such as spatial diversity, temporal spreading, and selective frequency fading, etc [9]. The multipath effect is more significant in shallow-water regions like coastal waters or estuaries, where multiple, repeated surface-bottom reflections are more likely to occur within a short range [10]. On the other hand, the ocean varies on a wide timescale (from milliseconds to hundreds of years) and a broad length scale (from millimeters to thousands of kilometers) [11]. In nature ocean environments, atmosphere-ocean dynamics (e.g., surface waves, swells, etc) modify the air-water boundary [12, 13, 14]; water motions (e.g., tides, currents and upwelling/downwelling) change water column properties, such as density, temperature, and salinity [15, 16]. Such environmental variability causes the acoustic multipath structure to fluctuate over time, leading to decreasing temporal coherence and shifting frequency bands [17, 18]. In short, the multipath effect and the time-varying ability together make underwater acoustic channels highly complicated, which are extremely challenging for underwater acoustic communications [19, 20].

One example of nature water environments that illustrates both challenges (the shallow-water multipath and time-varying environmental variability) at the same time
is a shallow-water estuarine environment. Estuaries are transitional zones connecting freshwater and seawater with high primary productivity, rich marine biological resources [11, 21]. As a very important coastal ecosystem, estuaries should be monitored for its environmental health and sustainable development. Underwater acoustic communication can provide effective technical support to construct underwater monitoring networks for long-term monitoring and protection of estuaries [22, 23]. However, the environmental variability in an estuary is extremely strong and complicated [24], due to the interaction of freshwater and seawater, the tidal-straining water dynamics, as well as the atmospheric dynamics between the land and the ocean. Hence, studying the connection between the physical ocean, ocean acoustic, and underwater acoustic communications, as a whole system, is the key to the fundamental improvement of the performance of underwater acoustic communication systems to apply in these highly time-varying, shallow estuaries.

The goal of this dissertation was to investigate the relationship between the underwater sound propagation, underwater acoustic communications, and the time-varying physical environment of a shallow estuary, which can be used to guide the design of future underwater acoustic communication and networking. The environmental variability investigated in this dissertation includes two different timescales: a timescale of seconds that captures fast fluctuation of acoustic surface groups due to surface winds and waves, and a timescale of hours that represents slow fluctuation of both acoustic direct path and surface groups due to water column variations. Field data analysis, integrated numerical modeling and laboratory experiment were used in this dissertation to explore the link between the physical oceanography, ocean acoustics, and underwater acoustic communications.

The work of this dissertation involves the following two aspects. On one hand, sound propagation and acoustic channel characteristics in a shallow-water estuarine environment were studied, based on data analysis of a field experiment and numerical modeling (Chapters 2 and 3). On the other hand, the variability of underwater acoustic channels due to the physical ocean environment was applied to the research of
underwater acoustic communication, to investigate the influence of the shallow-water estuarine environment on the performance of underwater acoustic communication systems (Chapters 4 and 5).

The four major research questions in this dissertation are: (a) The effect of water column variation due to water dynamics of a tidal-straining estuary on the variability of acoustic direct paths. (b) The effect of surface boundary variations due to the wind-driven surface waves on the variability of acoustic surface-bounced paths. (c) Numerically modeling the effect of wind speed on the performance of underwater coherent acoustic communication systems using an integrated numerical model. (d) Studying the effect of time-varying wind-driven surface waves on the performance of underwater coherent and non-coherent acoustic communication systems from a laboratory simulation experiment.

First, the effect of slow fluctuation of the water column on acoustic direct paths was investigated with the water dynamics of a tidal-straining estuary. Acoustic direct paths have no interactions with sea surface and seafloor and contribute the major acoustic energy at the receiver, so they are crucial for acoustic communications due to the stability and high energy. However, periodical intensity fading of the acoustic direct path was observed in the Delaware Bay, a shallow tidal-straining estuary, with an attenuation up to 20 dB. This is affected by the variation of water-column properties itself. With field data analysis and numerical modeling, results suggested that the repeated, significant fading in the sound direct path was the acoustic channel response to the tidal forcing dynamics in the Delaware Bay, due to the periodicity of salinity profile variation by the end of ebbing period, causing upward sound refraction and creating the shadow zone for the sound direct path at the sea bottom. The direct path fading should be taken into account in the future design of reliable underwater acoustic systems in these regions, particularly those based on the detection of direct path energy, which the direct path energy is crucial for signal detection and synchronization.

Second, the fast fluctuation of wind-driven surface waves on variations of acoustic surface paths was examined as a function of wind speed. The acoustic surface paths
interact with the sea surface, which has a short timescale within seconds and is highly related to surface winds. Underwater acoustic channels in estuaries can be drastically affected by coastal wind-wave dynamics, and the wind (or sea states) effects on underwater acoustic propagation and communication systems have been reported. Field data analysis and combined numerical modeling (including a shallow-water wind-wave spectral method and a 2-D rough-surface parabolic equation model) were conducted to investigated how the wind-driven surface roughness in shallow-water environments affects the variability of mid- to high-frequency broadband acoustic channels. Modeling simulations agreed with field data analyses, and together they revealed strong correlations between wind speed and pressure amplitude of acoustic surface bounces, indicating that increased wind-driven surface roughness is primarily responsible for the decrease of surface-bounced acoustic energy. These findings lead to a new empirical transmission loss formula for predicting wind-related surface acoustic energy.

Third, how the performance of underwater coherent acoustic communication systems varies with surface wind speed was studied using integrated numerical models, including physical oceanography, ocean acoustics, and underwater acoustic communication. Performance degradation and system failures in underwater acoustic communication were previously reported due to wind-induced surface waves, especially for coherent communication systems which utilize phase information during the modulation. A controllable numerical approach was proposed to study the effect of wind-driven surface waves on the performance of underwater coherent acoustic communication. Realistic acoustic channels for different wind conditions are numerically simulated with wind-wave spectral methods and a 2-D rough-surface parabolic equation (PE) model; Then, these time-varying acoustic channels are tested with quadrature phase-shift keying (QPSK) modulation, one of the most fundamental modulation schemes for underwater acoustic coherent communication in different wind conditions within a frequency band of 15–20 kHz. Preliminary results suggested that in a time-varying environment, the performance of underwater coherent acoustic communication degrades with increasing wind speed, as a result of increasing temporal variability of wind-impacted surface
waves. The proposed integrated numerical modeling method could be a helpful tool to study acoustic communication problems in time-varying ocean environments.

Finally, a laboratory simulation experiment with controllable environmental variables was set up to verify the numerical results obtained in the previous chapter and to discuss the influence of wind-induced sea surface time-varying on the performance of underwater acoustic communication systems. Similar to the advantages of numerical simulation, the controllable experimental environment is helpful for investigating the influence of the single environmental factor (wind) on the performance of underwater acoustic communication. The laboratory experiment was carried out in an indoor water tank experiment environment. Two underwater acoustic communication modulation schemes (QPSK and MFSK) were performed in the three different surface scenarios, namely no-wind, windy surface and static rough surface scenarios, to evaluate the communication performance. Underwater acoustic channel analysis shows that the roughness and time-varying nature of the surface boundary conditions shortened the multipath, enhanced the instantaneous variation and decreased the time coherence. The underwater acoustic communication results showed that the performance of the coherent water acoustic communication system is degraded by wind-driven time-varying surface waves, while the negative effect on the non-coherent communication system is less significant, and a slight performance improvement may be obtained at a certain symbol width and signal-to-noise ratio.

These four research questions were discussed in four individual chapters. The rest of the dissertation was organized as follows. The slow fluctuation of water column variability on the acoustic direct path was explored in Chapter 2. This chapter will be submitted to the Journal of the Acoustical Society of America. Chapter 3 investigated the fast fluctuation of winds and waves on variations of acoustic surface groups. This chapter is published in IEEE the Journal of Oceanic Engineering [25]. Chapter 4 investigated the effect of time-varying wind-driven shallow-water waves on coherent underwater acoustic communications using an integrated numerical model. This
chapter was published in the Proceedings of 2016 IEEE/OES China Ocean Acoustics (COA) [26]. Chapter 5 conducted a controllable laboratory experiment to study the time-varying wind-driven water waves on the performance of coherent and non-coherent underwater acoustic communications. This chapter will be submitted to a peer-reviewed journal soon. Finally, Chapter 6 summarized the dissertation.
Chapter 2
DIRECT-PATH SOUND FADING IN A SHALLOW TIDAL-STRAINING ESTUARY

Periodical fading of the acoustic direct path was observed in the Delaware Bay, a shallow tidal-straining estuary, within a source-receiver range of 387 m and the mean water depth of 15 m. The cycle of these fading events was about 12.4 hours and the intensity attenuation was up to 20 dB. Data analysis suggested that the repeated, significant fading in the sound direct path was associated with the tidal forcing dynamics in the Delaware Bay, as a result of the periodicity of salinity profile variation, which caused upward sound refraction and created shadow zone for the direct path near sea floor by the end of an ebb tide. This direct path fading may occur in most tidal-straining estuaries as long as the relation between the source-receiver configuration in depth and theoretical sound speed gradient is satisfied, which provides a guideline for future acoustic applications. This study also suggested that direct path fading problem is important for underwater acoustic applications that utilize the direct path energy, and should be taken into account for the design of reliable underwater acoustic systems in shallow tidal-straining estuaries.

2.1 Introduction

In ocean environments, water column variations are usually very slow and gradual, which influences underwater sound propagation on a large time scale, ranging from minutes to hours, days, and even years [11]. Therefore, the underwater acoustic variability due to water column variations is much slower compared to upper boundary variations caused by surface wind-wave dynamics, whose change is more rapid and violent on a timescale within seconds [1, 10, 25]. It is the slow variation of ocean...
water column that gives rise to the stability of acoustic direct paths, i.e., the paths of sound rays that directly connect the acoustic source and receiver without interacting with the sea surface or bottom. These acoustic direct paths are generally considered as deterministic because they are relatively stable in time and not affected by the fast fluctuation of ocean surface [10]. However, the effect of the water column on underwater sound propagation for a longer period cannot be ignored. In fact, a drastic change of the water column feature may break the stability of acoustic direct paths and fail many acoustic applications based on the detection of the direct path, and thus the water column variability can be acoustically important.

Effects of water column variability on underwater sound propagation on large time scales have been long noticed and widely reported in previous studies [1, 10, 2]. For instance, the diurnal solar heating in the upper layer waters leading to temperature variation of the water column can cause significant sonar performance degradation, well known as the Afternoon Effect [2]. Events like internal waves propagating for hours or days can result in focusing and defocusing of acoustic energy and pose a big challenge for acoustic applications in internal wave active regions [27]. Seasonal fluctuation of the ocean environment can be even more remarkable, accompanied by thermocline deepening or shallowing which alters the acoustic channel and completely changes the underwater acoustic pressure field [1]. Eventually, any acoustic variability due to the water column will influence underwater acoustic applications that utilize sound propagation in the water medium, e.g., acoustic communications, which have been received increasing research interests these years. In one previous study [28], remarkable effects of temperature fluctuation of internal tides on high-frequency acoustic communications have reported, The other studied [29] revealed that underwater acoustic communication is significantly affected by tidal variations, where higher SNR is obtained at low tides because of closer multipath components and smaller reverberation tails. However, despite the importance of these time-varying water column effects, studies that explore the link between physical environment and underwater sound propagation,
even to acoustic applications, are still rare. The environmental variability of underwater acoustic channels is currently one of the biggest challenges for adaptive underwater acoustic communication and networking systems, and improved knowledge of the physical environment can be beneficial for the design of reliable underwater acoustic systems in the future [1].

One water environment with significant water column variability is an estuary, i.e., a river outlet to the ocean. Estuaries are transition zones between freshwater and seawater, and the interaction between two water bodies and the tidal dynamics can significantly impact underwater acoustic transmissions. Moreover, coastal oceans are highly important regions with heavy human activities such as ship traffic and/or other coastal engineerings, and with high biological production due to strong freshwater-seawater mixing that nourishes marine life [11]. Therefore, estuaries deserve long-term monitoring and protection for ecosystem health and sustainability, which can use the help of underwater acoustic techniques such as acoustic communications to broadcast the control commands and retrieve collected in-situ data [24]. However, estuaries are shallow waters where sound propagation has complicated multipath structure, and moreover, the environmental variability due to coastal processes makes the acoustic problem even more complicated. Currently, only a few acoustic studies explored these regions [24, 10, 29, 30], and future practical underwater applications are calling for more knowledge about the environmental variability in these particular regions.

This paper focused on the variability of acoustic direct paths which captures only the effect from slow variations of the water column in a tidal-straining estuary. In September of 1997, periodical-like intensity fading (up to 20 dB) of the direct path was observed in an acoustic transmission experiment from the Delaware Bay, where the water-column variability is significant due to the interaction between the river water and ocean water in a tidal estuary. This direct-path fading phenomenon has been noticed in previous studies [24, 10], but no systematic explanation was given at that time. In this study, the cause of the direct path fading was explained based on field data analysis and theories, e.g., sound propagation and the physical ocean dynamics.
in a tidal-straining estuary; Acoustic modeling was applied to reconstruct underwater acoustic pressure fields numerically with observed sound speed profiles and source and receiver positions. Data-model analyses confirmed that the direct path fading was a result of the periodical variation of salinity profile in the Delaware Bay due to tidal forcing water dynamics forming upward-refracted sound speed profiles that redirected the sound energy away from the acoustic receivers at the bottom.

The rest of the paper was organized as following. Section 2.1 introduced the direct path fading observed in a high-frequency acoustic experiment in the Delaware Bay. In Section 2.3, two particular events from the experiment were selected and environmental and acoustic data were analyzed. Section 2.4 explained the mechanism that caused the direct path fading from physical oceanography to acoustics. In Section 2.5, acoustic modeling was presented as a verification of the proposed hypothesis. Section 2.6 discussed more on the direct path fading problem from physical oceanography and acoustics perspectives. Finally, conclusions were made in Section 2.7.

2.2 The Direct-Path Fading Phenomenon

2.2.1 Description of the HFA97 experiment

In September of 1997, a High-Frequency Acoustic experiment (HFA97) was conducted to transmit reciprocal acoustic signals for one week period in the center region of the Delaware Bay (39°1′N, 75°11′W) to explore the variability of sound propagation due to the time-varying physical environment [10]. The Delaware Bay is a shallow tidal-straining estuary located on the east coast of the United States, which is a perfect region for this study for three reasons. First, the interaction between the river freshwater and the ocean seawater gives rise to significant water-column variability that this study needs. Second, many physical oceanographic studies about the Delaware Bay have been done in the past [31, 32, 33], which can help us understand the physics and water dynamics in this region. Third, acoustic applications are highly needed for the long-term monitoring and preservation of the Bay, which requires a better understanding of the underwater sound propagation in this region.
Two acoustic tripods were positioned with 387 m apart on the seafloor of the Bay to continuously transmit acoustic chirp signals. Each tripod had a transducer, located at 3.13 m, and three hydrophones, located at 2.18, 1.33, 0.33 m, respectively, from the seafloor. The water mean depth of the experiment region is about 15 m. Both tripods were connected to a computer in a nearby lighthouse (39°2′54″N, 75°10′56″W) through cables. With this source-receiver positioning, the difference of travel distance between the direct path and the first single bottom reflection was extremely small, less than 5 cm. In terms of acoustic arrival time, the difference was about 0.032 ms, which cannot be well separated by the frequency resolution of source acoustic signal.

During the experiment, a series of up-sweeping acoustic chirps (1–18 kHz) were transmitted in this shallow water region with two sampling strategies. One is to transmit acoustic chirps continuously for 40 s every hour, and the other for 5 s every ten minutes. The data samples used in this study were both, where those fast variations less than 5 seconds, i.e., surface variations or other instantaneous interruptions, can be averaged out so the ensemble average only reflects the slow variation of the water column. In this study, the geological time for each sampling transmission was referred as \textit{geotime}. The sampling frequency of the system was 46876 Hz. Each geotime transmission had six channels of received data—three locally and three remotely. For convenience, the local transmitter was denoted as $S$, the local hydrophones from top to bottom were simply denoted as $L_1$, $L_2$ and $L_3$, and the remote hydrophones as $H_1$, $H_2$ and $H_3$. The local top hydrophone ($L_1$) was 1 m from the source, which was defined as the source level for that geotime transmission. Acoustic channel responses were obtained by matched filtering the received acoustic data with the source chirp. Then, ensemble averaging was applied to the whole sampling duration, either 40 s or 5 s, to eliminate temporal fluctuation within seconds. Note that the 3 dB resolution of acoustic pings was about 0.1 ms, calculated from the autocorrelation of the source chirp, which was not small enough for the separation of the direct path and the first single bottom reflection.

Meanwhile, atmospheric and oceanographic measurements, including wind, tide,
current, salinity and temperature, were measured regularly and well synchronized with
the acoustic data during the experiment. A weather station at the lighthouse observed
the wind at 15 m from ocean surface every 15 minutes. Two pressure sensors measured
the tide near our acoustic tripods. A 1200 kHz narrowband ADCP was mounted in the
middle at the bottom looking upward, measuring the current profiles. The R/V Cape
Henlopen surveyed around the experiment region and CTD casts were conducted to
measure the salinity and temperature profiles. These environmental observations are
helpful for understanding the dynamics of the sound channel and for numerical acoustic
modeling, which serves as modeling inputs. During the whole HFA97 experiment, a
total of 1502 geotimes of sound propagation data were collected (171 40-s and 1331
5-s data) across high tides and low tides, calm days and windy days, which provides
a valuable data set for studying environmental variability in a shallow-water coastal
region. More information about the HFA97 experiment can be found in Refs. [10] and
[34].

2.2.2 The observed phenomenon

Figure 2.1 shows a segment of tidal and acoustical data from the HFA97 experi-
ment during September 23-25 of 1997, which illustrates the direct path fading problem
this paper proposed, i.e., the periodical-like, significant energy fading of the acoustic
direct path observed in a tidal-straining estuary.

The observation of tide and current during September 23-25 of 1997 [Fig. 2.1
(a)] indicated that the tidal cycle in the Delaware Bay is semi-diurnal (M2 tide, 12.4
hr), and the water column variation is slow on a timescale of minutes or even hours.
The water depth variation due to the tide ranged from 14.3–16.1 m. The current had
the same 12.4-hr period, but there was a phase offset, about 5 hr, between the current
and the tide. The mean of east-west direction current ranged from -0.40 to 0.39 m/s.
In Fig. 2.1 (a), the variation of current velocity is not as smooth as the tide, because
it not only depends on the tidal ocean currents, but also the river outflow which is
affected by other physical dynamics in an estuary (discussed in Sec. 2.6). Noted that
Figure 2.1: Observed acoustic direct-path fading in the Delaware Bay estuary during the HFA97 experiment. (a) Tide and current measurements. Black curve is the tide and the blue curve is the east-west current amplitude averaging from the whole column. (b) Acoustic channel impulse response during September 23-25 of 1997. The arrival time of the acoustic response is relative to the direct path. Red lines indicate events when the fading occur, and the green line indicates the normal case. Two selected geotimes, $T_1 = 1997/9/23, 16:38$ GMT and $T_2 = 1997/9/23, 22:50$ GMT, are also denoted.
around 1997/9/24, 14:00 GMT, there was a storm tide occurred in the Bay. From the tidal records [Fig. 2.1 (a)], one can see that the storm tide overlapped with the semi-diurnal tide, which leads to a variation of the current pattern as well.

The acoustic channel response from the remote top hydrophone ($H_1$) for the period exhibited strong variability of underwater sound channels in both intensity and arrival time responding to environmental variations [Fig. 2.1 (b)]. As this paper only focused on the energy fluctuation of the acoustic direct path and the absolute arrival time was out of concern, the arrival time in Fig. 2.1 (b) was plotted as relative to the direct path for a better illustration of direct-path amplitude/intensity fluctuation. The intensity of acoustic multipath varied between -50 and -70 dB. The first arrival was the direct path, consisted of two individual paths (D/B). The direct path was strong at most of the time, but it somehow attenuated significantly, e.g., around 1997/9/23, 10:50 GMT, 22:50 GMT, or 1997/9/24, 11:00 GMT, as seen in Fig. 2.1 (b). There seemed to be a cycle for the direct path fading, about every 12.4 hours, same as the semi-diurnal tidal cycle in the Bay, with an attenuation up to 20 dB. The fading events sometimes lasted for more than one hour, suggesting that it was a result of slow water-column variation. Later arrivals after the direct path were surface related paths, which encounter at least one surface reflection. Thus, their intensity was affected by both water column and sea surface motion, but the later was more dominant for two reasons. On one hand, surface paths can change over seconds as a result of surface motions, much faster than the timescale of water column variations [25]; On the other hand, surface paths have deeper grazing angles whose intensity seemed to less subjective to the water column variation (further explored in Secs. 2.3 and 2.5).

In short, this direct path fading problem observed in the HFA97 experiment seemed to be a result of complicated water dynamics of an estuary rather than just the variation of water depth. The change of water depth itself only varies the arrival time of surface paths, but not the direct path, because it does not travel to the water surface nor sense the water depth. However, it was more likely to link with the variation of
water column properties due to physical water dynamics in the Bay or other tidal-straining estuaries. The similar period of 12.4 hr suggested that the direct path fading was related to the tidal cycle in the Bay, particularly, the occurrences of direct path fading were likely to associate with the end of ebbing periods. During those fading events, the mean current was about to change direction from offshore to onshore. Even more interestingly, by the end of September 24, 1997, the direct path fading did not occur as expected, suggesting that the storm tide as a physical process also somehow influenced this problem by disturbing the tidal processes.

2.3 Field Data Analysis

2.3.1 Environmental data

Two geological times were selected to the further investigation of the direct path fading problem (marked in Fig. 2.1). One was $T_1 = 1997/9/23, 16:38$ GMT, when the direct path intensity was normal (referred as the normal case); The other was $T_2 = 1997/9/23, 22:50$ GMT, when the direct path fading was observed (referred as the fading case). Since the fading case ($T_2$) occurred at the end of the ebb tide, as an opposite, the normal case at the end of a flood tide was chosen. According to the tidal records [Fig. 2.1 (a)], for the normal case ($T_1$), the tide was 15.7 m (close to high tide) and the mean current was 0.08 m/s towards the south; while for the fading case ($T_2$), the tide was 14.4 m (close to low tide) and the mean current was about 0.10 m/s towards the north.

Figure 2.2 displays vertical water-column profiles for current, salinity, temperature and sound speed at two selected geotimes. These profiles are all typical estuary-type water profiles where the water column is separated into two relatively well-mixed layers with a transient zone between them. Current profiles [Fig. 2.2 (a)] for both cases were very similar, except for a small difference in the upper 7 m where the water moved in the same direction but at different current speeds for the two geotimes. The surface-layer current was mainly driven by the river outflow, which related to the physical processes such as precipitation; Therefore, the difference of surface current between
Figure 2.2: Measured water profiles for the normal case and the fading case. (a) Current; (b) Salinity; (c) Temperature; (d) Sound speed. The normal case ($T_1 = 1997/9/23, 17:00$ GMT) is illustrated in black, and the direct-path fading case ($T_2 = 1997/9/23, 22:50$ GMT) in red. The current profile is the north-south component.

two cases suggested different physical processes occurred at $T_1$ and $T_2$ (discussed in Sec. 2.6). The bottom layer current was mostly dominant by the seawater flow. For both geotimes, the current speed was close to zero because $T_1$ and $T_2$ were either the end of flood tide or the end of the ebb tide when the ocean flow was about to switch direction.

Unlike the current, salinity and temperature profiles for the two cases were remarkably different [Figs. 2.2 (b) and (c)]. For the normal case ($T_1$), the entire water column was almost homogeneous. The salinity was about 28.6 ppt with a difference less than 0.1 ppt and the temperature was about 21.8 °C with a difference less than 0.01 °C. For the fading case ($T_2$), however, the water column was strongly stratified with a transient zone separating the surface layer and the bottom layer. The upper layer water had a mean salinity of 26.3 ppt and a mean temperature of 21.3 °C. In the transient zone, both the salinity and the temperature increased significantly within the three-meter depth. The salinity raised 1.8 ppt and the temperature increased 0.2 °C at depth from 5 m to 8 m. In the bottom layer, the salinity and temperature slightly increased. The salinity reached 28.5 ppt and the temperature reached 21.6 °C at the
depth of 12 m. The in-situ salinity and temperature measurements suggested that the direct path fading ($T_2$) was associated with a more stratified water column while the normal case ($T_1$) was associated with a well-mixed water column. Also, the overall similarity of between salinity and temperature variations suggested that the driving factor of their variations in the Bay was the same.

The sound speed profile [Fig. 2.2 (d)] shared a pattern similar to the salinity and temperature profiles. The sound speed was calculated from salinity and temperature using Eq. 2.1 [35]:

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016z$$ (2.1)

where, $T$ is the temperature in °C, $S$ the salinity in ppt, and $z$ the depth in m. Like salinity and temperature, the sound speed profile was very uniform in the normal case ($T_1$), but it split into two layers due to the water stratification in the fading case ($T_2$). The sound speed at $T_1$ was 1519 m/s with a variation over the water column within 0.3 m/s, but at $T_2$, the sound speed difference between the surface layer and the bottom layer was 3.2 m/s, creating a positive sound speed gradient in the water column. Thus, the normal case was associated with a uniform sound speed profile while the fading case was associated with an up-refracting sound speed profile which tended to bend acoustic rays towards the surface layer.

Table 2.1 summarizes the statistical values for the salinity, temperature and sound speed in the surface (2–6 m), middle (6–8 m) and bottom (8–12 m) layers at the two geotimes. At $T_1$, all three layers had a much smaller difference and standard deviation values for water properties than that at $T_2$, indicating the water column changing from uniform to non-uniform between two geotimes. Particularly, more significant standard deviation values in the middle layer at $T_2$ confirmed the appearance of a steep-changing transient zone in the fading case. These variations in water column properties between two geotimes suggested strong water mixing and stratification activities in the Bay, which may be significant enough to affect the underwater acoustic propagation and lead to a big change of acoustic direct path energy.
Table 2.1: Statistical values for the water properties during the HFA97 experiment

<table>
<thead>
<tr>
<th>Salinity (ppt)</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Diff</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$(S):</td>
<td>28.57</td>
<td>28.60</td>
<td>28.55</td>
<td>0.05</td>
<td>0.017</td>
</tr>
<tr>
<td>$T_1$(M):</td>
<td>28.65</td>
<td>28.71</td>
<td>28.60</td>
<td>0.10</td>
<td>0.033</td>
</tr>
<tr>
<td>$T_1$(B):</td>
<td>28.70</td>
<td>28.72</td>
<td>28.66</td>
<td>0.06</td>
<td>0.021</td>
</tr>
<tr>
<td>$T_2$(S):</td>
<td>26.27</td>
<td>26.32</td>
<td>26.19</td>
<td>0.14</td>
<td>0.048</td>
</tr>
<tr>
<td>$T_2$(M):</td>
<td>27.29</td>
<td>28.21</td>
<td>26.37</td>
<td>1.85</td>
<td>0.596</td>
</tr>
<tr>
<td>$T_2$(B):</td>
<td>28.37</td>
<td>28.51</td>
<td>28.23</td>
<td>0.28</td>
<td>0.088</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Diff</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$(S):</td>
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<td>21.75</td>
<td>21.74</td>
<td>0.01</td>
<td>0.003</td>
</tr>
<tr>
<td>$T_1$(M):</td>
<td>21.76</td>
<td>21.76</td>
<td>21.75</td>
<td>0.01</td>
<td>0.002</td>
</tr>
<tr>
<td>$T_1$(B):</td>
<td>21.76</td>
<td>21.77</td>
<td>21.75</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>$T_2$(S):</td>
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<td>21.32</td>
<td>21.28</td>
<td>0.04</td>
<td>0.014</td>
</tr>
<tr>
<td>$T_2$(M):</td>
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<td>21.55</td>
<td>21.33</td>
<td>0.23</td>
<td>0.069</td>
</tr>
<tr>
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<td>21.60</td>
<td>21.55</td>
<td>0.04</td>
<td>0.013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sound speed (m/s)</th>
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<th>Max</th>
<th>Min</th>
<th>Diff</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$(S):</td>
<td>1519.05</td>
<td>1519.11</td>
<td>1518.99</td>
<td>0.12</td>
<td>0.040</td>
</tr>
<tr>
<td>$T_1$(M):</td>
<td>1519.21</td>
<td>1519.30</td>
<td>1519.12</td>
<td>0.17</td>
<td>0.055</td>
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<tr>
<td>$T_1$(B):</td>
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<td>1519.33</td>
<td>1519.30</td>
<td>0.03</td>
<td>0.008</td>
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<td>$T_2$(S):</td>
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<td>1515.37</td>
<td>1515.08</td>
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<td>0.104</td>
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<tr>
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<td>1518.20</td>
<td>1515.45</td>
<td>2.75</td>
<td>0.877</td>
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<tr>
<td>$T_2$(B):</td>
<td>1518.47</td>
<td>1518.71</td>
<td>1518.23</td>
<td>0.48</td>
<td>0.151</td>
</tr>
</tbody>
</table>

### 2.3.2 Acoustical data

Figure 2.3 shows the acoustic channel impulse responses for two selected geotimes ($T_1$, $T_2$) from all three remote hydrophones ($H_1$, $H_2$, and $H_3$). The amplitude of channel impulse response was normalized to the source level using the local top hydrophone ($L_1$), and the arrive time was relative to the arrival of the direct path. From Fig. 2.3, three facts can be observed with the close comparison between these acoustic channel impulse responses. First, compared direct path amplitude at the same depth
Figure 2.3: Acoustic channel response for all three hydrophones at different depths at $T_1$ and $T_2$. (a) Top hydrophone; (b) Middle hydrophone; and (c) Bottom Hydrophone. The amplitude of the channel response is relative to the acoustic source pressure amplitude at 1 m.

between two cases, one can see that direct path amplitude at $T_1$ was always larger than that at $T_2$ at all three different depths. For the top hydrophone ($H_1$), the relative direct-path amplitude was about 0.5 (-3 dB) at $T_1$, but it was strongly attenuated at $T_2$, being less than 0.1 (-10 dB), even less than some surface reflected energy. For other two lower hydrophones ($H_2, H_3$), the fading was also evident, with the energy ratio between $T_1$ and $T_2$ being about 0.1 (-10 dB), suggesting that the direct path fading can occur in more than one depth at the same range.

Second, compared direct path amplitude between different depths, the direct path amplitude decreased as the receiver depth increased in both cases. Although the source energy of each transmission is the same, the direct path amplitude was depth-dependent, and the direct path energy received by the lowest hydrophone ($H_3$) was...
much less than top hydrophone ($H_1$). For example, in the normal case ($T_1$), the direct path amplitude for $H_1$ to $H_3$ decreased from 0.953 to 0.034, about -29 dB; while in the fading case ($T_1$), it decreased from 0.05 to 0.006, about -18 dB. In other words, one can consider the direct path faded in $H_3$ compared to $H_1$, especially using surface path amplitude as a reference. Also, the attenuation of direct path amplitude over depth in the fading case ($T_2$) was noticeable but less significant than that in the normal case ($T_2$), suggesting that the direct path fading amplitude was related to the depth of the receiver.

Third, despite the significant difference in direct path amplitude, surface reflected sound energy for two geotimes remained at the same level, suggesting that the fluctuation of acoustic surface paths was independent to the process that caused the direct path fading. In fact, the amplitude of surface paths is mainly affected by the fast-moving surface waves and has a high correlation with local surface wind speeds [25]. According to the wind measurement, wind speed at $T_1$ was 10 m/s, and at $T_2$ was 11 m/s, which explained the same level of surface path amplitude between two different cases. However, if one compares the two cases closely, the multipath structures of surface paths for the two cases were very different. One interesting fact in Fig. 2.3 was that the fading case ($T_2$) seemed to have a slightly higher surface energy than the normal case ($T_1$) at any hydrophone depth, suggesting that when the direct path fading occurred, some of the energy loss in the direct path was redistributed and probably deposited into later surface paths.

### 2.3.3 Correlations

Sound speed is an important link between physical water environment and underwater acoustic pressure field. For this problem, the vertical gradient of a water property (e.g., sound speed, salinity, and temperature) is more important than its absolute value. On one hand, the water column is usually horizontally stratified, and the vertical gradients of salinity and temperature decide the stratification of the water column. On the other hand, the sound speed profile works as the sound refracting index
Figure 2.4: Relation between sound speed gradient and (a) salinity gradient, and (b) temperature gradient during the HFA97 experiment. The bottom layer data are colored in dark, the surface layer data in light, and the transient zone in between.

which redirects sound propagation and changes the acoustic pressure field. Therefore, the correlations of sound speed gradient with other environmental parameters were further examined to explore the direct path fading problem.

Figure 2.4 shows the salinity gradient and the temperature gradient as a function of sound speed gradient calculated from observed HFA97 environmental data, where significant correlations were seen. The range of these gradients was larger at the surface layer than at the bottom layer. The decrease of gradient range over depth suggested that buoyancy force was stronger in the freshwater outflow in the Bay. The correlation of sound speed gradient with salinity gradient was significant ($R_{S,C} = 0.94$), while the correlation with the temperature gradient was slightly less ($R_{S,T} = 0.8$). The relationship between the sound speed gradient and the salinity gradient was almost linear at all depths [Fig. 2.4 (a)]. The offsets in the temperature gradient plot revealed poor correlation in the surface layer, suggesting that the salinity was the dominant factor for the surface layer [Fig. 2.4 (b)]. The sound speed gradient in the Delaware Bay was mainly dominant by the salinity, but the temperature was also a major factor.
especially in the bottom layer.

**Table 2.2:** Correlation coefficients of sound speed gradient at different depths with tide ($R_{h,c}$) and current velocity ($R_{u,c}$).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>2</th>
<th>7</th>
<th>12</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{h,c}$</td>
<td>-0.0179</td>
<td>-0.4440</td>
<td>-0.3647</td>
<td>-0.4740</td>
</tr>
<tr>
<td>$R_{u,c}$</td>
<td>-0.1789</td>
<td>-0.2588</td>
<td>-0.0040</td>
<td>-0.1096</td>
</tr>
</tbody>
</table>

Table 2.2 lists correlation coefficients of the sound speed gradient for different depths with the tide and the current velocity. Overall, the tide had a better correlation with sound speed gradient than the current velocity. The overall correlation between sound speed gradient and tide for the whole water column was significant ($R_{h,c} = -0.4740 > 0.1$). The negative sign suggested that the low tide was associated with a positive sound speed gradient while the high tide was with a negative one. The sound speed gradient in transient and deeper layers (7 or 12 m) was much more correlated with the tide than the surface layer (2 m). However, the surface layer sound speed gradient correlation with the current velocity ($R_{h,u} = -0.1789$) was higher than the deeper layer, despite the overall poor correlation of the whole water column ($R_{h,u} = -0.1096$), indicating that the sound speed gradient in surface layer was dominant by the river outflow, while the sound speed gradient of bottom later was more related to the tidal cycle. Good correlation with the tide suggested that the variation of sound speed was linked to the physical processes that with the same phase of the tide, which drives the water column variation and further to the direct path fading problem.

### 2.4 The Mechanism

Theoretically speaking, the fluctuation of sound direct paths can only be induced by the inhomogeneity of the water column, including a wide variety of factors such as water properties, suspending particles biomass, etc., which redistributes the sound energy by reflection, scattering, and refraction. Field observations and data analysis suggested that the direct path fading was associated with a positive sound
speed gradient at the bottom layer which is more likely to form during the end of an ebb tide as a result of salinity and temperature variations due to the water dynamics in the Delaware Bay. This section continued to explore how the water dynamics in a tidal-straining estuary produces the up-refracting sound speed profile during the ebb tide through physical oceanography and the conditions on which direct path fading occurs through acoustics.

2.4.1 Physical oceanography

The water-column structure of an estuary can be simplified as a two-layer model (Fig. 2.5), with lighter freshwater flowing out from the top and denser seawater flooding
in and ebbing out from the bottom [11]. The semi-diurnal tidal variation acts on top of this structure, which leads to periodical interactions between two different water flows with significantly different salinity and temperature values. As a result, this estuarine tidal dynamics, also known as the shear flow circulation, creates different states of water stratification/mixing within a tidal cycle, leading to a redistribution of water properties in the water column [36]. Generally speaking, the water stratification of an estuary is usually salinity-dominant due to the significant salinity difference between the freshwater and seawater [11], and so is the Delaware Bay estuary. Here, the variation in the distribution of water properties, particularly salinity, within a regular tidal cycle in a tidal-straining estuary was further explored.

During the flooding period, seawater goes landward from below, opposite to the direction of the river outflow [Fig. 2.5 (a)]. This structure causes a strong current shear at the freshwater-seawater interface, which creates strong turbulence and stirs the water column. The stability of a water column is usually measured by the Richardson number—a ratio between the buoyancy term to the flow gradient term [11]:

\[
Ri = \frac{N^2}{(du/dz)^2}
\]  

(2.2)

where, \( u \) is flow speed, and \( N \) is buoyancy frequency:

\[
N = \sqrt{-\frac{g}{\rho} \frac{d\rho}{dz}}
\]  

(2.3)

where, \( g \) is gravity, \( \rho \) is the potential density, depending on temperature and salinity. If the Richardson number is greater than unity, the buoyancy force is significant and the water column is stable; Otherwise, the current shear is significant and strong water column mixing is expected. The Richardson number during the flood tide was smaller than unity, suggesting strong water column mixing. This procedure mixes water properties, such as salinity or temperature, towards homogeneity. In other words, the tidal flooding is a process of water mixing that decreases the stratification of the water column.

As an opposite, the seawater flows outward in the same direction as the river outflow during the ebbing period [Fig. 2.5 (b)]. The current shear during this period
is much less than the flooding period. Thus, the Richardson number is greater than unity and the buoyancy force is dominant, suggesting a stable, stratified water column. As a result, water flows move horizontally with small vertical property exchange. With less heavy and less saline river water steadily flowing out in the surface layer without much interaction with the deep, the salinity of upper layers continuously decreases. Eventually, the isohaline tilts seaward during the ebbing period [Fig. 2.5 (b)] as the time goes on. By the end of the ebb tide, the incline of the isohaline reaches the maximum, and in terms of the vertical profile, it appears as a strong positive salinity gradient. In other words, the ebb tide increases the stratification of the water column, which reaches a maximum by the end of ebbing, and the water column ends up with a strong positive salinity gradient. In terms of sound speed, which increases with salinity, temperature and pressure (Eq. 2.1), a uniform sound speed profile is more likely to form at the end of flood tide, while a positive sound speed gradient at the end of ebb tide, as a result of shear flow circulation in a tidal straining estuary.

2.4.2 Acoustics

Sound bends towards the layer that has lower sound speed. The positive sound speed gradient appearing at the end of ebb tide refracts the sound energy away from the bottom. The possible explanations for the decrease of acoustic direct path energy include two folds. One is due to the energy defocusing of a refracted ray cone [1]. The other is due to the existence of the bottom boundary that blocks the possible incoming energy from below. An extreme example is the shadow zone, i.e., when the sound speed gradient is significant enough, a direct path shadow zone will be created near the seafloor, which can cause significant intensity fading for the direct path signal. For the HFA97 experiment, the source and receivers were all close to the bottom, we suggested that the cause of significant direct path fading was similar to the shadow zone theory. However, in order for the significant direct-path fading to occur, a relation between the geometrical condition of the acoustic source and receiver, together with the sound speed gradient of the water column must be satisfied.
The acoustic refraction at the interface between two media with different sound speed is governed by the Snell’s Law:

\[ c_1 \cos \alpha_1 = c_2 \cos \alpha_2. \]  

(2.4)

where, \( c \) is sound speed, and \( \alpha \) is sound grazing angle. In nature, the water column is usually vertically stratified. For a water column with a linear sound speed profile (i.e., constant sound speed gradient for all depth), the trajectory of acoustic ray path is a circle (Fig. 2.6), whose radius can be calculated with [1]:

\[ R = \frac{c_0}{\frac{dc}{dz} \cos \alpha_0}, \]  

(2.5)

where, \( \alpha_0 \) is sound grazing angle at depth \( z_0 \), and \( \frac{dc}{dz} \) is sound speed gradient. Assuming at depth of \( z \), the ray has a horizontal grazing, about to turn upwards (\( \alpha_z = 0 \), so \( \cos \alpha_z = 1 \)), then Eq. 2.5 becomes:

\[ R = \frac{c_z}{\frac{dc}{dz}}. \]  

(2.6)

The sound speed in the water usually ranges from 1450 m/s to 1550 m/s. Note that in Eq. 2.6, the influence of \( c_z \) on the result is less significant than the variation of denominator—the sound speed gradient, \( \frac{dc}{dz} \). Therefore, one can assume a reasonable value for \( c_z \) (e.g., \( c_z = 1500 \) m/s), and then for any given sound speed gradient, the critical radius \( R \) is calculable.

Here, define the critical acoustic ray path, i.e., the one that comes out from the source at a particular angle and just slightly touches the seafloor, illustrated in Fig. 2.6. To satisfy the geometric condition, the critical ray path is unique and fixed. In the 2-D plane, letting the range that critical circle reaches the seafloor be \( X_c \), the critical ray circle satisfies the following equation:

\[ (x - X_c)^2 + (z - R)^2 = R^2 \]  

(2.7)

Substituting the depth of the source \( H_s \) in to Eq. 2.7, the horizontal range of the point that the ray hits the bottom or the center of the ray circle \( X_c \) can be calculated:

\[ X_c = \sqrt{2H_sR - H_s^2}. \]  

(2.8)
Finally, let us consider the receiver position. For any receiver range $X_r$, there is a unique depth that the critical ray reaches, namely the critical depth of the receiver, $H_c$, which can then be calculated with Eq. 2.8:

$$H_c = R - \sqrt{R^2 - (X_r - X_c)^2}. \quad (2.9)$$

Similarly, for any receiver depth $H_r$, the critical range $R_c$ is:

$$R_c = X_c - \sqrt{R^2 - (H_r - R)^2}. \quad (2.10)$$

When $x < R_c$ or $y > H_c$ (e.g., $H_A$ in Fig. 2.6), direct path can reach the receiver; Otherwise (e.g., $H_B$ in Fig. 2.6), the receiver is in the shadow zone.

Figure 2.7 illustrates critical rays for some different sound speed gradients using Eqs. 2.9 and 2.10 input with the HFA97 configuration. The shadow zone is on the right side of a critical ray path. Results suggested that for a small sound speed gradient, the receiver range that allows the existence of acoustic direct path is long. On the contrary, for a large sound speed gradient, the direct path is more likely to fade out when the range of the receiver is placed not close enough, or the depth is not shallow enough. As seen from Fig. 2.7, the maximum sound speed gradient that allows for $H_1$ and $H_3$ to have a direct path is about 0.2 and 0.1 s$^{-1}$, respectively. When the gradient
is greater than this value, the receiver will be in the direct-path shadow zone and the received direct path intensity will significantly decrease.

2.5 Acoustic Modeling

Though the wave equation that governs sound propagation has been mathematically studied since the 1960s, the complexity of the ocean environment still raises many interesting acoustic questions that are difficult to purely understand by mathematics. With the development of numerical computation, acoustic modeling, based on laws of acoustic propagation, offers a new approach for acoustic problems and to help analyze laboratory experiments and observations and to understand a real acoustic problem [37]. To testify the proposed hypothesis that the direct path fading observed in the HFA97 experiment was caused by the upward-refracting sound speed profile formed by the end of ebb tide, underwater acoustic pressure fields were reconstructed with acoustic models that follow fundamental rules of sound propagation, and the wave equation in heterogeneous fluid-solid media was numerically solved with observed environment inputs. If one can recreate the direct path fading numerically with acoustic models
using measured sound speed profile as model inputs, it is fair to say that the fading is a result of sound propagation in a particular sound speed profile.

2.5.1 Methods

One acoustic model used here to reconstruct underwater acoustic wave fields was a 2-D parabolic equation (PE) model, developed by Smith [38] and modified by Senne [39], which supports broadband acoustic source and coherent and incoherent energy from rough surface boundaries. The PE method was introduced into underwater acoustics in the early 1970s as an efficient numerical solution scheme based on fast Fourier transforms, and now it has now become the most popular wave-theory technique for solving ocean acoustic propagation problems [37]. PE also supports broadband signals through dividing the wide bandwidth into narrow frequency bands. For each band, PE model treats it as single-frequency and simulate the acoustic field, and the whole band is a sum of results from all frequencies. PE modeling has a better accuracy for the estimation of broadband acoustic pressure fields that this study needs. The other model used here was the Bellhop model, which was used to simulate acoustic ray paths [40]. The Bellhop is a popular, effective ray-tracing model for the visually analyzing acoustic ray paths by solving eigen roots of the wave equation. Bellhop is accurate in tracing ray paths and calculating arrival times, but it only supports single frequency, so the center frequency of the HFA97 experiment (10 kHz) was modeled.

There was one problem for applying acoustic modeling to the HFA97 experiment. Due to the limits of the HFA97 data, the water column measurement data only were available for depth from 2 to 12 m, but the depth of sound speed profile that mattered this problem most was the lowest three meters (below 12 m) where the source and receivers were located. Here, a modified modeling approach was used. Because the mechanism that caused the direct path fading in the HFA97 experiment was the up-refracted sound speed profile formed by the end of ebb tide, we can slightly tweak the sound speed profile for the portion that does not have sound speed data based on our proposed theory (i.e., the relationship between sound speed gradient and direct
path amplitude/intensity) to obtain acoustic modeling results similar to the field data as an alternative approach to verify this hypothesis. For water depth below 12 m without in-situ measurement, sound speed was simply assumed linear, which was also consistent in the proposed theory (Sec. 2.4).

The acoustic modeling in this section included two steps: First, PE model was used to simulate a few cases with sound speed gradients ranging from 0 to 1 s$^{-1}$ to investigate how direct path energy is associated with the sound speed gradient, i.e., the relation between the direct path energy loss and sound speed gradient with the HFA97 source and receiver configuration. Second, the exact sound speed gradient needed for each geotime transmission was calculated from observed direct path intensity of HFA97 field data (Fig. 2.1) based on the obtained relationship in the previous step. Third, full sound speed profile was generated and acoustic propagation was modeled by PE or Bellhop using the HFA97 source/receiver positions.

2.5.2 Modeling the effect of sound speed gradient

Because sound speed gradient is an important factor for the direct path fading problem, PE model was used to model the multipath acoustic channel impulse response to investigate the effect of sound speed gradient on shallow-water, broadband acoustic transmissions in the HFA97 experiment. To better examine the effect of a constant sound speed gradient, other variables were fixed in these simulations. The water depth was fixed at 15 m, and the source depth was 3.13 m from the bottom, same as the HFA97 experiment. The surface and the bottom boundary were both set flat. The sound speed on the surface was 1450 m/s and increased linearly with depth to the bottom. The gradient tested here ranged from 0 to 0.1 s$^{-1}$ with an increase of 0.05 s$^{-1}$.

Figure 2.8 compares of the acoustic channel impulse response for the whole water column with two different sound speed profiles: a homogeneous water column and a constant sound speed gradient ($\frac{dc}{dz} = 0.1$ s$^{-1}$). The arrival time was normalized to the arrival of the direct path. In Fig. 2.8, each horizontal cut is an acoustic channel
impulse response for that given depth. For a homogeneous water column, the direct path intensity is consistently strong over the whole water column [Fig. 2.8 (a)]; For a positive sound speed gradient, the direct path intensity will fade significantly compared to a homogeneous case [Fig. 2.8 (b)], and as the receiver depth increases, the received direct-path intensity decreases.

Compared Fig. 2.8 (a) to (b), significant differences can be observed between the two scenarios. First, the intensity for a given depth is much lower when the gradient is large. Second, the arrival time difference between the direct path and surface path is smaller in the homogeneous case. Note that the difference stems from the change of travel distance and sound speed between two cases. Third, there is a sign that the sound speed gradient of a water column can affect the acoustic intensity of the direct

**Figure 2.8:** PE modeling of two different sound speed gradient.
Figure 2.9: BELLHOP ray tracing for (a) the normal case and (b) the fading case.

path and the first surface bounce. For deeper depths ($z > 8$ m), the direct path fading is significant, and the energy surface path energy seems to slightly increase; For the shallower depths ($z < 8$ m), both direct path and the surface path attenuate. For later arrivals, the sound speed gradient does not affect much, and the later surface paths look almost identical in two figures.

Figure 2.9 illustrates the ray trajectories of underwater sound propagation using Bellhop model for the same two cases in Fig. 2.8. When the sound speed profile is uniform [Fig. 2.9 (a)], the ray paths are nearly straight, and there is a direct path straightly connecting from source to receiver. However, when a strong positive sound speed gradient is present [Fig. 2.9 (b)], the acoustic ray paths are bent with a noticeable curvature. One can expect that, as the sound speed gradient increases, there will be a
Figure 2.10: Path energy (in terms of transmission loss) as a function of sound speed gradient. The direct path is denoted as $D$, and the surface groups are denoted as $S_n$, where $n$ specifies the times of surface bounces.

shadow zone near the sea floor where no acoustic direct paths can be measured.

Figure 2.10 shows the transmission loss associated with the direct path ($D$) and later surface groups ($S_1$–$S_3$) for the top hydrophone location ($H_3 = 2.18$ m). Some interesting facts can be observed: The received intensity of the direct path decrease almost linearly (exponentially) with the sound speed gradient, about 7.4 dB for every 0.1 m/s change of sound speed in a depth of 1 m. Between $\frac{dc}{dz} = 0$ s$^{-1}$ and $\frac{dc}{dz} = 1$ s$^{-1}$, the difference in the direct path transmission loss is about 74 dB. Based on Fig. 2.10, sound speed gradient needed for the 20 dB fading is about 0.25 s$^{-1}$, which agrees with the analysis of our critical ray theory (Fig. 2.7). Overall, the intensity of surface paths does not change much with sound speed gradient. The relative sound intensity levels
for $S_1$, $S_2$ and $S_3$ are 1.5 dB, -2 dB and -7 dB, respectively. However, the receiving intensity of first surface bounce ($S_1$) clearly increases when the gradient is greater than 0.75 s$^{-1}$. It increases 9 dB from 0.75 s$^{-1}$ to 1 s$^{-1}$. This is the redistribution of acoustic energy and also associated with our source-receiver configuration. For $S_2$ and $S_3$, the increase was not obvious.

Therefore, the relationship between the direct path transmission loss and the sound speed gradient is:

$$TL = 20 \log(A) = -7.4g_c,$$  \hspace{1cm} (2.11)

where, $g_c$ is the sound speed gradient, $A$ is the relative received acoustic pressure amplitude.

2.5.3 Modeling the direct path fading in the HFA97 experiment

Accurate environmental measurements for the HFA97 experiment are needed for fully modeling the underwater acoustic fields. Unfortunately, water column measurements were only available between 2-12 m, but the depth of sound speed profile that mattered this problem most was the lowest three meters. The sound speed profile was assumed linear for the depth below 12 m, and based on the relationship between sound speed gradient and direct path energy. With the understanding of the problem, the HFA97 experiment can be redone with measured environmental measurements and extrapolated sound speed profile. The exact sound speed gradient needed for each geotime was calculated from observed direct path intensity of HFA97 field data [Fig. 2.1 (b)] based on above relationship (Eq. 2.11). For example, according to Fig. 2.10, a sound speed gradient of 0.2 s$^{-1}$ was needed for 20 dB of direct path fading to occur. Note that this was a verification for the energy fading of the direct path. The arrival time was out of concern here, so was the intensity of surface paths. Generate full sound speed profile and run the PE model using the HFA97 source and receiver positions. The water depth was decided by the tide. The surface boundary conditions were from the JONSWAP model and the surface generation model. The geotime resolution for modeling was every 20 minutes.
Figure 2.11: Modeling acoustic channel responses for all three hydrophones at different depths at $T_1$ and $T_2$. (a) Top hydrophone; (b) Middle hydrophone; and (c) Bottom Hydrophone. The amplitude of the channel response is relative to the acoustic source pressure amplitude at 1 m.

Figure 2.11 shows the modeling results for acoustic channel impulse response at two selected geotimes ($T_1$, $T_2$) at three hydrophone depths ($H_1$, $H_2$ and $H_3$) in the HFA97 experiment as a comparison to Fig. 2.3. Note that the amplitude of channel impulse responses was normalized to the source level using the local top hydrophone, and the arrival time was relative to the arrival of the direct path. Despite the amplitude difference, modeling results (Fig. 2.11) exhibited similar features seen in the field data (Fig. 2.3), including normal/fading difference and depth dependency, etc. The PE model was able to capture the three facts that we observed in the field data, including the direct path amplitude difference between two geotime cases, the direct path amplitude decreasing over depth within the same case, and similar surface path amplitude level. However, our model estimates less significant fading the direct path,
**Figure 2.12**: PE modeling the acoustic direct-path fading in the Delaware Bay estuary during the HFA97 experiment (September 23-25 of 1997). The arrival time of the acoustic response is relative to the direct path. Red lines indicates events when the fading occur. Two selected geotimes, $T_1 = 1997/9/23, 16:38$ GMT and $T_2 = 1997/9/23, 22:50$ GMT, are also denoted.

which may be a result of a mismatch of sound speed profile and bottom properties settings. After all, the overall agreement between the modeling results and the field data confirmed that the sound speed profile by the end of ebb tide can result in less direct path acoustic energy than that by the end of the flood tide.

Figure 2.12 illustrates the acoustic channel impulse response from PE modeling outputs for the HFA97 experiment from 23 to 25 of September 1997, indicating a periodical-like pattern of direct path fading similar to Fig. 2.1. Despite the different surface path feature due to flat surface assumption and the sound speed profile tweaking (discussed in Sec. 2.6), the PE model successfully captured the remarkable intensity attenuation of the direct path around $1997/9/23, 10:50$ GMT, $22:50$ GMT,
and 1997/9/24, 11:00 GMT, confirming that the unique water column feature during the end of ebb tide, particularly the positive sound speed gradient, was responsible for the direct path fading phenomenon. The tidal pattern in the surface paths (Fig. 2.12) also revealed the link with the end of the ebb tide. Our PE model was able to capture the direct path fading with the sound speed gradient and confirmed the variation of sound speed can cause the fading of the acoustic direct path in the HFA97 experiment configuration. More data-model comparisons will be discussed in Sec. 2.6.

2.6 Discussions

During the HFA97 experiment, the acoustic direct path exhibited a strong tendency to attenuate significantly during the end of low tide periods in the Delaware Bay estuary (Fig. 2.1). Data analysis found significant water column differences between the normal case and the fading case, especially that the direct path fading is associated with a stratified water column formed during the ebbing period (Fig. 2.2). This lead to a hypothesis that the periodical variation of salinity profile in the Delaware Bay due to tidal-forcing water dynamics (Fig. 2.5) formed a positive sound speed gradient that can redirect the sound energy away from our deep receivers (Figs. 2.6 and 2.7). Then, the acoustic model was used to analyze the problem and confirm the positive sound speed profile is able to cause the significant direct path fading feature through reconstructing underwater acoustic pressure fields similar to the HFA97 field data using up-refracting sound speed profiles. The direct path fading is an interesting case of acoustic propagation in the complicated, nature time-varying ocean environment. In this section, physical oceanography and acoustic perspectives of the direct path fading were further discussed.

2.6.1 Physical oceanography

Though the direct-path fading was more likely to occur during the later portion of the ebb tide due to the significant water stratification forming positive sound speed gradient at that period, the HFA97 data records (e.g., around the end of September 24,
1997 in Fig. 2.1) also suggested that this fading may not occur in every tidal cycle. The truth is, the stratification of the water column is a very complicated process influenced by local water dynamics and many other physical processes [11]. Though the main factor for the stratification and mixing in estuaries like the Delaware Bay is the tidal forcing, other factors could also contribute to the mixing of the water column.

First, the semi-diurnal tidal straining is the major driving factor responsible for the direct path fading phenomenon periodically observed during the HFA97 experiment. Tidal processes in the Delaware Bay influence sound speed profile on a daily basis through modification of water column properties such as salinity and temperature. The water column modification by the shear flow circulation is the case for many tidal-straining estuaries [36]. Previous study suggests the salinity variation is the most prominent factor among all water column properties in a tidal estuary that causes the water stratification [36]. The strong correlation between sound speed and the salinity from the HFA97 field data agrees that the salinity difference is the dominant factor that leads to this problem in the Delaware estuary. Besides, other parameters such as temperature or pressure contributes to the variation of sound speed profile in the Delaware Bay in a minor degree during the September 1997. The sound-speed correlation coefficients for temperature and for pressure during the HFA97 experiment were 0.5 and 0.3, respectively, suggesting they are minor factors in sound speed profile fluctuations compared to salinity variations; However, there is a possibility that seasonal variability for temperature may be significant enough to overcome the salinity difference. For instance, if the experiment was carried out in summer, we might expect different direct path fading pattern as the temperature difference for the ocean and the river varies. After all, the salinity variation during the tidal forcing is the most important factor in a tidal straining estuary.

Second, the stratification of the water column is also related to environmental processes such as storm tide, local wind history, river discharge and precipitation, etc. Wind blowing over the sea surface can increase water mixing, especially for a high wind with a long period [11]. In terms of this problem, it implies that after a long
period of strong, consistent winds, we may not expect the direct path fading to occur, because the water column will be increasingly well-mixed. During the low tide period (00:00 GMT) on September 26, 1997, the measured direct path had high amplitudes throughout the whole low tide period, because the water column was nearly well-mixed due to a continuous 12-hr high winds (greater than 9 m/s). Moreover, precipitation and river discharge might increase the water stratification [11], and they can result in the direct path fading during non low-tide periods, since they are not related to tidal forcing. For example, there was a precipitation event occurred around 00:00 GMT 1997/9/24, which strengthened the upper freshwater layer. This might be the main reason for the low intensity seen in Fig. 2.1 at that period. Noted that the river discharge and precipitation also have strong seasonal variability. In some cases, they may overcome the tidal forcing effect and become a dominant factor for the direct path fluctuation. Also, one may expect a longer direct path fading period and a more significant direct path fading, if the current strength increases which can achieve the positive sound speed gradient earlier and stronger.

2.6.2 Acoustics

It was once thought that the direct path fading was a result of the bottom path and the direct path coming in opposite phases and canceling each other, but this explanation was soon found not hold for many reasons. First, the acoustic frequencies used in the HFA97 were broadband, and therefore it was almost impossible for the whole frequency band with a total of 18 kHz bandwidth to cancel out at the same time. Second, the direct path fading occurred in more than one depths of the water column, with the direct path fading being more significant at the increased depth. This observation can not be explained by the phase constructing/destructing theory. Third, the bottom of the Bay was not perfectly flat where the specular reflection occurs, so the perfect cancellation of coherent phase was almost impossible to occur in the HFA97 field experiment. Though the phase destruction was not the major cause of the direct path problem, this problem was indeed frequency dependent. Due to the sound
propagation nature, sound waves with high frequency are more likely to bend than the ones with low frequency. Therefore, one might expect the direct path fading to occur with high frequency acoustic signals.

If the phase destruction was not the cause of this direct path fading, the other factor that can cause significant acoustic energy fading was the variation of sound speed profile. The remarkably different water column features, e.g., homogeneous water column in the normal case verse the positive sound speed gradient in the fading case from the HFA97 measurements (Fig. 2.2), was a strong evidence, which was further supported by theory—the physical oceanography in a tidal straining estuary (Fig. 2.5). Theoretically, the direct path fading can be explained by up-refracted sound speed profile using acoustic propagation theory (Sec. 2.4), but fully verification of the relationship between the received direct-path energy with measured sound speed gradient from the HFA97 field data was impossible. One drawback of the HFA97 field data for this study was the missing in-situ water column data for the surface layer and for the bottom layer due to the insufficient measurement and data truncation, especially the lowest 3 meters as a result of the HFA97 source-receiver configuration. However, acoustic modeling (Sec. 2.5) successfully confirmed this relationship with a range of sound speed gradients using the HFA97 source and receiver positions (Fig. 2.10), and obtained similar direct path fading pattern (Fig. 2.12), which provided an alternative verification for this problem.

Overall, the direct path intensity from the acoustic modeling results (Fig. 2.12) agreed with the field data (Fig. 2.1). However, minor differences can still be seen due to some other factors. First of all, the arrival time difference between direct path and the surface paths, i.e., the time gap, between the field data and acoustic modeling were slightly different. This mismatch stemmed from the missing of sound speed profile for the surface part and the bottom part, and the sound speed profile we assumed did not perfectly match the real case. Second, the surface intensity features were very different from field data. Surface intensity is found mostly associated with the surface wind speed [25]. The modeling of surface energy itself is a complex acoustic problem which involves
reflection, scattering, bubble effect, out-of-plane acoustic energy, etc. When modeling Fig. 2.12, we focused on the direct path intensity so we simply assumed the flat surface, but the more close modeling can be achieved in the future. Third, we assumed range-independence in this study, but it was not the case in most estuarine environments. In fact, the salinity and temperature distribution in an estuary is definitely range-dependent, which will change of the curvature of the acoustic ray circle. However, the modeling analysis we did in this paper did not account for the horizontal variation of sound speed profile due to the limits of water column measurement, which may result in the minor difference of direct path fading between the field data and the modeling results. Finally, other assumptions from the PE model, e.g., 2-D plane, no bubble effect, etc., all contributed to the data-model difference in some degrees. However, the overall data-model agreement supported the variation of sound speed profile was the major cause of the direct path fading.

Last but not least, this fading of sound direct path can pose serious problems for acoustic systems that utilize the detection of acoustic direct path to apply in tidal estuaries like the Delaware Bay. Note that the detection of the direct path in the fading case (Fig. 2.2) was based on the tracking of direct path with previous and subsequent sampling chirps, and as well as the calculation of the theoretical acoustic arrival time. If there was only one single event, e.g., in real-time acoustic communication scenario, it would be impossible to for the system to identify the direct path which may end up with poor system performance due to so much weaker energy in direct path than in surface paths. Though surface path energy components are strong, they are fast fluctuated and highly time-varying (i.e., very unstable). In previous study, the temporal variability of the surface paths have been found harmful for underwater coherent acoustic communication [26]. The fading of direct path together with fast fluctuating surface paths may be the reason for acoustic communication system failures as previously reported due to the effects of tide [29]. If acoustic communication was performed in such underwater acoustic channel, i.e., fading direct path and fluctuating, the acoustic system can only relay on the fast changing surface path. Such a process
requires a series sophisticated phase tracking and channel equalization, which is a super challenging topic for underwater acoustic communications. Though the HFA97 did not transmit acoustic communication data during the experiment, we believed that the effect of direct path fading on acoustic communication is significant and should be further explore in the future.

2.7 Conclusions

This study explored the periodical-like intensity fading of the acoustic direct path observed in the HFA97 experiment with a focus on the physical water dynamics in a tidal-straining estuary as well as the acoustic propagation theory. This is a common acoustic problem for many estuaries influenced by tidal forcing dynamics. Data and model analyses confirmed that the periodical variation of sound speed profile due to tidal forcing water dynamics in the Delaware Bay and the source and receiver positions of the HFA97 experiment together are responsible for this phenomenon. Generally, the fading of direct path increases with the increased gradient or decreased receiver depth. Our direct path theory with source-receiver positions configuration can help to plan future experiment or design acoustic applications in shallow tidal-straining estuaries or similar water environments.

The direct path fading problem analyzed in this paper suggested that the acoustic propagation links closely with the physical environment and the processes and dynamics within it. Therefore, the acoustic propagation cannot be separated from the physical environment and so does the acoustic applications that utilize the acoustic propagation knowledge. Also, the fading of direct path found in this paper can is important for underwater acoustic communication in these regions and the environmental variability should be considered when designing next-generation reliable underwater acoustic systems. The effect of the direct path fading on acoustic communication and other sonar systems will be further explored in the future.

The numerical models are useful tools for an actual time-vary acoustic problem, which can help verify a theory and re-examine field data. This paper only used a
2-D PE model with range-independence. In the future, the range-dependent sound speed profile should be taken into account in future acoustic models, as well as other inhomogeneity (ocean currents, bubbles), for a better capture of acoustic intensity. A joint-oceanography modeling needs for more complicated ocean acoustic problem.
Applications like underwater acoustic communication and acoustical oceanography depend critically on understanding broadband acoustic transmission in very shallow water regions such as estuaries. Since the underwater channels in these regions can be drastically affected by wind-wave dynamics, this study investigates how the wind-driven surface roughness in shallow-water environments affects variability of the mid-to high-frequency broadband (0.1–20 kHz) acoustic channel. One week of concurrent oceanographic and acoustic data were collected inside the Delaware Bay estuary where the water depth is 15 m. Combined modeling of surface hydrodynamics and acoustic propagation was performed using a shallow-water wind-wave spectral method and a 2-D rough-surface parabolic equation model. Modeling simulations agreed with field data analyses, and together they revealed strong correlations between wind speed and pressure amplitude of acoustic surface bounces, indicating that increased wind-driven surface roughness is primarily responsible for the exponential decrease of surface-bounced acoustic energy. These findings lead to a new empirical transmission loss formula for predicting wind-related surface acoustic energy. Our combined model worked for time-varying surface conditions, but more accurate acoustic modeling will need to consider 3-D and bubble effects.

3.1 Introduction

Shallow-water acoustic channels vary in temporal and spatial domains as a function of changing physical environment. Part of this variability stems from disturbance
by surface winds [10]. Generally, wind raises roughness of the air-water boundary, increases bubble entrainments and evokes other wave dynamics [41], causing deflection of underlying sound propagation and fluctuation of acoustic pressure at receiver ends [2]. In shallow waters, these wind effects can be highly complex due to the multipath effect from surface-bottom interactions that occur in depth-confined water columns [1]. Such environmental variability makes shallow water acoustic channels extremely challenging when designing reliable, adaptive underwater acoustic communication systems or other sonar systems [42]. Thus, improving the performance of these systems requires understanding of the effects of wind-wave dynamics on shallow acoustic channels.

Over the recent decades, many have studied the effects of surface winds and waves on underwater acoustics. Early research focused on acoustic backscattering from sea surface for monostatic SONAR systems [5, 43]. However, due to increasing demands for underwater acoustic communication, recent studies have shifted their attention to high-frequency broadband bistatic systems, exploring the influences of wind-driven dynamics that include varying signal coherence [17, 44], fluctuating arrival time [45], focusing and defocusing [46], spreading angle [14], and shifting frequency [47]. Moreover, several studies have investigated sound scattering from rough surfaces [44, 48, 14, 49]. However, a systematic examination of the wind-wave-acoustics relation has been rare [50, 51], and only Weston and Ching [51] have focused on the single-frequency sound propagation problem in a bistatic regime.

The complexity of this relation stems from two factors. First, differentiating the various environmental effects in field acoustic data is difficult because this recorded data has tangled within it many wind-related effects [10]. Second, there are presently no well-acknowledged acoustic channel models [39] and this study requires numerical models that can handle a joint atmosphere-ocean-acoustics system. Our previous studies explored the arrival fluctuation of surface-return paths with a JONSWAP wave spectrum and BELLHOP ray-tracing modeling [34], and they developed a 2-D rough surface parabolic equation (PE) model for time-evolving surface boundaries [39]. This paper uses that 2-D rough-surface PE model and a more advanced shallow-water wave
spectrum for surface realization [52] in order to model acoustic propagation in shallow water with a time-varying rough surface.

We investigate the effect of wind-driven surface dynamics on high-frequency broadband bistatic acoustic transmission in a shallow fetch-limited estuarine environment using data from a High-Frequency Acoustic (HFA97) experiment conducted in September 1997 in the Delaware Bay [10]. We focus on the amplitude fluctuation of acoustic surface-bounced paths. Data and model analyses both support that pressure amplitudes for surface groups decay exponentially when wind-driven surface roughness increases. We propose a simple exponential decay model to predict theoretical pressure amplitudes for higher wind speeds and higher surface groups.

The rest of the paper is organized as follows. Section II introduces the HFA97 field experiment and analyzes the field data. Section III presents the numerical models and their comparable simulation results. Section IV predicts acoustic channel responses for ideally increasing wind speeds using our combined model and an exponential decay relationship that we propose predicts the theoretical amplitude for any wind speed. Section V compares measured data to model results. Section VI discusses our findings, and Section VII concludes the paper.

3.2 Field Data Analysis

3.2.1 Description of the Experiment

The HFA97 was a broadband acoustic field experiment conducted in the Delaware Bay (central region: 39°1′N, 75°11′W; [Fig. 3.1(a)]) [10]. Two acoustic tripods were built to transmit 0.345 s, 0.1–20 kHz acoustic chirp signals with a range of 387 m. Each tripod had a transducer at 3.13 m and three hydrophones at 0.33 m, 1.33 m and 2.18 m from the base of the tripod. Acoustic chirps were transmitted and received with two sampling strategies: 40-s transmission every 90 minutes, and 5-s transmission every 10 minutes. The time for each sampling task was referred as a geotime.
Figure 3.1: (a) Map of the Delaware Bay and locations of the HFA97 experiment (square) and nearby lighthouse (circle). Inset enlarges experimental location and shows the direction of acoustic path (AC), which is 150° from the north (counter-clockwise). (b) Geometry of acoustic transect with source-receiver setup and typical acoustic surface groups for the HFA97 experiment. Note that the direct path and the single surface bounced are not shown. (c) Mean sound speed profile in the Delaware Bay during the HFA97 experiment.

3.2.1.1 Acoustic channel

The sound channel had a mean water depth of 15 m, and an approximately flat seafloor. The two acoustic tripods were positioned on the seafloor. The acoustic response in this shallow-water channel comprises a direct path plus a single bottom reflection (D/B), and a series of surface groups, each group including four individual surface-return paths [Fig. 3.1(b)]. In this source-receiver configuration where the source and receivers are close to the seafloor, received signals are separated in terms of surface groups. Except the first arrival (D/B) that is only associated with the water column, later arrivals are all surface-interacted acoustic paths that relate to both water column and upper boundary. Note that Fig. 3.1(b) illustrates only the surface groups, not every individual surface path, and ignores the direct path and the first bottom reflection since they do not interact with the surface boundary and have no surface effects.

Sampled data over the week indicated that environmental variability led to strong variability of the shallow-water acoustic channel. Here we only address wind- or wave-induced surface effects on sound propagation, and neglect effects on sound refracting index of relatively slower water profile variations. For simplicity, surface
groups are denoted as $S_n$, where $n$ is the number of surface interactions, e.g., $S_1$ is the first surface group that includes a surface path (S), a surface-bottom path (SB), a bottom-surface path (BS) and a bottom-surface-bottom path (BSB). Similarly, $S_2$, $S_3$, $S_4$ denote the second, the third and the fourth surface groups, respectively. Acoustic scattering also depends on the grazing angle [51], and for $S_1$ to $S_5$, the theoretical grazing angles, $\theta$, at sea surface in a homogeneous medium are 4.43°, 8.81°, 13.09°, 17.23° and 21.19°, respectively. Although, these angles varied slightly due to tidal variation of water depth and water properties, the fixed set up of this experiment was helpful.

3.2.1.2 Surface measurements

A weather station at a nearby lighthouse [39°2′54″N, 75°10′56″W, marked as a circle in Fig. 3.1(a)] measured the wind at 15m from ocean surface every 15 minutes during the HFA97 experiment. A directional wind histogram (Fig. 3.2) shows that winds blew at varying speeds and from various directions, causing strong wind-wave interactions and dynamic surface conditions. Wind speeds (that we denote $U_z$ with $z$ specifying the height in meters) ranged from 0 to 16 m/s with low-wind and high-wind periods that evoked different stages of surface wave development. The dominant wind directions were offshore, with high speed winds ($U_{15} > 10$ m/s) rarely coming from southern directions.

Surface waves were measured indirectly by processing acoustic chirps received by local hydrophones (referred to as “overhead acoustics”). Although the HFA97 experiment did not directly measure surface wave spectra, a previous study [34] showed that this overhead acoustics approach works in the Delaware Bay and can be used for surface wind-wave spectral modeling. Waves were also captured via video and photography of the ocean surface by a fixed camera in the nearby lighthouse. All surface photos were dated so sea state could be categorized at particular times.
Figure 3.2: (color online) Directional wind histogram for wind measurements taken by a nearby lighthouse, with each directional bin being exactly 15° and a total bin number of 24. The observation period was from 1997/9/23 08:37:11 UTC to 1997/9/29/1 01:14:47 UTC.

3.2.1.3 Oceanographic measurements

Oceanographic variables (tide, current, water temperature and salinity) were measured every 30 minutes and were well synchronized with acoustic transmission schedule. Tide was recorded by two pressure sensors near the acoustic tripods; and current profile was measured by 1200 kHz narrow-band bottom-mounted ADCP located in the middle of sound transmission transect. Salinity and temperature profiles were observed by CTD casts from the R/V Cape Henlopen that surveyed the experiment region and they were used to calculate the sound speed profiles [Fig. 3.1(c)]. These environmental observations serve as initial input for our numerical model, help understand the dynamics of the sound channel and help interpret our results.

3.2.2 Data Analysis

The multipath structure is the key to understanding shallow water acoustic channels. The acoustic data analyzed here comes from sound transmitted by tripod A
to the top hydrophone of tripod C [Fig. 3.1(b)]. With the sensitivities of transducer and hydrophones calibrated, we take the fluctuation of the acoustic response to reflect only environmental variability. Acoustic impulse channel responses obtained by matched filtering let us examine individual paths (or groups) rather than the total multipath effect.

### 3.2.2.1 Two wind cases

**Figure 3.3:** Ensemble channel impulse responses for two wind states ($T_1$ and $T_2$) from the HFA97 experiment, showing pressure amplitudes for the surface groups $S_1$ to $S_4$ (a) with plot expanded for $S_1$ and $S_2$ (b). Responses are averaged from 40-s acoustic data. Arrival time is relative to the direct path. The two geotimes represent low-wind $T_1 = 1997/09/25$, 05:04:04 UTC ($U_{15} = 3.8$ m/s), and high-wind $T_2 = 1997/09/24$, 06:04:04 UTC ($U_{15} = 13.8$ m/s).

Since surface boundaries evolve within seconds, acoustic channel responses, particularly surface groups, vary rapidly. We can identify the “overall” effects from the
ensemble average of a series of acoustic channel responses at a given wind state. We selected two wind cases for comparative analysis: low-wind $T_1 = 1997/09/25, 05:04:04$ UTC ($U_{15} = 3.8$ m/s), and high-wind $T_2 = 1997/09/24, 06:04:04$ UTC ($U_{15} = 13.8$ m/s).

The ensemble channel responses for $T_1$ and $T_2$ (Fig. 3.3) show three notable differences in pressure amplitudes. First, high and sharp peaks (in $S_1$, $S_2$, $S_3$, etc.) occur only in low wind not high wind. These peaks come from the part of the sound energy that associates with each individual surface path, and can be explained by specular reflection of sound waves from a flat/rough surface. When wind stress is absent or weak, the sea surface is relatively calm and motionless, so the specular point at the surface boundary is essentially fixed in position, rarely varying from ping to ping. Thus, acoustic energy is perfectly reflected and restricted inside its original paths. However, when wind speed increases, these peaks become blunt and cannot be distinguished from each other because (a) wind-induced surface wave motion causes travelling distance and time to fluctuate so peaks flatten during the averaging process; (b) wave curvature scatters sound waves into a variety of angles so sound energy leaks into other directions; and (c) bubbles entrained in the surface layer at high winds attenuate sound further.

Second, the total energy of a surface group (integral over arrival time $t$) is stronger at low winds than at high winds. This relates to surface roughness and signal coherence. When two waves are coherent, they are in phase and their total pressure is constructive and has a maximum amplitude. Then most of the acoustic energy is in coherent paths, i.e., any acoustic reflections other than coherent reflection contain much less energy due to smaller wave construction or deconstruction. This coherent specular reflection produces the high amplitude seen for the relatively calm surface in $T_1$. Furthermore, increasing bubbles may attenuate the total energy.

Third, the tails of surface groups (e.g., during $1.4$–$2$ ms or $4$–$4.5$ ms in Fig. 3.3) are slightly raised in a high wind. This interesting but unexpected observation “conflicts” with the theory of the Rayleigh parameter. We suggest that this extra tail
energy comes from sound that scatters off nearby points on the rough sea surface. Since these points are not specular reflection points, the paths are slightly longer, increasing the energy that arrives later and creates the tail of a surface group.

### 3.2.2.2 Surface roughness and Rayleigh parameter

![Figure 3.4:](image)

**Figure 3.4:** Calculated RMS surface roughness $\sigma_\xi$ across wind speeds from 40-s HFA97 overhead acoustic data. The solid line denotes LSE-based best linear fit.

From the above ensemble averaging analysis, we proposed that the drop of surface-group pressure with increasing wind speeds is due mainly to an increase in surface roughness. We tested this by exploring the surface conditions as a function of wind speed. First, we used arrival time fluctuations of overhead acoustic signals to calculate surface displacement $\xi$ as:

$$
\xi(t) = \frac{1}{2n} \tau \cdot \Delta \tau_n(t) \sin \theta_n,
$$

(3.1)
where \( n \) is number of surface bounces, \( \Delta \tau_n \) is \( n \)-th arrival time difference to its mean, \( \bar{c} \) is average sound speed, and \( \theta_n \) is grazing angle at the surface for \( n \)-th surface bounces. Figure 3.4 plots the root-mean-square (RMS) surface displacement across wind speeds for all 40-s acoustic data, with each point estimating surface roughness at a given geotime. As expected, surface roughness increased with higher wind speeds. The best-fit linear trend was based on least-square-error (LSE) methods.

Second, we computed the Rayleigh parameter, a measure for characterizing reflection (or scattering) of acoustic returns from a rough surface \([1]\), given by:

\[
P = 2k\sigma_\xi \sin \theta \tag{3.2}
\]

where \( k \) is acoustic wavenumber, \( \sigma_\xi \) is RMS surface roughness, and \( \theta \) is acoustic grazing angle. Sound is specular reflected at sea surface when \( P \ll 1 \), and is almost completely scattered when \( P \gg 1 \). We took the RMS surface roughness \( \sigma_\xi \) from the best-fit line in Fig. 3.4 and plotted the Rayleigh parameter as a function of wind speed for the upper, center and lower frequencies used in the HFA97 experiment (Fig. 3.5). At a wind speed of 10 m/s, frequencies of 100 Hz to 20 kHz give Rayleigh parameters ranging from 0.01 to above 2.0; at 10 kHz, \( P = 1 \). Thus, low frequencies are mostly reflected (\( P \ll 1 \)), high frequencies (\( > 20 \) kHz) are more scattered than reflected as wind speeds rise above 3.5 m/s, and most frequencies are scattered for wind speeds over 5 m/s.

### 3.2.2.3 Wind speed correlation

The above results show that rising wind speeds increase the surface roughness and Rayleigh parameter. To determine the relation between wind speed and surface-group pressure, we analyzed the peak amplitude of each surface group. We chose this instead of the total energy integral over time, because strong variability of surface paths makes it hard to extract the duration of the time integral.

Figure 3.6 graphs the peaks of the first \((S_1)\) and fourth \((S_4)\) surface groups as a function of wind speed, with curves based on exponential LSE best fit (explained in Sec. 3.4). For both groups, the pressure amplitude decreases with rising wind speed.
Figure 3.5: Rayleigh parameters across wind speeds for the upper, center and lower frequency ranges used in HFA97 experiment.

For wind speeds increasing from 1 to 15 m/s, this drop in amplitude is approximately 4-fold (12 dB) for $S_1$ and up to 16-fold (24 dB) for $S_4$. The correlation coefficient $r$ (Table 3.1) between these two variables is also significant, -0.70 and -0.71 for $S_1$ and $S_4$, respectively, and remains high even up to $S_5$ ($r = -0.56$). No clear correlation was found with wind direction ($r = -0.1$).

The correlations between wind and pressure amplitude for all surface groups in the HFA97 data show very similar patterns. Notably, higher surface groups display steeper wind-pressure relationships, presumably due to multiple surface interactions and steeper grazing angles for high-order surface groups (discussed in Sec. 3.6). Therefore, we chose to model this relationship as an exponential decay rather than a linear trend.
Figure 3.6: Peak pressure amplitude for surface groups $S_1$ (top) and $S_4$ (bottom) as a function of wind speed from all HFA97 data. Amplitude is normalized to $p_0$, the source pressure measured at 1 m. The best fit curve for $S_1$ is $0.0029e^{-0.057W}$, and for $S_4$ is $0.0008e^{-0.0527W}$.

Table 3.1: Correlation Coefficients between Surface Wind Speed and Surface-Group Pressure Amplitude

<table>
<thead>
<tr>
<th></th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{DATA}$</td>
<td>-0.70</td>
<td>-0.73</td>
<td>-0.65</td>
<td>-0.68</td>
<td>-0.56</td>
</tr>
<tr>
<td>$r_{MODEL}$</td>
<td>-0.40</td>
<td>-0.65</td>
<td>-0.70</td>
<td>-0.71</td>
<td>-0.60</td>
</tr>
</tbody>
</table>

3.3 Modeling

3.3.1 Modeling Methods

In this section, we combined wind, wave and acoustic models to simulate acoustic propagation under a time-varying wind-wave surface. Modeling this problem requires two necessary steps: (a) realizing shallow-water surface waves from winds, and (b) reconstructing underwater acoustic pressure fields from a rough surface boundary.
Figure 3.7: Surface wave spectra modeled using JONSWAP/TMA spectra with a fixed fetch \((F = 30 \text{ km})\) and a shallow water depth \((h = 8 \text{ m})\) for different wind speeds \((U_{10} = 5, 10, 15 \text{ m/s})\).

3.3.1.1 Shallow-water waves

Modeling surface waves realistically for the HFA97 experiment requires a wave model that works for a fetch-limited shallow-water region. We previously used a JONSWAP spectral model in the Delaware Bay [34], but that neglected wave energy dissipation due to bottom friction in shallow water. Thus here we adopted a more reasonable spectral model, the TMA model for shallow waters.

The TMA spectrum \(S_T\) takes the form [52]:

\[
S_T(\omega) = S_J(\omega) \cdot \phi(\omega, h)
\]  

(3.3)

where \(S_J\) is the JONSWAP spectrum calculated from wind speed \(U_{10}\) and wind fetch
\[ F[34]; \text{and } \phi \text{ is a depth-dependent factor:} \]

\[
\phi(\omega, h) = \frac{k^{-3}(\omega, h) \frac{\partial k(\omega, h)}{\partial \omega}}{k^{-3}(\omega, \infty) \frac{\partial k(\omega, \infty)}{\partial \omega}} \tag{3.4}
\]

where \( \omega \) is angular frequency of surface waves and \( h \) is water depth.

Figure 3.7 compares simulated wave spectra from TMA and JONSWAP for three wind speeds \((U_{10} = 5, 10, 15 \text{ m/s})\). With both models, as wind speed rises, the spectral peak moves to lower frequencies and increases in amplitude. For instance, 5 m/s wind-generated waves peak at 0.35 Hz, while 15 m/s ones peak at 0.25 Hz with about 10-fold more energy. These models only differ markedly when the shallow-water condition is \( D > \frac{1}{2} L \), which is more likely to occur at high winds because the wavelengths driven by high winds are much longer. For the 15 m/s wind speed, this energy difference is about 0.3 m²/Hz. We suggest that TMA models offer a more realistic approach for the HFA97 experiment because 15 m is shallow for surface waves with frequencies below 0.2 Hz [52].

From these wave spectra, we reconstruct realistic 2-D rough surfaces using a time-evolving surface generation algorithm [53, 39]. This surface model uses Fourier transforms to convert a given wave spectrum from the frequency domain to a 2-D spatial domain. The initial sea surface is determined by a random initial phase vector to retain stochastic features. The resulting surface elevation is generated with a time stepping technique that uses the Rung-Kutta integration algorithm [53]. More details on time-evolving surface realization can be found in [53, 39, 34]. Modeling results show that higher wind speeds produce longer, faster and bigger surface gravity waves. The surface boundary is elevated up to 0.6 m for a 5 m/s wind, and 1 m for a 15 m/s one.

### 3.3.1.2 Acoustic modeling

For the acoustic propagation model, we used a 2-D rough-surface PE model, first developed by Smith [54] and further improved by Senne [39], for time-varying rough surfaces. This PE can model broadband acoustic forward propagation with a given rough surface boundary, and can estimate the total acoustic pressure field, both
coherent and incoherent. The surface inputs for this PE include surface elevation ($\xi$), and its second ($\xi'$) and third derivatives ($\xi''$). Other inputs include water depth, source-receiver configurations, and sound speed profiles. For a broadband signal, this PE divides the whole bandwidth into some small frequency bins, so that each bin can be treated as a single frequency. Summing all these bins gives the total acoustic pressure field.

Here we simulated acoustic channel responses based on source-receiver setup and surface wind speeds. For each geotime (one surface spectrum), we generated a series of 2-D surface inputs that step in time, and performed them with the PE model. Note that this PE model does not account for the bubble effects and out-of-plane energy, but will enable a systematic examination of how wind-induced roughness affects acoustic propagation and may provide perspective on how bubbles affect sound propagation.

### 3.3.2 Modeling Analysis

We conducted a number of numerical simulations, and analyzed the modeling outputs in a way that allowed comparison with our field data analysis (Sec. 3.2). To our knowledge, this is the first attempt to use a 2-D PE model to simulate a large number of time-evolving rough surfaces (spanning one-week of geotimes) in order to solve an actual time-varying problem. Due to this model’s computational complexity, most numerical simulations were computed with parallel processing techniques on a high-performance computer cluster.

#### 3.3.2.1 Two wind cases

Using our numerical models, we computed ensemble-averaged acoustic channel responses for two wind cases. Although the field data analysis used 40-s ensemble averages, due to the heavy computational load, we only simulated acoustic transmissions for 10 s. This approach is reasonable as long as the timescales of surface waves are less than 10 s, as they were in our case (Fig. 3.7). Although our model overestimates the peaks for high winds (discussed in Sec. 3.5), the modeling results (Fig. 3.8) closely
Figure 3.8: Numerical modeling of ensemble-average channel impulse responses for the two wind states selected in the HFA97 experiment shows pressure amplitudes for surface groups $S_1$ to $S_4$ (a) with plot expanded for $S_1$ and $S_2$ (b). Arrival time is relative to the direct path. Amplitude is relative to the source ($p_0 = 1$ Pa).

agree with observed acoustic data (Fig. 3.3), even capturing all three features noted in field data analysis (Sec. 3.2): sharp peaks in $T_1$, lower energy in $T_2$, and increased tail amplitude in $T_2$. This overall agreement indicates that our combined model works properly and can capture effects from time-evolving surfaces.

3.3.2.2 Roughness and Rayleigh parameter

For each TMA spectrum, we simulated the 2-D surface conditions and computed the RMS surface roughness (Fig. 3.9). This roughness shows a strong linear relationship, almost proportional, with wind speed. Comparing Fig. 3.9 with Fig. 3.4, we notice two differences. First, our model predicted zero surface roughness as wind
Figure 3.9: Calculated RMS surface elevation $\sigma_\xi$ across wind speeds from TMA spectral model for the HFA97 experiment. Solid line denotes LSE-based best linear fit.

speed reaches zero, which disagrees with the field data. Our model estimation is theoretically correct, but in nature tiny surface elevations exist even without wind (Fig. 3.4). Second, the deviations around the best-fit line are larger in field results than in modeling, especially at high winds. This probably results from field data including different states of surface wave development (particularly for different wind duration), while our model assumes a fully-developed sea state.

We calculated the Rayleigh parameters for the frequency band used in the HFA97 experiment (Fig. 3.9). Our model estimates slightly higher Rayleigh parameters than field data (Fig. 3.4), most likely because it overestimates surface roughness $\sigma_\xi$ not grazing angle $\theta$. The difference between field data and model results is small for low winds, but becomes larger for high winds and high frequencies, suggesting that our model has more scattering under these conditions.
Figure 3.10: Rayleigh parameters across wind speeds for the upper, center and lower frequency ranges used in HFA97. The RMS surface roughness $\sigma_\xi$ comes from simulated TMA spectra.

3.3.2.3 Wind correlation

We modeled the acoustic fields over the entire one-week HFA97 experiment for all 5-s and 40-s data. The model’s input variables included wind speed, wind fetch (i.e., maximum distance to shore of Delaware Bay in that wind direction), water depth, and sound speed profile. Due to time and computational cost, we computed only one instant acoustic channel response instead of averaging from a continuous progressing surface. Although this may cause disagreement with our field data, it will essentially preserve the effects of rough sea surfaces. Our model and field results for $S_1$ and $S_4$ are similar (Fig. 3.11 vs. Fig. 3.6). In addition, for all surface groups, wind speed and surface group amplitude are significantly correlated (Table 3.1). More details will be compared in Sec. 3.5.
Figure 3.11: Simulated peak pressure amplitude for surface groups $S_1$ (top) and $S_4$ (bottom) as a function of wind speed for HFA97 data. Amplitude is relative to the source ($p_0 = 1 \text{ Pa}$). The best fit curve for $S_1$ is $0.0024e^{-0.085W}$, and for $S_4$ is $0.0006e^{-0.1432W}$.

### 3.4 Model Prediction

The overall agreement between our model and the field data supports the idea that the wind’s primary effect on the sea surface is due to wind-induced roughness of the surface boundary. In this section, the exponential relationship found in previous sections is applied to predict the pressure amplitude of a surface group.

We simulated acoustic channel responses for pure wind-induced surface variations, without directional dependency, bubble effects and sound speed variations. We took wind speed as the only changing variable, ascending from 0 to 15 m/s with a step of 1 m/s, and kept the other variables fixed with wind direction from true north, wind fetch of 25 km, water depth of 15 m, and homogeneous sound speed profile. For each wind speed, we generated 50 surface conditions, each with a random phase initialization. We then averaged these 50 modeling outputs to obtain the final results for each speed.

The averaged acoustic channel responses for wind speeds from 0 to 15 m/s
Figure 3.12: Simulated acoustic channel responses show pressure amplitudes over arrival time for wind speeds from 0 to 15 m/s. Pressure amplitude is normalized to the direct path.

show that as speed gradually increases, the pressure amplitude of each surface-bounced group decreases (Fig. 3.12). For each group, as speed increases, the interactions between different paths within that surface group become stronger. Notably, higher order surface groups fade away faster than lower groups.
To determine the pressure amplitudes of these groups, we assumed an exponential decay relationship between wind speed and peak amplitude of surface groups (see Figs. 3.6 and 3.11) that takes the form:

\[ p = p_0 \cdot A_n e^{-\alpha_n W}, \]  

(3.5)

where \( p_0 \) is acoustic source pressure, \( n \) is number of surface bounces, \( W \) is wind speed, \( A \) is amplitude constant, and \( \alpha \) is decay constant.

Equation 3.5 has two unknown coefficients. One, amplitude constant \( A \), is responsible for the transmission loss of the sound path reflected from a flat sea surface without the wind effect, and depends only on acoustic geometric spreading and attenuation within a water column. For spherical spreading in uniform sound speed waters, \( A = \frac{1}{r} e^{ikr} \). Two, the decay constant \( \alpha \), decides the decay rate of a surface-group’s pressure due to wind stress, and is a function of surface roughness \( \sigma \), grazing angle \( \theta \), and acoustic frequency \( f \). The last term of Eq. 3.5, \( e^{-\alpha_n W} \), determines the acoustic pressure peak in response to surface winds. In terms of a SONAR parameter, this term becomes wind-induced energy loss (WL) at the sea surface for a surface path:

\[ WL = \gamma_n W \]  

(3.6)

where \( \gamma_n \) is the \( n \)-th logarithmic decay parameter. Here, \( \gamma_n = -20 \log(e)\alpha_n \).

The two unknown coefficients, \( A_n \) and \( \alpha_n \), can be solved by fitting the best exponential curve from data or modeling results. The optimization process based on LSE is:

\[ \min_x \| F(a, x) - y \|_2^2 = \min_x \sum_i (F(a, x_i) - y_i)^2 \]  

(3.7)

where \( F \) is exponential decay function (Eq. 3.5), \( x \) is wind speed, \( y \) is pressure amplitude, \( a \) is coefficient vector for \( A \) and \( \alpha \). Notably, this is a practical approach and only works for smaller surface numbers \( n \). If \( n \) is too large, i.e., \( n = 5 \), the pattern decays too fast so solving for \( \alpha_5 \) and \( A_5 \) is inaccurate. Based on Eq. 3.7, Figure 3.13 plots the results of \( A_n \) and \( \alpha_n \) for \( S_1 \) to \( S_4 \).
Figure 3.13: Decay constant $\alpha$ and amplitude constant $A$ for different $n$’s for decay model (Eq. 3.5) with the HFA97 experimental setup. Solid dots indicate values based on LSE best fit, and open dots are linearly extrapolated from the solid dots.

Figure 3.14: Simulated transmission loss for upper boundary variation induced by surface wind speed calculated using the exponential decay model (Eq. 3.5) for the HFA97 experimental setup.
Substituting these solved coefficients into Eq. 3.5 gives the transmission loss for $S_1$ to $S_4$ for wind speeds from 0 to 15 m/s (solid lines in Fig. 3.14). These $\alpha_n$ and $A_n$ estimates also let us predict transmission loss for any wind speed (dashed lines in Fig. 3.14). Furthermore, these results allow us to make predictions for higher-order surface groups where coefficients $A_n$ and $\alpha_n$ are difficult to solve. Since $\alpha_n$ increases with $n$, while $A_n$ decreases (Fig. 3.13), we can linearly extrapolate to obtain for $S_5$ the coefficients $A_5 = 0.0006$ and $\alpha_5 = 0.1432$ (Fig. 3.13). With these values, we can solve the decay pattern for $S_5$ (Fig. 3.14).

Although this section only showcases one simple application of the wind-acoustics relationship, this approach can be very practical for acoustic channel prediction.

### 3.5 Data-Model Comparison

Our model assumes full development of surface gravity waves, no bubble formation, no out-of-plane scattering, uniform medium attenuation, no Doppler effect from surface waves, simple rigid bottom properties, and no biological effects. These assumptions must be kept in mind when comparing modeling and field data results.

Overall, our numerical results closely agree with our field data. Modeling ensemble averages for two geotimes (Fig. 3.8) reproduced three main features seen in the field data (Fig. 3.3). Modeling of surface roughness (Fig. 3.9) and Rayleigh parameter (Fig. 3.10) predicted the same trends as field data (Figs. 3.4 and 3.5). Most importantly, our modeling showed decay patterns similar to field data (Figs. 3.6 and 3.11). These agreements indicate that wind-induced surface roughness plays a key role in attenuating acoustic surface returns.

However, some disagreements were seen that might stem from minor factors other than surface roughness. First, at high wind speeds ($U_{10} > 7$ m/s), our model (Fig. 3.11) predicts higher pressures than field observations (Fig. 3.6). We assert that this is mainly because the PE model we used did not account for bubble effects [39]. Air bubbles attenuate acoustic energy [14] and are more likely to form in the surface water layer (via wave breaking) at high wind speeds [2]. Thus, at these speeds, they are...
more likely to lead to discrepancies between modeling and field data results. Moreover, bubble attenuation is more prominent for small grazing angles [55], and thus for small surface groups like $S_1$. Consequently, it may explain our model’s overestimation of $S_1$ in high-wind scenarios (Fig. 3.8).

Second, at low wind speeds, the model (Fig. 3.11) predicts lower pressure amplitudes than field data (Fig. 3.6). This disagreement could arise for many reasons: the field data could have more surface roughness at low winds (see Fig. 3.4); the ocean surface in nature could have pre-existing bubbles that rise from the water column or ocean bottom and overtake small surface scatterings at low winds [51, 55]; and the sea state [56] in field data could be less developed than the fully-developed state our model assumes.

Third, our model results (Fig. 3.11) fluctuate less at low winds but more at high winds than the field results (Fig. 3.6). This discrepancy stems from us performing insufficient simulations due to the computational complexity of the problem. Instead of modeling ensemble averages over time (as in Fig. 3.6), we only simulated one acoustic channel response for each individual rough surface. This causes focusing and defocusing of sound energy [46] and thus leads to the fluctuation at high winds (Fig. 3.11).

Fourth, our numerical models slightly underestimate the overall acoustic amplitude of the surface groups (Fig. 3.11 vs. Fig. 3.6). This difference could be due to a mismatch of medium attenuation in the model, or to a 2-D model that neglects out-of-plane acoustic energy, or more complicated water column properties and bottom properties. Fortunately, however, since the influences of these factors on sound propagation are independent of wind speed, they should not affect our conclusions on wind effect.

### 3.6 Discussions

In this paper, we confirmed, both with HFA97 field data and numerical modeling, that all surface-bounced sound energy decreases with increasing wind speeds
because of greater wind-generated surface roughness, results consistent with many previous field experiments [51, 55, 57, 58]. Since our modeling, which only incorporates surface roughness, agreed overall with field data, we conclude that among all wind effects, surface roughness is the major factor that decreases surface-return sound waves in the HFA97 experiment. Other factors that influence sound propagation are discussed below.

**Number of surface groups**

Both our field (Fig. 3.6) and modeling (Figs. 3.11 and 3.12) results indicate that higher surface groups (e.g., $S_4$, $S_5$) experience more surface effects, i.e., more attenuation than lower surface groups due to multiple, repeated interactions with surface fluctuation. Furthermore, for a given source level, the maximum number of surface groups $n$ decreases as wind speed increases, as shown in our model (Figs. 3.12 and 3.14), and reported in a previous study [51].

**Bubble effects**

Bubbles play a much smaller role in attenuating acoustic intensity than the scattering loss caused by surface roughness. However, our data-model comparison indicates that air bubbles have a stronger effect on lower surface groups (smaller $n$). In a fixed acoustic setup like HFA97, the grazing angle decreases as number of surface bounces $n$ increases, and small grazing angles cause more significant bubble attenuation [43]. Hence, we expect greater bubble attenuation in $S_1$ than in $S_4$. Indeed, we find that our model displays much more overestimation for $S_1$ than for $S_4$ (Fig. 3.3 vs. Fig. 3.11), most likely due to the PE model not including bubble effects.

**Sound frequency**

Wind effects on sound propagation are frequency-dependent [51]. Surface roughness (Figs. 3.5 and 3.10) and bubble attenuation [1] affect high frequencies more strongly than low frequencies, even at high wind speeds. Unfortunately, the HFA97
experiment transmitted broadband acoustic chirps so our results could not demonstrate frequency dependency. However, the Rayleigh parameter analysis suggests that using frequencies under 10 kHz would significantly reduce these wind-induced surface effects for a region like the Delaware Bay, where wind speeds remain mostly below 15 m/s (Fig. 3.2).

Wind direction

The HFA97 experiment demonstrated no clear relationship between wind direction and sound attenuation. However, other studies have shown that the direction of wind on the surface might play a role [58]. In our experiment, all wind directions produced a range of surface-group intensities, with the exception of directions between 120° to 200° that only evoked high intensities. In the Delaware Bay the wind in these directions was fairly low speed (Fig. 3.2), so our decay pattern predicts a high acoustic intensity. Directional dependency in a fetch-limited estuary is more likely to contribute combination effects of directional waves and of varying fetch length [59] due to bay geometry, both interesting problems that deserve further research.

Wind fetch and wind duration

Other wind properties can also affect underwater sound propagation by evoking different developments of the sea state. Generally, a longer fetch with enough duration has the potential to develop a rougher sea surface, and thus leads to smaller surface-returned acoustic energy [59]. Although these effects on surface roughness are much smaller than wind speed, they still account for some fluctuations in surface roughness (Figs. 3.4 and 3.9) and surface group pressures (Figs. 3.6 and 3.11), especially at high winds.

3.7 Conclusions

Our analysis leads to the following explanation for the effects of wind on acoustic wave propagation. Wind generates ocean surface gravity waves, causing rough boundary conditions of the sound channel (Figs. 3.4 and 3.9) and entrainment of air bubbles
during wave breaking, both of which can attenuate surface-returned sound. As wind speeds increase, the ocean surface is dominated by more complex waves, with lower peak frequencies, extended spectral range and intensified wave energy (Fig. 3.7). This wave motion gives rise to fluctuations in sound arrivals [34] as the acoustic wavefront captures the surface curvature [58]. Increased roughness results in incoherent scattering of the sound waves [1], i.e., higher Rayleigh parameters (Figs. 3.4 and 3.5). Meanwhile, breaking of surface waves leads to further acoustic energy attenuation as sound waves pass the surface layer waters. Thus, as wind speed increases, the surface-returned acoustic pressure decreases (Fig. 3.12).

Here we examined the sea surface roughness and broadband sound fluctuation in a shallow estuary as a function of wind speed, using both field data analysis and numerical modeling. Results from both conclude that wind affects shallow-water sound propagation as follows: (a) wind-induced surface roughness, among all wind effects, is primarily responsible for acoustic attenuation with an exponential decay relationship; (b) bubble attenuation is the second major factor, and its effects should be incorporated in future acoustic models, especially in high wind cases; and (c) wind direction, fetch and duration may jointly affect this problem and require further investigation.

Numerical modeling offers a useful tool for studying acoustic propagation problems in highly dynamic environments that have a variety of factors influencing sound propagation. Overall agreement between our model and field results establishes that our approach works for acoustic modeling under a time-evolving surface. With 2-D rough surface PE, we were able to examine in-plane acoustic fields which are the dominant part of energy components, but more accurate modeling will need to consider out-of-plane scatterings in a 3-D PE. Also, since this problem is inherently linked to physical ocean dynamics, full understanding will require a joint oceanography-acoustics model.

Future study will be extended to underwater acoustic communication whose performance decreases at high winds. Our realistic wind-impacted acoustic channel model and the better understanding of channel variability will help design a more
reliable communication system for shallow-water time-varying acoustic channels.
Chapter 4

MODELING ACOUSTIC COHERENT COMMUNICATION UNDER WIND-DRIVEN OCEAN SURFACE WAVES

Winds raise time-varying roughness on the air-sea interface, which deflects underlying sound and modifies underwater acoustic channel in short timescale. Performance degradations and system failures in underwater acoustic communication were reported due to wind-induced surface waves, especially for coherent communication systems which utilize phase information during the modulation. Here, we propose a controllable numerical approach for this problem: Realistic acoustic channels for different wind conditions are numerically simulated with wind-wave spectral methods and a 2-D rough-surface parabolic equation (PE) model; Then, these time-varying acoustic channels are tested with quadrature phase-shift keying (QPSK) modulation, one of the most fundamental modulation schemes for underwater acoustic coherent communication. Preliminary results suggest that in consideration of a time-varying environment, system performance for coherent communication degrades with increasing wind speed, as a result of increasing temporal variability of wind-impacted surface waves. Our numerical modeling method could be a helpful tool to study acoustic communication problems in time-varying ocean environments.

4.1 Introduction

Underwater acoustic communication in shallow waters has been a challenging research topic over recent decades, due to the complexity of acoustic multipath structure in nature time-varying environment [60, 61]. There has been a series of schemes and methods proposed for acoustic communication in such challenging regions. Most popular communication schemes are based on coherent methods, where data modulation
is based on the phase information of the sound carrier [42, 62, 20]. Though coherent schemes can achieve a better data rate during transmission, especially when the channel condition is good, they are very dependent to the channel variability (i.e. channel coherence time) and may not be as robust as some incoherent methods [63]. Designing better coherent communication systems requires a better understanding of the physics of shallow-water acoustic channels and the variability of nature water environments [64].

For shallow waters, the variability of underwater acoustic channels stems from temporal and spatial variations of the water environment [61]. Basically, there are two sources of variations—from surface boundary and from water column. In this paper, we only focused on the surface boundary variations. These surface boundary variations are usually wind driven, which have a timescale within seconds, and associated with a broad spectrum of different surface waves [11]. The wind-driven time-varying sea surface roughness can cause sound scattering and therefore can influence underwater acoustic field by shifting sound paths and resulting in fluctuation of arrival time and intensity of acoustic signals [1, 48, 14, 58]. For high-frequency shallow-water acoustics, the signal variability may become even more complicated due to multiple reflections between surface and bottom boundaries [10].

Previous studies have found that as surface wind intensifies, ocean surface roughness increases, with sound energy being scattered away and acoustic returns changing from coherent to incoherent [1]. Underwater acoustic systems end up with decreasing signal-to-noise ratio (SNR) and degradation of system performance. System degradation and failures in underwater acoustic communication experiments were found related to surface winds and sea states [65], as different ocean wave conditions can lead to different acoustic reflections at the surface boundary. However, thorough understanding of the effects of winds on ocean waves, and further to acoustics has not been fully addressed in the past, which can be only explored by analysis of comprehensive experimental data and development of combined numerical models.
The goal of this paper is to study the effects of time-varying wind-driven surface roughness on coherent acoustic communication. Here, we present a numerical modeling approach to investigate this time-varying problem. Realistic time-evolving wind-impacted acoustic channels were simulated based on wind condition, which was then used to test underwater acoustic coherent communication. The quadrature phase-shift keying (QPSK) modulation, one of the most fundamental coherent modulation schemes, was tested in different wind conditions within a frequency band of 12.5–17.5 kHz. Results indicated that in a time-varying environment, the performance of acoustic coherent communication systems degrades as surface wind speed increases, which is a result of temporal variability of acoustic energy scattering and incoherent phase from random surface reacting to wind-wave dynamics.

4.2 Modeling Methods

The flow chart of our modeling is illustrated in Fig. 4.1. The system includes a wind-impacted acoustic channel simulator and an acoustic communication system. The acoustic channel simulator transforms surface wind information into time-evolving acoustic channel impulse responses based on wind-wave-acoustics theory; Then, the acoustic communication system was tested with the acoustic channel responses. With
this regime, system performance of underwater acoustic communication can be numerically simulated with adjustable environmental parameters, such as wind speed, wind fetch, water depth and ambient noise level.

4.2.1 Wind-impacted time-evolving acoustic channel

The acoustic channel simulator includes three numerical models—a wave spectral model, a surface realization model, and a full-wave acoustic propagation model (left three components in Fig. 4.1). This acoustic channel simulator has been used in previous studies to investigate effects of surface winds on time-varying acoustic propagation [39, 25]. Basically, the wave model converts wind information to wave energy spectrum; the surface realization model generates surface elevation from the wave spectrum; and the PE acoustic propagation model constructs acoustic pressure field with rough surface boundary.

First of all, the spectrum of wind-driven surface waves was generated by a wave model based on environmental variables. The wind-wave spectral method adopted here was the TMA model [66]. TMA is an empirical wind-driven ocean wave model, particularly optimized for shallow waters. It estimates the theoretical wave spectrum for fully-developed wind-driven surface gravity waves, with an adjustment term validated from field data, and a depth-dependent factor accounting for the wave dissipation due to limited water depth [52]. TMA is more suitable for shallow water studies than other wave models that do not consider the water depth, because acoustic multipaths and rough ocean waves would have even more effects on acoustic channel in these shallow regions [25]. Using this model, wave spectra were numerically generated with controllable environmental inputs, i.e. wind speed, wind fetch, and water depth.

Second, time-varying surface waves were generated by the surface model. With a given wind-wave spectrum, 2-D rough sea surfaces was realized by a surface model [53]. The surface model converts a frequency-dependent wave spectrum to surface wave heights using Fourier transform pairs, from the frequency domain to the spatial domain. Furthermore, due to the nature evolution of ocean waves, this problem is
Figure 4.2: Surface wave spectral modeling using TMA spectra with a fixed fetch ($F = 30$ km) and a shallow water depth ($h = 15$ m) for different wind speeds ($U_{10} = 1, 6, 13$ m/s).

a time-evolving problem, where the following surface wave is related to the previous surface wave. For such wave evolution, this model initializes random phases for the first surface; For following surface elevations, the model adopts the Rung-Kutta integration algorithm to step in time from the previous surface roughness [53]. Note that this model can simulate both time-evolving or randomly-varying surface elevations for a same surface wave spectrum, which enables us to study acoustic communications with different scenarios.
Figure 4.3: Simulated time-evolving ocean surface waves from the TMA spectra as in Fig. 4.2.

Finally, acoustic pressure fields were constructed by a 2-D rough-surface parabolic equation (PE) model [39] with rough surface input. This study required a full-wave
acoustic model which can handle broadband acoustic transmission and rough surface scattering. This PE used in this study is based on a 2-D split-step Fourier transformation and range-marching algorithm, and more importantly, it accounts for the surface scattering caused by rough surface conditions [39]. For acoustic scattering from a rough surface, the pressure release boundary is shifted from a flat surface to a rough surface, which modifies the reflection angles and the reflected energy. Therefore, this model is capable of computing acoustic arrival time and pressure amplitude under rough sea surfaces [39].

4.2.2 QPSK acoustic communication system

The incoherent components of acoustic signals, caused by acoustic scattering from time-varying rough sea surface, can influence underwater acoustic coherent communication, where phase information of received acoustic signals is the key to demodulate the transmitted data [25, 20, 61]. Here, we focused on phase shift keying – the most fundamental acoustic coherent scheme, which many other more sophisticated coherent communications were built on. The system we tested here was the quadrature phase shift keying (QPSK) [20]. Note that we only tested the basics of the QPSK scheme with simple carrier recovery; while we did not apply further adaptive mechanism to track and compensate the temporal variability of acoustic channel (i.e. examples in [63]).

The QPSK system was demonstrated in the box of Fig. 4.1. The transmitter had two main components – signal generation and quadrature modulation. The system first generates to-be-transmitted signals for the QPSK modulation, which include a chirp signal (for signal detection), a single-frequency signal (for carrier recovery), a known M-sequence (for fine time synchronization and signal recovery), and the data series (also modulated by the M-sequence). Next, all these signals were transformed from baseband (0-5 kHz) to passband (12.5-17.5 kHz) via carrier modulation in both real and imaginary components.
In the receiver end, there are four components: quadrature demodulation, signal detection, carrier recovery, and QPSK demodulation. The received signals were first shifted back from passband to baseband. Then, the system detects the preset source chirp signal. If the signal is detected, carrier recovery estimates and corrects the frequency and phase offset of the received signal using the received single-frequency signals. Next, the received M-sequence (a preset, known signal) is used to process the fine time synchronization and signal recovery for the following data signals. Finally, the equalized received data were demodulated through QPSK symbol mapping.

To mimic the underwater acoustic channel effects, the generated transmitted signals were convoluted with the time-varying wind-impacted acoustic channel response. Also, we applied additive white Gaussian noise, random time delay, and random frequency and phase offset to the output signals. Here, we defined two convolution schemes for two different surface scenarios—the static surface and the time-evolving surface. For the static surface scenario, the channel effect is the same as regular convolution (Eq. 4.1) between the whole transmitted signal, \( s(t) \), and the channel impulse response, \( h(t) \).

\[
x_S(t) = (s * h)(t) = \int_0^T s(t) \cdot h(t - \tau) d\tau
\]

For the time-evolving surface scenario, we mimicked the time-varying channel impact by cutting the whole signals into segments based on channel coherence time and applied convolution to each segment with associated time-varying channel impulse response. Finally, total channel effects were the sum of results from all segments:

\[
x_E(t) = \sum_{n=0}^{N} (s_n * h_n)(t) = \sum_{n=0}^{N} \int_0^T s_n(t) \cdot h_n(t - \tau) d\tau
\]

where, \( h_n(t) \) is the time-varying channel response for that specific time frame, and \( s_n(t) \) is the whole signal modulated by a moving time window.

### 4.3 Modeling Results

In this section, QPSK system was tested with wind-impacted shallow-water acoustic channels using our proposed structure (Fig. 4.1). For each wind speed, we
Figure 4.4: Acoustic channel impulse responses from 2D rough-surface PE based on time evolving surfaces at different wind speeds: (a) $W = 1 \text{ m/s}$, and (b) $W = 13 \text{ m/s}$. The black line is the channel response for the original surface, while the line with lighter colors are those for consequential evolving surfaces. The time span for the evolving surface simulation is 0.2 s.

calculated one surface wave spectrum, generated a series of time-evolving surfaces, and simulated the associated acoustic channel responses. Then, with each acoustic channel response, we ran multiple communication tests with different SNRs.
Figure 4.5: Constellation of the QPSK demodulation. (a) $W = 1$ m/s, static scenario; (b) $W = 13$ m/s, static scenario; (c) $W = 1$ m/s, time-varying scenario; (d) $W = 13$ m/s, time-varying scenario. For these simulations, the QPSK bits rate of 500, and the SNR of 0 dB. For the time-varying scenario, the resolution between two surface is 0.2 s.

4.3.1 Environmental and channel variability

Figure 4.2 shows surface wave spectra for three different wind speeds (1, 6, and 13 m/s) using the TMA model. For these three cases, the wind fetch was 30 km and the water depth was 8 m. From Fig. 4.2, one can see that surface waves generated by high winds have higher energy than those generated by low-speed winds. As the
wind speed increases, surface wave energy increases and the energy peak shifts to lower
frequencies. The 13-m/s wind-wave spectrum has the peak frequency of 0.23 Hz and
the amplitude of 0.91 m²/Hz, while the energy for 1 m/s wind is very low and almost
negligible. We also tested different water depths and wind fetches, and results showed
that wave energy also increases with increasing wind fetch and increasing water depth.
However, the effect of wind speed is more significant than water depth and the wind
fetch on surface wave spectrum. Therefore, we only focused on the effects of wind
speed and kept the water depth and the wind fetch fixed for the following simulations.

Figure 4.3 illustrates the time-evolving surface roughness for three different wind
speeds. The interval between two consecutive evolving surfaces in these simulations
was 0.2 s, which is smaller than the timescale of dominant surface motions (according
to Fig. 4.2). The maximum amplitude of the surface elevation for 1, 6 and 13 m/s were
0.005, 0.07 and 0.2 m, respectively, indicating that the surface roughness generated by
low winds is much smaller than that generated by high winds. Also, we noticed that
the temporal variability, i.e. the roughness difference between two surfaces, for the low
wind case is smaller than that for the high wind case. In other words, the fluctuation
of the ocean waves generated by higher winds is even severer both in space and in time
than by low winds.

Figure 4.4 shows acoustic channel responses for 1 m/s and 13 m/s wind cases
simulated by the 2-D rough-surface PE model. For these simulations, sound speed
profile was uniform (1500 m/s), and the ocean bottom was flat. Noted that in Fig.
4.4, the first peak is the direct path, while the following energy components are all
surface-related acoustic paths. Results showed that the surface paths have a relatively
high amplitude at low winds, and also, the fluctuation in time is relatively small.
However, as the wind speed increases, the surface energy attenuates significantly, and
the temporal fluctuation intensifies. This suggested that the multipath structure of
acoustic channel have stronger variability at high winds than at low winds.
4.3.2 Acoustic communication performance

For acoustic communication, we tested two different wind speeds (1 and 13 m/s), with two different scenarios (static surface and time-evolving surface) under the SNR of 0 dB. Results in terms of demodulation constellation were shown in Fig. 4.5. For a static surface scenario, the high wind case has a better separation in the constellation diagram than the low wind case [Figs. 4.5 (a) and (b)], suggesting that a better communication performance would be achieved at high winds when the surface is rough but static in time. However, for a time evolving scenario, the results were totally different. For low winds, the constellations for both surface scenarios were very similar [Figs. 4.5 (a) and (c)], with the time-evolving case being slightly worse than the static case. For high winds, the constellations for two scenarios were completely different [Figs. 4.5 (b) and (d)]. The demodulation constellation for a time-evolving surface become much worse than a static surface, even both scenarios had the same roughness level. In addition, comparing Figs. 4.5 (c) and (d), the demodulation was worse at high wind speed than at low wind speed when the surface evolution in time was considered.

Figure 4.6 shows the bit error rate (BER) for two wind speeds (1 m/s and 13 m/s) in two surface scenarios with the SNR of 0 dB. For low wind case, the BER for both surface scenarios is at the same level—about 0.025, with the time-evolving surface slightly larger than the static case. For high wind cases, the static case has an improved BER performance while the time-evolving case had a degraded performance. The BER for the non-evolving surface was 0.010, and that for the time-evolving case was 0.05. Noted that the BER for the static case have a wider distribution than the time-evolving case, especially when the surface wind speed increases.

4.4 Discussions

Modeling results indicated that as wind speed increases, surface roughness and wave variability increases (Figs. 4.2 and 4.3), and the acoustic channel exhibits decrease in energy and increase in variability for surface-related sound paths (Fig. 4.4). Also,
Figure 4.6: Modeling results of QPSK system performance for two different wind speeds (1 m/s and 13 m/s) with two different surface scenarios. The gray color is for the static scenario; while the black color is for the time-varying scenario.

the performance of acoustic coherent communication systems improves as increasing surface wind speed in the static rough surface scenario; however, it decreases in time-varying rough surface scenario (Figs. 4.5 and 4.6).

Two completely opposite wind-dependent relationships were found from our numerical modeling results (Figs. 4.5 and 4.6). We proposed that the time-evolving approach was a more realistic scenario for underwater acoustic communications, e.g. Fig. 4.5 (c) and (d). On one hand, previous field experiment [29] reported a negative correlation between wind/sea state and the communication performance, which agreed with our time-varying scenario. On the other hand, the result for the static scenario, i.e. increasing performance with increasing wind speed, is only true for the sea surface
which has a roughness but is still motionless. In real nature, however, the rough
sea surface is impossible to be static due to the gravity. We argued that to model
a realistic communication performance for a rough surface boundary, time-varying
acoustic channels should be used instead of static acoustic channels.

We suggest that the cause of the decrease of communication performance at
high winds is due to the increasing temporal variability of surface waves, not due to
the increasing incoherent signals from rough surface scattering. Actually, the increas-
ing roughness does not degrade the performance of acoustic communication systems
[Fig. 4.5 (a) and (b)]; Instead, it can improve the performance by providing a simpler
multipath structure for underwater acoustic communication. Considering an extreme
case, if the surface boundary is extremely rough and all surface energy are completely
scattered away, there will be a very little surface return which leaves only a strong
direct path component, which is perfect for the communication system. The temporal
variability, however, can degrade the system performance by failing the carrier recov-
ery and channel equalization. For this reason, coherent communication system requires
well-designed channel adaptive methods whose reaction time should be shorter than
the coherence time of the physical channel [63]. In our basic QPSK system, we did not
adopt such mechanism to compensate the variability of channel in time, so the carrier
recovery processing was based on the channel at the beginning moment, which did not
account for the channel variability for following moments, so that it leads to failure of
phase recovery and therefore the decrease of system performance.

In addition, there were some aspects we did not consider in this study which
might affect the communication results. We did not account for the bubble effect in our
PE modeling. Bubble forming is inevitable at high sea states along with wave breaking,
which causes attenuation of acoustic intensity but it is usually considered having little
effects on forward scattering problem. Also, the realistic sound transmission in the
ocean is a 3-D problem, but we limited our analysis and discussion in a 2-D PE model,
which did not account for the out-of-plane acoustic reflection and scattering. However,
this is still a realistic approach as our 2-D PE mimics the most energy component of the
acoustic fields, because the out-of-plane acoustic energy is relatively small comparing to the in-plane energy [14, 25].

4.5 Conclusions

This study presented a combined numerical modeling approach to investigate the wind-wave effects on acoustic coherent communication. With time-varying nature of ocean surface waves, the QPSK performance will decrease with increasing wind speed, due to the increasing temporal variability of surface paths at high winds, instead of the increasing roughness of the ocean surface itself. As the system performance of underwater acoustic communication is strongly related to the physical environment, which is complex and time-varying, the full understanding of the time-varying environment on acoustic communication will need further work on realistic oceanography-acoustics combined models. Future study will be continued on effects of QPSK system with channel tracking, and how acoustic communication performance links with signal coherence time and water environment variability. Also, effects on other acoustic communication methods and coding schemes will be further explored.
Chapter 5

WIND-WAVE EFFECTS ON COHERENT AND NON-COHERENT UNDERWATER ACOUSTIC COMMUNICATIONS: A LABORATORY EXPERIMENT

Atmospheric winds raise surface water waves that can cause fast fluctuations of underwater acoustic channels and further influence underwater acoustic communications. The link between winds and underwater acoustic communications is an extremely complicated inter-discipline study, which is not well understood yet, mostly because directly studying this problem from ocean acoustic experiments, where environmental variables are difficult to control or separate, is extremely challenging. In this paper, a laboratory water tank experiment is proposed to provide a fresh look of this problem. Two fundamental modulations schemes (one coherent, one non-coherent) are investigated in a controllable laboratory environment, where wind is the only changing environmental variable. Results show that, the performance of coherent communications decreases at high winds due to increased acoustic channel variations and decreased temporal coherence, while the performance of non-coherent communications may increase as a result of smaller acoustic surface returns and less channel sensitivity of the non-coherent detection method. Results also suggest that winds effect on communication performance depends critically on modulation schemes, which should be considered differently for modeling and design of underwater acoustic networks in the future.

5.1 Introduction

Rapid developments of marine sciences and ocean explorations promote a series of underwater technologies and applications for ocean engineering. Underwater
acoustic communications, which enable wireless data and information exchange among underwater devices, have been a research hotspot for many years due to the extensive usage in civil engineering and scientific research [67]. Underwater information transmission with high data rate and reliability has been the goal for underwater acoustic communication researches. For recent decades, the data rate of underwater acoustic communications has greatly improved from only a few bits per second (bps) to several thousand bps, with system reliability increasing steadily as well.

Currently, the top challenge that hinders the further improvement of underwater acoustic communications stems from complex nature ocean environments, which are extremely diverse and highly time-varying [61]. For instance, variation of sea surface roughness driven by surface winds and waves [25, 26], water mixing and stratification driven by tidal forcing [68, 28], variation of thermocline due to the internal wave [27, 69], noise interruption from marine life and human activities [70, 71], etc, can all affect the variability of time-varying underwater acoustic channels and further the performance of underwater acoustic communication systems. Until today, there are still no effective acoustic communication schemes existed that can work in all ocean environments and guarantee high data rate and reliability at the same time. The leap of underwater acoustic communication performance requires a deeper understanding of the connection between physical ocean environments, underwater acoustic channels and acoustic communication systems [10, 61, 25].

Among all environmental variability, winds and surface waves at the air-sea interface are the most common one for the fast fluctuation of underwater acoustic channels, which has a significant influence on underwater acoustic communications. Driven by atmospheric winds, sea surface waves increase the roughness of the air-sea interface and alter sound paths under the water, which has been challenging the design of underwater acoustic communication systems for a while. Evidences that winds, surface waves or sea states influence the performance of underwater acoustic communication have been widely reported in previous studies (e.g., on underwater acoustic channels [10, 2, 51, 61, 67, 72, 73, 74, 75, 76, 60, 77], field experiments
As a complex and inter-discipline scientific research problem, the inside link between the wind/wave and the performance of underwater acoustic communication systems has not been fully understood yet [26]. Next-generation underwater acoustic communication systems are calling for a physics-based design that offers a better adaptability of time-varying physical ocean environments, which can use a better understanding of the relationship between the physical oceanography, ocean acoustics, and underwater acoustic communication.

Many wind-related effects on underwater acoustics have been previously studied, and the two key effects are the increased ambient noise due to surface wind-wave dynamics, and the increased acoustic scattering due to wind-driven surface waves, both of which can influence underwater acoustic communications. On one hand, the spectrum of wind-generated ambient noise ranges from 10 to 10^4 Hz [89], well overlapped with the frequency bands used by mid- to large-range underwater acoustic communications [61]. When the wind force strengthens, ambient noise increases within its entire spectrum, with noise peak slightly shifting to lower frequencies. Louder background noise in a windy environment reduces the signal-to-noise ratio (SNR) at the receiver end, posing a negative effect on the underwater acoustic demodulation. On the other hand, wind blowing on top of the water causes water wave dynamics at the interface, changes underwater sound propagation paths, and eventually causes fluctuations of phase, arrival time and intensity of received acoustic signals on a wide timescale, ranging from a millisecond to tens of seconds [25]. Due to the complexity of the wind-wave mechanism itself [41, 53], which involves a series of complicated processes including wind built, wave dynamics and wave breaking, the wind-related effects on underwater acoustic channels, and the performance of acoustic communication systems are still not clear at this point [44, 57].

Most studies that focused on these wind or surface wave effects on underwater sound propagation and acoustic communication channels are too complicated for practical applications in real underwater communication systems. Direct studies on
the link between the wind and underwater acoustic communications (with either field experiments or numerical modeling) are very rare, due to lack of the ability to control environmental variables in field experiments and lack of realistic acoustic channel simulators that can handle this complicated time-evolving problem [39]. This problem needs an intermediary method that bridging the gap between field experiments and realistic numerical simulations.

Currently, underwater acoustic communications can be classified into two major categories: coherent communications, which modulate the to-be-transmitted data into the phase of acoustic carriers, and non-coherent communications, which use other acoustic information such as frequency and/or amplitude of sound carriers to carry data information. In general, coherent communications can achieve higher data transmission rates due to its higher bandwidth efficiency, but they are more sensitive to channel variability; Besides, maintaining high performance in a highly time-varying ocean environment requires a series of sophisticated equalization and tracking of underwater acoustic channels [60, 20]. Non-coherent communications, on the other hand, achieve lower data rates, but they are very robust and the systems are generally easy to implement, which make them very reliable and suitable for underwater communications in the ocean [60, 63]. So far, there have been a variety of ideas or methods proposed to solve the communication problem for time-varying ocean channels, but there are still no perfect solutions at this moment. At current stage, most popular underwater communication schemes are based on coherent methods [42, 62, 20], but non-coherent methods are still widely used for reliable communications (such as transmitting control commands) in the commercial acoustic modems. In short, the underwater non-coherent acoustic communications are robust and the coherent communications are sensitive to acoustic channels. Therefore, how the surface wind wave dynamics influence the underwater coherent and non-coherent acoustic communications (e.g., will the coherent methods perform better than the coherent method?) is a question that requires further investigation.

The goal of this paper was to explore how winds above plays a role in coherent
and non-coherent acoustic communications in the water through the effect of time-varying wind-driven surface waves. This study is helpful for understanding how wind waves can affect the underwater acoustic communication systems and which can be used to guide the system design or switch schemes based on wind/wave conditions. With a laboratory water tank experiment, three different surface scenarios (non-wind, windy and static roughness surface) were compared to investigate how the time-varying surface variation driven by surface wind on the coherent and non-coherent communication. The quadrature phase shift keying (QPSK) modulation, one fundamental coherent scheme, and the multiple frequency shift keying (MFSK), one fundamental non-coherent scheme, were tested inside a water tank with different preset wind/surface conditions. Results indicated that the wind affects very differently on coherent and non-coherent acoustic communications: the performance of coherent acoustic communications downgrades with increased wind speed due to higher channel variations and lower signal temporal coherence at high wind, while non-coherent communication performance increases with the increased winds due to smaller multipath energy.

The rest of the paper was organized as follows. Section 5.2 introduced the setup of the water tank experiment and the two tested acoustic communication schemes. Section 5.3 analyzed the characteristics of underwater acoustic channels for each surface scenarios in the water tank. Section 5.4 presented the results of QPSK and MFSK acoustic communication with preliminary analyses. Section 5.5 discussed the effect of the wind on the two modulations schemes based on the results. Finally, conclusions were drawn in Sec. 5.6.

5.2 The Water Tank Experiment

To investigate the effect of wind-driven surface waves on the performance of underwater acoustic communications straightforward, a laboratory water tank experiment was designed as a controllable environment where two representative modulation schemes – QPSK and MFSK were tested and compared. The main consideration of conducting a laboratory experiment instead of a field experiment was to minimize the
Figure 5.1: Setup of the controllable laboratory water tank experiment. The dimension of the water tank is $0.8 \times 0.6 \times 0.6$ m. The electric fan that generates surface waves is positioned at 0.3 m away from the water tank, with a grazing angle of 15° looking downward.

Influence of other environmental variables, such as the elevation of water depth due to tide, the variation of water column properties, or surfaces waves or surges coming from remote region (i.e. non-local wind driven waves), which are common in nature ocean environment and almost impossible to control or separate in an actual field experiment. With a laboratory experiment, surface condition can be changed with other environmental variables fixed, which is very helpful for the understanding of the effect of time-varying surface roughness on the performance of coherent and non-coherent underwater acoustic communications.

5.2.1 The environment and experimental setup

Figure 5.1 illustrates the setup of the laboratory water tank experiment. The water tank used in this experiment was 0.8 m long, 0.6 m wide, and 0.6 m deep. During the experiment, it was filled with fresh water up to a height of 0.55 m. One acoustic transmitter and one receiver were positioned at the bottom on opposite sides of the water tank, being about 0.6 m apart. The transmitter was a cylindrical transducer with a diameter of 5 cm and a 3-dB bandwidth of 20–30 kHz; The receiver was B&K 8105...
broadband hydrophone with a bandwidth of 0.1–160 kHz and a receiving sensitivity of -250 dB re 1 V/\mu Pa. An industrial electric fan was positioned at 0.3 m away from the transducer side of the water tank to generate controllable atmospheric winds (the wind speed $W = 4.5, 5, 5.5$ m/s, measured at 1 m from the fan) and create time-varying surface water waves in the tank. Due to the short range between the source and receiver, no power amplifiers or signal pre-amplifier were needed in this experiment. The acoustic signals were distributed and collected with a data acquisition (DAQ) system – NI USB-9162, which supports up to four analog-to-digital inputs and one digital-to-analog output.

To investigate the effect of time-varying surface roughness, three different surface conditions (referred as surface scenarios) were defined in this study: no wind (NW), windy surface (WS) and static rough surface (RS) conditions. The windy surface scenario was generated by the electric fan with a wind speed of 5.5 m/s; the static rough surface was mimicked by an air bubble foam covering on the water surface. The air bubble foam created a static rough surface at the air-water boundary, which was used to compare the time-varying rough surface in the windy surface scenario. The diameter for bubbles of the foam is about 3 cm, and the overall RMS roughness is about 2 m. The motor of electric fan increased the background noise for the windy surface scenario. The noise level was 60 dB (Z-weighting) with the fan off and 91 dB and with the fan on. Limited by the dimension of the water tank, the maximum wind fetch was very short, i.e., less than 1 m, so the magnitude of wind-driven surface waves in the water tank was small. To increase the surface waves, the fan was slightly adjusted, with a grazing angle of 15° looking down. This adjustment may affect the quantitative analysis of the problem, but not for the purpose of this study which focused on a qualitative investigation of wind effects.

During the experiment, linear frequency modulation (LFM) signals were transmitted for channel testing, and acoustic communication signals were transmitted for the investigation of communication performance, under above three surface scenarios. The peak-to-peak amplitude of the wind-driven surface waves in the water tank for
a wind speed of 5 m/s was about 4 cm. To guarantee surface waves being sensed by the acoustic waves, we used broadband acoustic signals with a center frequency of 27.5 kHz. Therefore, the acoustic wavelength was 5 cm, on the same length scale as the surface roughness created by winds or by the air bubble foam. The acoustic transmissions were only performed after surface waves were full-developed for the given wind speed, and acoustic data were directly recorded and stored for future analysis. During the experiment, the room temperature was maintained at 27°C, and the sound speed in the water tank was homogeneous.

5.2.2 Tested acoustic communication schemes

Two traditional underwater acoustic communication schemes were tested in this experiment: a QPSK modulation representing coherent communications and an MFSK modulation representing non-coherent communications. To compare the effect of wind waves on the performance of these two schemes, the frequency bandwidth for both schemes were set to 25–30 kHz, corresponding to an underwater acoustic communication range up to 10 km.

QPSK is one of the most fundamental coherent communication methods, upon which many popular modulation methods are based, such as multi-carrier communication, orthogonal frequency division multiplexing (OFDM). The QPSK system implemented here included seven main components: QPSK mapping, pulse shaping, quadrature carrier modulation, quadrature carrier demodulation, signal detection, and synchronization, matched filtering, QPSK de-mapping. At the transmitter, the quaternary symbols were modulated into phase information using absolute phase shift, then pulse shaping was applied with the raised cosine function, and finally, the based band acoustic signal modulates to 27.5 kHz carrier. At the receiver end, the system first moved the received underwater acoustic signal from carrier frequency band back to baseband, then signal synchronization was performed using M-sequence. After the received base-band signals were matched filtered, the phase information was restored.
and information symbols were recovered. More information about the QPSK modulation can be found in the relevant literature [26]. The data rate of QPSK tested in this paper was 200 bps, corresponding to a symbol length of 10 ms. Considering the purpose of this paper is to study the influence of time-varying sea surface on the performance of phase-shift keying modulation, the QPSK system does not use the channel equalization algorithm. The channel equalization algorithm is used in the coherent demodulation process to improve the communication performance and wind, which is beyond the scope of this article.

MFSK is one of the most classic non-coherent modulation methods, which uses the frequency information of the carrier instead of the phase to carry digital information. In order to compare with QPSK, the frequency shift keying system tested in this paper was also quaternary ($M = 4$), i.e., 1 symbol corresponds to 2 binary bits of data. The MFSK was conducted at the frequency band of 25 – 30 kHz, with an available bandwidth of 5 kHz, as a result, the frequency spacing between adjacent symbols was 1.25 kHz. The MFSK system includes four basic components – frequency modulation, carrier modulation, carrier demodulation, frequency demodulation. The transmitter maps the quaternary symbols into frequency information and modulates each to a carrier with corresponding frequency. At the receiver, the system uses the Fourier transform (FFT) to detect the frequency of the carrier and then maps the detected frequencies back to four symbol symbols. Due to the existence of underwater acoustic multipath delay, the received signal may be seriously contaminated by inter-symbol interference (ISI). MFSK systems are often combined with frequency hopping technique to overcome ISI, but since this paper only aims to investigate the impact of wind waves on the essential communication schemes, no frequency hopping techniques were implemented in our MFSK system. Also, considering the influence of ISI, two different data rates for the MFSK modulation scheme were tested – 100 bps and 20 bps. The symbol duration for the 100 bps is 20 ms, less than the multipath delay; while the symbol duration for the 20 bps is 100 ms, representing the case where the symbol width is larger than the multipath delay.
For each water surface scenario, on-minute channel testing was conducted using a 0.5 s, 25 – 30 kHz chirp signals before the acoustic communication transmissions. Also, in each transmission of the MFSK and QPSK communication, the same chirp signal was added before the communication signals as a preamble for signal detection and synchronization, and for auxiliary analysis of the characteristics of the channel. For each modulation method, the transmitting power was adjusted to test the communication performance at different signal-to-noise ratios (SNRs).

5.3 Analysis of Underwater Acoustic Channels

5.3.1 Acoustic channel impulse response

Before diving into the acoustic communication results, acoustic channel impulse responses (CIRs) for three different surface scenarios – non-wind (NW), rough surface (RS) and windy surface (WS) scenarios, were collected and analyzed to help us understand the physical environment. The water-tank acoustic channel was sampled with a series of chirp signals which has a bandwidth of 25-30 kHz and a duration of 0.2 s. The chirp signal was re-transmitted every half second for a total of one minute. The channel impulse response was obtained by matched filtering the received signal with the source LFM signal. The waveform output of the matched filter was signal compression, which reflects the multipath structure of the acoustic channel.

Figure 5.2 shows an example of underwater acoustic channel impulse responses for non-wind, windy and static rough surface. The amplitude of the sound pressure is normalized to the sound pressure amplitude of the direct signal for the non-wind scenario. As seen in Fig. 5.2, all scenarios exhibited a same macroscopic feature in their acoustic channel impulse responses, with a strong direct path arrived at first ($\tau = 0$ s) and later paths decreased exponentially over the time due to the strong acoustic reverberations occurred inside the small water tank. The total multipath delay extended up to $\tau = 0.08$ s. Carrying out underwater acoustic communication experiment in a confined space like a water tank, acoustic waves experience strong reverberation due to the existence of the water tank’s four walls, resulting in a continuous exponential decay.
of acoustic pressure amplitude, very different from experiment results where the multipath channel structure has separate and distinct acoustic paths. Such reverberation channels, however, do not affect the analysis of wind-induced sea-surface roughness, since all sea-surface reflections (wind-wave effects) are still effectively reflected by the four walls and incorporated into the acoustic reverberations. In addition, Fig. 5.2 shows some small characteristics of acoustic multipath amplitude. In some particular subpeaks (e.g., $\tau = 8, 10, 12$ ms), lower wind or no-wind scenario seemed to have a

**Figure 5.2:** Acoustic channel impulse responses for different surface scenarios. For better illustration of envelop of the acoustic impulse response, a low pass filter was applied before the plotting.
Figure 5.3: The measured underwater acoustic channel impulse responses in the water tank for non-wind (NW), rough surface (RS) and windy surface (WS) scenarios. The acoustic intensity was normalized to the direct path signal in the non wind scenario.
higher the sub-peak amplitude (comparing three windy cases), while the no-wind case had the highest sub-peak amplitude.

Figure 5.3 illustrates 20 seconds of the underwater acoustic channel impulse response for three defined surface scenarios. The x-axis is the arrival time of the acoustic signal, the y-axis is the geological time, and the intensity of the multipath signal is normalized to relative value (unit dB, where 0 dB corresponds to the direct signal intensity of the no-wind scenario). Similar to Fig. 5.2, channel multipath structures for all scenarios are very similar at the macroscopic scale, peaked at $\tau = 0$ ms and then quickly decayed over time. However, one can find very distinct characteristics among them, especially for the windy surface scenario. For the no-wind and rough surface scenarios [Figs. 5.3 (a) and (b)], their acoustic multipath structures are very stable in time and do not change over time, due to the absence of surface wave motions. For the static rough surface scenario, the reverberation is reduced, mainly due to the surface scattering and absorption of the air bubble foam (discussed in Sec. 5.5). For the windy surface scenario [Fig. 5.3 (c)], the channel impulse response is highly time-varying with fluctuation, which is due to the influence of the time-varying wave of the water surface, which shifts the surface reflection point and modify the surface roughness and eventually change the received acoustic signal. The environmental factor that causes this signal fluctuation was the wind-driven surface waves, whose timescale is less than the LFM sampling resolution – 0.5 s, implying a small, but fast changing surface motion.

5.3.2 Channel variability

Though the acoustic channel impulse responses for three defined surface scenarios were very similar (Fig. 5.2), the time-varying features were very different (Fig. 5.3). To further highlight the time-varying characteristics of the channel in the windy surface scenario, the instantaneous variation of underwater acoustic channel is defined as:

$$\Delta h(t, \tau) = h(t, \tau) - h(t - \Delta t, \tau)$$  \hspace{1cm} (5.1)
Figure 5.4: The instantaneous variation of the underwater acoustic channel impulse response from the water tank for three defined surface scenarios. The instantaneous variation was defined in Eq. (5.1), and here $\Delta t = 0.5$ s. The acoustic intensity is normalized to the intensity of the direct signal in the no-wind scenario.
where, $h(t, \tau)$ is the acoustic channel impulse response at a geological time $t$ with an arrival time $\tau$. The instantaneous variation of the channel impulse response is the dynamic change of the signal multipath structure with different arrival time $\tau$, and the time-varying nature of the channel is reflected in some cases.

Figure 5.4 shows the instantaneous variation of underwater acoustic channels for three defined surface scenarios, calculated from Eq. (5.1). Similar to Fig. 5.3, the intensity of the acoustic multipath was normalized to the intensity of the direct signal for the no-wind scenario. The arrival time interval used to calculate $\Delta h(t, \tau)$ is $\Delta t = 0.5$ s, the channel sampling resolution. As seen in Fig. 5.4, there is an essential difference in the instantaneous variation of the acoustic channel impulse response between the no-wind and windy surface scenarios, due to differences between the stationary surface in the no wind scenario and the dynamical surface in a windy surface scenario. For the no-wind and rough surface scenarios [Figs. 5.3 (a) and (b)], the instantaneous variation of the channel is small ($< -60$ dB) all the time, while for the windy surface scenario, the instantaneous variation of the channel ranged from -60 to -10 dB, which fluctuates over both the arrival time and the geological time. From the analysis of the amplitude envelope, the instantaneous variation of the channel increases rapidly near the direct path and reaches the peak (about -10 dB) at about $\tau = 10$ ms, then decrease after $\tau > 30$ ms. The small channel variation is still visible after 80 ms. The effect of surface waves in the tank generated by 6 m/s wind on the underwater acoustic channel variation is the maximum near the direct signal, mainly with first 10 ms (0 to -30 dB). With the arrival time increased, the influence of the follow-up path gradually decreased, lasting up to 100 ms. Comparing Fig. 5.3 (a) to Fig. 5.4 (c), one can notice that the duration of the channel variation in the windy surface scenario is as same as the multipath delay in the no-wind scenario, suggesting that the wind only increased the channel variation, but did not significantly extend the multipath delay of acoustic signals.
5.3.3 Temporal coherence

To further analyze the time-varying characteristics of wind conditions, the temporal coherence coefficients at different wind speeds ($W = 4.5, 5.5, 5.5 \text{ m/s}$) were calculated based on the measured channel impulse response from the water tank. Figure 5.5 shows the variation of the correlation coefficient over time for one minute. Temporal coherence quantifies the similarity between the received signal at a particular time to that at a reference time (i.e., the start-up moment), indicating the time-varying ability of the acoustic channel. As seen in Fig. 5.5, the temporal coherence coefficients for the no-wind and static rough surface scenarios were always 1, i.e. the underwater acoustic channel did not change over time. For three windy cases ($W = 4.5, 5$ and $5.5 \text{ m/s}$), temporal coherence quickly decreased below 0.97 within one or two seconds and then fluctuated up and down over the time. Obviously, the decrease of the temporal coherence coefficient at three wind speed is due to the variation of surface roughness caused by wind-driven wave motions, resulting in the fluctuation of sea surface reflections and decrease of the temporal coherence of the acoustic channel. Table 5.1 summarizes the statistical properties of the temporal correlation coefficient for each wind speed case. The low wind speed has a relatively high temporal coherence, and the fluctuation of the coefficient is small; the temporal coherence for the high wind speed is poor. As the wind speed gets higher, the variation is larger. In particular, the time correlation coefficient for the no-wind and the rough surface scenarios was 1 and the standard deviation was 0, indicating that the underwater acoustic channel has fluctuation and is very stable.

Table 5.1: List of all wind/surface scenarios and their associated signal temporal coherence from the tank experiment.

<table>
<thead>
<tr>
<th>$W$ [m/s]</th>
<th>0</th>
<th>4.5</th>
<th>5</th>
<th>5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_t$ Mean</td>
<td>1</td>
<td>0.9610</td>
<td>0.9486</td>
<td>0.9355</td>
</tr>
<tr>
<td>$r_t$ STD</td>
<td>0</td>
<td>0.0062</td>
<td>0.0082</td>
<td>0.0119</td>
</tr>
</tbody>
</table>
Figure 5.5: The temporal coherence as a function of arrival time for three different wind speeds ($W = 4.5, 5.5, 5.5 \text{ m/s}$) measured from the water tank. The temporal coherence was calculated from 0.2 s chirp signals (20-25 kHz) that repeat every 0.5 s.

5.4 Performance Analysis of Acoustic Communication

5.4.1 Coherent communication

Figure 5.6 shows the bit error rates (BER) of 200-bps QPSK acoustic communication for three different surface scenarios as a function of the receiving signal-to-noise ratio (SNR). Overall, the error rate of QPSK decreases with the increase of SNR. The effect of winds on coherent communication performance can be intensified by comparing the curves between different surface scenarios. First, compared the no-wind and
windy surface scenarios, the bit error rate curve for both scenarios are very close at low SNRs ($E_b/N_0 < 3$ dB), but QPSK communication has a much higher BER in the windy surface scenario than that in the no-wind scenario at high SNRs ($E_b/N_0 > 5$ dB). When $E_b/N_0 = 13$ dB, the bit error rate for no-wind condition is 0, but the error rate for wind conditions is still above $10^{-3}$.

Second, compared the no-wind and static rough surface scenarios, the static
roughness has a slight increase performance in BER than the no-wind scenario. Although the variation trends of these two scenarios are similar, the static rough surface scenario always has a lower bit error rate than the no-wind scenario under the same SNR, and the performance improvement is even more significant at high SNR. For instance, at $E_b/N_0 = 1$ dB, BER increases from 20.9% to 15.7% (about 1.2 dB) from the static rough surface scenario to the no-wind scenario, while at $E_b/N_0 = 13$ dB, the BER increases from 0.14% to 0.04% (about 5.4 dB), suggesting that a static rough surface is more beneficial for QPSK communication than a calm and flat water surface. Therefore, the increase of the roughness is not the reason for the degradation of the coherence underwater acoustic communication performance, and the error rate can be reduced and the communication performance can be improved if the increased surface roughness is static.

Finally, compared the static rough surface and windy surface scenarios, though both scenarios have a certain degree of roughness, a large performance difference exists between the wind-induced time-varying water surface and bubble film simulation of static rough water surface. At low SNRs, the BER performance for both scenarios is close. However, the difference gradually increases as the SNR increases. In Fig. 5.6, at $E_b/N_0 = 11$ dB, the bit error rate of the windy surface scenario ($\sim 10^{-1}$) is much worse than that of the static rough surface scenario ($\sim 10^{-2}$) by an order of magnitude, suggesting that there is a fundamental difference between the time-varying roughness driven by wind and the static roughness mimicked by the air bubble film. Through comparison, the time-varying variability of surface waves driven by the wind is the main reasons for the two opposite performance trends.

Figure 5.7 shows an example of the demodulation constellations for the three preset surface scenarios. The data rate is 200 bps and the received SNR is $E_b/N_0 = 13$ dB. First of all, compared Fig. 5.7 (a) and (b), the static rough surface scenario (RS) is associated with a clearer and more compact constellation distribution, suggesting that the sea surface roughness increases the output signal-to-noise ratio, leading to system performance improvement of the coherent underwater acoustic communications. Next,
the QPSK constellation of the windy surface scenario is much more scattered than that of the non-wind scenario, indicating that the phase of the received symbols becomes more random at higher wind speeds, which directly lead to performance degradation of coherent communication systems. Second, compared Fig. 5.7 (a) and (c), the windy surface scenario has a more scatter constellation than the no-wind scenario, suggesting that the more random received symbols at higher wind speed may lead to a worsened QPSK performance in the windy surface scenario. Third, compared Fig. 5.7 (b) and (c), despite the similar roughness RMS values, the windy dynamic surface case shows a more scattered constellation than the static rough surface case created by the air bubble foam, suggesting the effect of time-varying channel variability is greater than the static surface roughness in worsening the demodulation constellation. By comparing the demodulation constellations of the three different surface scenarios, it can be concluded that while the increased surface roughness induced by the wind may help to converge constellation, but the increased time-varying channel variability increases the phase fluctuation of received signals.

Compared Fig. 5.6 and Fig. 5.7, one can found that: On one hand, the roughened surface makes the surface paths of acoustic waves gradually changing from coherent specular reflection to non-coherent scattering, which leads to the decrease of the multipath component of the received acoustic signal. In other words, the reduced
multi-path energy from the sea-surface reflection highlights the energy of the main
direct-path signal, which helps to reduce inter-symbol interference and improve the
communication performance. On the other hand, the wind caused by the wave has
a high time-varying channel variability, which continues to affect the amplitude and
phase of the received signal, severely reducing the stability of the QPSK phase infor-
mation, and ultimately disrupt the coherent communication in the underwater signal
coherence required. Therefore, the performance degradation of coherent underwater
acoustic communication in the presence of wind is not caused by wind-induced envi-
ronmental noise or roughness increase, but rather by increased instantaneous channel
variation and reduced temporal coherence. Moreover, for coherent acoustic communi-
cation, the negative influence caused by time-varying is greater than positive influence
caused by wind-induced sea roughness.

5.4.2 Non-coherent communication

Figure 5.8 shows the bit error rate performance of the underwater acoustic
communication system in no-wind, static rough surface, and wind surface scenarios for
the acoustic MFSK \((M = 4)\) system. The data rate here is 100 bps and the associated
symbol duration is 20 ms, while the multipath delay of the water tank channel is more
than 80 ms (Fig. 5.2), which is the longer than the symbol duration. First, comparing
the no-wind and windy surface scenarios, the BER performances for both are very
similar, both decrease with the increase of SNR, and eventually remain at 0.04 when
\(E_b/N_0 > 20 \text{ dB}\). One can see that the wind-driven surface waves in the laboratory
water tank environment have little effect on the performance of MFSK non-coherent
communication systems. Second, comparing the no-wind and static rough surface
scenarios, the stationary, rough surface boundary in the static rough surface scenario
improves the BER performance of non-coherent communication systems. When the
SNR is low \((E_b/N_0 < 6 \text{ dB})\), the performance of the static rough surface scenario is
similar to that of the no-wind scenario, but with the increased SNR, the BER of the
static rough surface scenario decreases rapidly and reaches zero error at \(E_b/N_0 = 18\)
Figure 5.8: The bit rate performance curve for the MFSK \((M = 4)\) communication system at a 100 bps communication rate in a laboratory tank environment. The three curves represent three different surface boundary scenarios, namely, no wind (NW), static rough surface (RS) and wind (WS, wind speed \(W = 5.5 \text{ m/s}\)) scenarios.

dB. Finally, comparing the static rough surface and windy surface scenarios, the MFSK underwater acoustic communication system exhibits better system performance in the static rough surface scenario than in the windy surface scenario. Though the roughness of the two surface boundaries is different, channel time-variant may have a negative impact on non-coherent communication systems.

As seen in Fig. 5.8, the time-varying surface fluctuation caused by the surface
wind in the laboratory tank environment has little influence on the performance of the non-coherent communication system when the symbol duration is much shorter than the channel multipath delay. In the no-wind scenario, due to the influence of inter-symbol interference generated by the multipath delay of the underwater acoustic channel, the MFSK system cannot complete the correct frequency demodulation even under the high SNR condition. In the windy-surface scenario, the time-varying, rough surface boundary fluctuations caused by the surface wind did not significantly affect the performance of non-coherent communication systems. In the static rough surface scenario, the performance of the non-coherent underwater acoustic communication system is greatly improved due to the reduced channel multipath energy and the shortened delay, which significantly reduces the inter-symbol interference.

Figure 5.9 shows the bit error rate performance of the MFSK \((M = 4)\) underwater acoustic communication system at 20 bps for the communication rate, in the no wind (NW), static rough surface (RS), and windy surface (WS) scenarios. In the case that the symbol duration (100 ms) of MFSK system is greater than the channel multipath delay (about 80 ms), the performance of the MFSK system in three different scenarios is significantly different. When the received SNR \(E_b/N_0 < 30\) dB, the bit error rates of the three scenarios are reduced with the increase of the received signal-to-noise ratio (BER: NW > WS > RS; decreasing trend: RS > WS > NW).

When \(E_b/N_0 = 13\) dB, the bit error rate of the no-wind scenario is about 0.1, the wind scenario is 0.02, and the static roughness scenario is \(3 \times 10^{-4}\). When the received signal-to-noise ratio is in the range of \(20 \text{ dB} < E_b/N_0 < 34\) dB, the BER of the no-wind scenario decreases rapidly with the increase of SNR, while the BER of the wind scenario remains at the same order of magnitude (about 0.001), does not vary significantly with the signal-to-noise ratio. When \(E_b/N_0 = 35\) dB, the no-wind and windy surface scenarios have similar bit error rates \((10^{-3})\), but the static rough surface scenario has reached zero error. Particularly, for the no-wind scenario, when the signal-to-noise ratio \(E_b/N_0 < 20\) dB, the bit error rate changes slowly with the increase of SNR, but when \(E_b/N_0 > 20\) dB, the bit error rate decreases rapidly after. For the windy-surface
Figure 5.9: The bit rate performance curve for the MFSK ($M = 4$) communication system at a 20 bps communication rate in a laboratory tank environment. The three curves represent three different surface boundary scenarios, namely, no wind (NW), static rough surface (RS) and wind (WS, wind speed $W = 5.5$ m/s) scenarios.

scenario, the bit error rate drops rapidly before the signal-to-noise ratio $E_b/N_0 < 20$ dB, but then remains within in the same level (about 0.002). For static rough surface scenario, the bit error rate decreases rapidly with the increase of SNR, and reaches zero error at $E_b/N_0 = 15$ dB. When the received signal-to-noise ratio is high ($E_b/N_0 > 40$ dB), the bit error rate of the wind surface scenario and the static rough surface scenario are both zero, while the error of the windy surface scenario increases with the
signal-to-noise ratio, ending at about $10^{-3}$.

The effect of wind speed on the performance of non-coherent communication systems is less pronounced than that of coherent communication systems. Rough surface roughness caused by wind waves improves or decreases the performance of non-coherent communication systems, which also depends on a number of other conditions, such as the relationship between the symbol width and the multipath delay of the channel, or the received signal-to-noise ratio of the system.

### 5.5 Discussions

Two classical and representative underwater acoustic communication modulation schemes (MFSK and QPSK) were tested and analyzed in a three surface boundary scenarios, i.e., no-wind and static rough surface and windy surface scenarios through a laboratory simulation experiment platform with controllable environment variables. Results show that the time-varying roughness boundary caused by wind-driven surface waves will lead to the performance degradation of the coherent water acoustic communication system (Figs. 5.6 and 5.7), while the performance of the non-coherent underwater acoustic communication system is less influenced (Fig. 5.8), and there can be a slight performance increase (Fig. 5.9) with low signal-to-noise ratio and longer symbol delay than channel multipath. Acoustic channel analysis revealed that in the windy surface scenario, surface boundary condition becomes rougher and more dynamic due to surface winds, and received acoustic signals experience a smaller surface-returned energy, a stronger channel variation (Fig. 5.4) and a lower temporal coherence (Fig. 5.5). Here, the effect of the wind as a common physical environment variable on underwater acoustic and underwater acoustic communication systems is further discussed.

First, the results of QPSK underwater acoustic communication experiment obtained in the lab water tank experiment are in agreement with the previous simulation results [26], and the other sea test results [29, 79, 80], on the negative correlation between surface wind speed (or sea state) and the performance of underwater coherent acoustic communications. However, based on the analysis of the experimental results
from no-wind, static rough surface and windy surface scenarios, we did not fully agree with some previous research on the explanation of the adverse effects of wind and waves on coherent communications. For example, van Walree [29] claimed the main reason for the decrease in the coherence of underwater acoustic communication was due to winds/waves is the decrease of the coherent energy of the signal caused by the increase of environmental background noise and the increase of sea surface roughness. Results show that, on the one hand, the effect of wind noise on the performance of coherent underwater acoustic communication is far less than that of wind-induced time-varying sea surface roughness. In the laboratory tank experiments, the wind-induced background noise is small. However, previous research [89] showed that wind-induced noise is mainly concentrated at low frequencies (10 kHz or less), which will not have a significant impact on the performance of medium and high frequency underwater acoustic communication systems. Therefore, the increase of wind-induced noise is not the main cause of deterioration of coherent communication performance. On the other hand, comparing the demodulation constellation and the BER curve (Figs. 5.6 and 5.7), one can see that the increase of the static roughness not only does not reduce the performance of coherence communication system. Instead, it improves the performance. In addition to the increase of roughness, the wind generated by the wave has a higher time-varying, affecting the stability of signal phase in the coherent communications, destroying the coherent communication system underwater acoustic signal coherence required for demodulation. Therefore, the increase of channel variability and the decrease of signal correlation are the main reasons for the negative correlation between the sea surface wind velocity and the performance of the coherent water acoustic communication in the sea-trial experiment of the coherent communication system.

The experimental results show that the time-varying rough boundary caused by the wind does not significantly reduce the performance of non-coherent underwater acoustic communication. Under some certain condition (based on symbol duration and SNR), the performance of incoherent underwater acoustic communication systems may be improved to a certain extent. The results of the MFSK underwater acoustic
communication experiment in the water tank experiment environment also agree that the non-coherent modulation method of the underwater acoustic channel environment is more robust. Non-coherent communications are energy-based. As long as the energy of the direct signal is strong enough, the small multipath energy fluctuation caused by wind-driven waves only interferes with the demodulation of the next symbol to a certain extent, but not significant enough to affect the overall performance of the system. (Fig. 5.8). Therefore, the performance of the MFSK underwater acoustic communication system is more complicated than that of the QPSK and other coherent communications. In some cases, the performance of the MFSK is enhanced with the increase of the surface waves (Fig. 5.9); while in other cases, the effect of wind waves on the performance of incoherent underwater acoustic communication is not clear (Fig. 5.8). As a result, the influence of wind waves on the performance of incoherent communication systems may be masked by other environmental influences (variation of water-column properties). For example, Pu et. Al. [82] reported that the Benthos ATM-885 underwater acoustic modem (using MFSK modulation) has a better performance in the presence of wind conditions in a sea trial, but the experiment results were not further investigated or discussed. However, in another study [81], the MFSK modulation method achieved better performance at lower wind speeds than in the case of high wind speeds, but the author concluded that the results mainly by the change in the sound speed. In short, the adverse impact of wind and waves on non-coherent communication system is less significant, whose performance is more robust in time-varying underwater acoustic channels.

Third, the influence of wind waves on the performance of the underwater acoustic communication system is closely related to the underwater acoustic communication modulation and signal processing methods. Results from the water tank experiment showed that the non-coherent underwater acoustic communication systems are more robust than the coherent system when influenced by surface winds and waves. The main results are as follows: On the one hand, non-coherent communication systems based on energy detection is not sensitive to the change of the underwater acoustic
channel influenced by surface winds and waves, so it is more robust than the coherent system based on phase detection. On the other hand, the study [72] showed that the phase fluctuation is more significant than the amplitude fluctuation caused by wind waves, so that it is easier for non-coherent underwater acoustic communication systems based on amplitude detection than for the coherent underwater acoustic communication based on phase detection to deal with channel variations in a wind-wave environments. Therefore, the wind speed can be used as one of the environmental parameters for the next-generation intelligent underwater acoustic communication systems to help the system select a more appropriate communication modulation mode in the actual time-varying marine environment. For example, when the wind is below a certain speed, the system automatically chooses to coherent communication method to make full use of the effective bandwidth and obtain a higher communication rate; When the wind is higher than a certain speed, the system switches to non-coherent communication mode to perform reliable transmission of underwater information. In addition, the concept that wind waves have different performance effects of different modulation modes is very important for underwater acoustic network simulations as well. The impact of wind-driven surface waves depends on the modulation methods used by the physical layer, which should be treated differently. Some previous studies on network protocols or simulation channel equalization algorithms simply treated wind speed as one of the environmental variables. However, they only considered the influence of wind-induced environmental noise, not the effect of a time-varying rough surface boundary on underwater acoustic channels and underwater acoustic communication modulations. Therefore, the obtained network performance results were not accurate. As mentioned earlier, for coherent underwater acoustic communication, the noise effect caused by the wind is much less than the effect of time-varying roughness caused by the wind. Therefore, future simulation studies need to consider the effects of time-varying roughness caused by winds in different modulation methods.
Finally, in the real marine environment, the wind effect on underwater communications is more complicated than the effect of wind-induced surface reflection on acoustic communication performance based on our results. In our water tank experiment, only the influence of surface boundary variation on the performance of underwater acoustic communication under the condition of uniform wave growth was considered, but the ocean wind wave involves many complicated marine environmental variables. For example, a consistent, strong wind blowing on the sea surface will increase water mixing, deepening the thermocline, and thus affecting the speed of sound profile, and ultimately change the entire underwater sound field and channel multipath structure completely. On a larger time scale, the changes in the water column (e.g., temperature or salinity variations) may exceed the effect of wind-induced time-varying sea-surface roughness and completely alter the underwater sound field (as reported in [81, 76]). Besides, the high-speed conditions of the wave breaking and underwater bubble generation, scattering, absorption of sound energy, resulting in the further multipath energy losses at the receiver end. Though in the laboratory water tank environment, the wind waves are small and there is no wave breaking or bubble forming, research showed that the influence of air bubbles on the underwater acoustic channel is mainly increased energy attenuation and increased background noise. Therefore, the underwater air bubbles caused by wind and waves will also lead to multipath energy attenuation, reduce the signal to noise ratio of the received signal. In addition, Bubbles motion and breaking will produce a certain channel instantaneous change. Based on our results from time-varying surface waves, it can be deduced that air bubbles may have a negative effect on the coherent underwater acoustic communication system, but does not affect much on the performance of incoherent underwater acoustic communication systems. This conclusion will be further studied in the future.

5.6 Conclusions

In this paper, a controllable experimental environment was constructed, and a laboratory tank experiment was used to investigate the problem. The goal of this
paper was to explore the effect of wind-induced time-varying sea surface on coherent and non-coherent underwater acoustic communication modulation schemes through a controllable method and analyze the performance of the two modulation methods in response to surface winds and waves. Results show that the influence of the wind on coherent and non-phase acoustic communication is very different: the performance of coherent underwater acoustic communication decreases remarkably with the increase of wind speed, which is mainly due to the increased channel variability and the reduced signal temporal coherence under high wind speed; and the presence of wind does not result in a significant decrease in the performance of non-coherent communication due to its less sensitivity to the channel variability, and in some cases, smaller multipath reflected signals at high wind speed can even increase the performance of non-coherent communications.

The influence of the wind on the underwater acoustic communication includes two aspects: on the one hand, the increase of roughness, on the other hand, increases the time-varying channel variability. The increase of roughness is beneficial to communication, while the increase of time-varying is not. Coherent communication is much more sensitive to time-varying channel variability than non-coherent communication. Coherent communication performance degraded under wind waves, while non-coherent communication performance remained unaffected, but performance may be improved due to increased roughness. Therefore, in the presence of wind, non-coherent communication can guarantee the higher reliability of the system, especially when the SNR is low; In the absence of wind conditions, switching to coherent communication mode can take full advantage of effective bandwidth to achieve a higher transmission rate. This study is helpful for guiding the design of underwater acoustic communication system, such as to assist the selection of communication modes according to the present wind-wave condition. However, the relationship between the performance of different wind speed, especially the effect of the bubble forming under high wind speed, still needs to be further studied.

Future study may include following aspects. Since the tank channel is still very
different from the actual ocean time-varying environment, the performance variation of underwater acoustic communication due to the wind effect in the real ocean should be studied. Also, the impact of the wind on many sub-components of the communication system will be investigated, such as synchronization, signal detection, and channel equalization schemes of coherent underwater acoustic communication systems.
Chapter 6
CONCLUSION

The reliable acoustic communication in a highly time-varying ocean environment is an extremely challenging research topic. Because underwater sound propagation is closely related to the physical processes and water dynamics of the ocean, underwater acoustic communication research should not be isolated from the variability of the physical environment. However, it was treated as a separate research topic under electrical engineering, which lacks consideration of the nature of the physical ocean and hinders the development of underwater acoustic communication systems. This dissertation focused on the link of underwater acoustics with the physical environment. Studying the sound propagation in estuaries, where environmental variability is strong due to the interaction between the freshwater and seawater, can significantly help the understanding of underwater acoustic channel characteristics and the design of next-generation underwater acoustic communication systems. Field experiment data analysis, integrated numerical modeling, and a laboratory experiment were combined together to study the internal link between physical oceanography, ocean acoustics and underwater acoustic communications in a shallow tidal-straining estuary.

On the environmental variability of underwater acoustic channel in a tidal-straining estuary, acoustic direct path and surface-bounced paths were found affected by very different time-varying physical processes: (a) Influenced by tidal water dynamics, acoustic direct paths exhibit periodical intensity fading, as a result of water column variation (water mixing and stratification) in a tidal-straining estuary. (b) Affected by surface winds and waves, the pressure amplitude of acoustic surface-bounced paths is highly correlated with surface wind speed, as a result of increased wind-driven
surface roughness at high winds significantly scattering away the acoustic energy of surface-bounced paths.

On the link between the environmental variability and underwater acoustic communications, the effect of the fast fluctuation of wind-induced surface waves on the performance of underwater acoustic communications was investigated. Numerical modeling and laboratory experiment results suggested that, the increase roughness at high winds is beneficial for the system performance; while the increased channel variability is not. How wind-driven surface waves influence the performance of underwater acoustic communication is a result of the competition between these two factors: (a) For coherent acoustic communication, the system performance may decrease remarkably with increasing wind speed, due to the increased channel variability and the reduced temporal coherence; (b) For the non-coherent acoustic communication, the system performance may not decrease because the non-coherent modulation is less sensitive to the channel variation, and moreover, the performance of non-coherent communication may improve at high winds because of the reduced multipath energy.

This dissertation focused on the relationship between physical oceanography, ocean acoustics and underwater acoustic communications. Each of the four research questions in this dissertation represents an additional small step towards the goal of this relationship. To fully understand the influence of time-varying environment on acoustic communication, it is necessary to continue to develop integrated numerical models that can handle physical oceanography, ocean acoustics and underwater acoustic communications at the same time. Considering the great potential and future applications of underwater acoustic communication and underwater acoustic network, the link between physical oceanography, ocean acoustics and underwater acoustic communications deserves more attention and further study.

Future study includes but is not limited to the following aspects: Explore the link with field experiment that including data from long-term ocean observations, underwater acoustic transmissions, underwater acoustic communications; Study the influence of time-varying characteristics of marine environment on more underwater acoustic
communication schemes; Study the influence of time-varying characteristics of marine environment on individual components in an underwater acoustic communication system, such as synchronization, signal detection, equalization, etc.
BIBLIOGRAPHY


Appendix A

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Title: Modeling acoustic coherent communication under wind-driven ocean surface waves

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