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Modeling Acoustic Coherent Communication Under Wind-Driven Ocean Surface Waves

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***Abstract*—Wind raises time-varying roughness on 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.**

Keywords*—acoustic communication; modeling; surface waves; underwater acoustic channel; wind effects

I. 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 [1], [2]. 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 [3]–[5]. Though coherent schemes can achieve a better data rate during transmission, espcially 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 [6]. Designing better coherent communication systems requires a better understanding of the physics of shallow-water acoustic channels and the variability of nature water environement [7].

For shallow waters, the variability of underwater acoustic channels stems from temporal and spatial variations of the water environment [2]. 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 [8]. 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 [9]–[12]. For high-frequency shallow-water acoustics, the signal variability may become even more complicated due to multiple reflections between surface and bottom boundaries [13].

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 [9]. 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 [14], as different ocean wave conditions can lead to different acoustic reflections at the surface bournday. However, thorough understanding of the effects from winds to ocean waves, and further to acoustics has not been fully addressed in the past, which can be only explored by anlysis 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 were 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.

II. Modeling Methods

The flow chart of our modeling is illustrated in Fig. 1. The system is comprised of a wind-impacted acoustic channel

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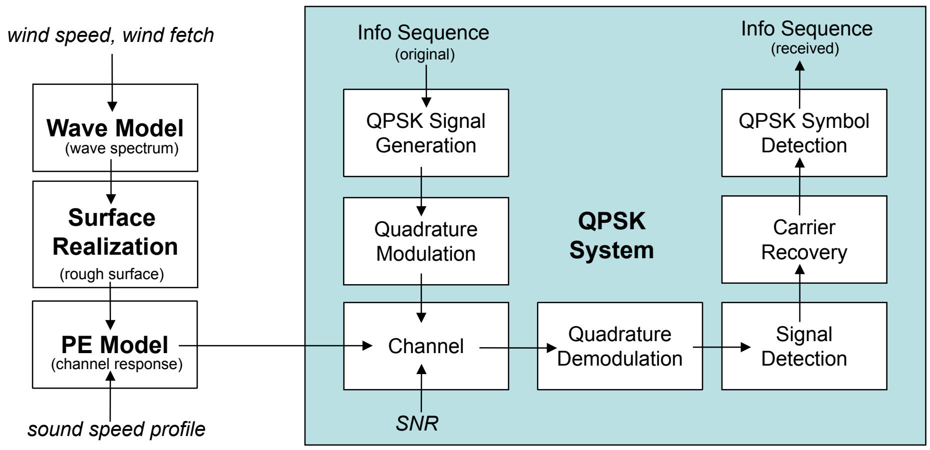

Fig. 1. The structure of our modeling system. The whole system includes a combining wind-induced underwater acoustic channel simulator (the wave model, surface realization model and the PE model) and a to-be-tested communication system, which is QPSK in this study.

simulator and an acoustic communication system. The acoustic channel simulator transforms surface wind information into time-evovling 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.

A. *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. 1). This acoustic channel simulator has been used in previous studies to investigate effects of surface winds on time-varying acoustic propagation [15], [16]. 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 filed with rough surface boundary.

First of all, the spectrum of wind-dirven surface waves was generated by a wave model based on environmental variables. The wind-wave spectral method adopted here was the TMA model [17]. TMA is an empirical wind-driven ocean wave model, particularly optimized for shallow waters. It estimates the theoritical 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 disspation due to limited water depth [18]. 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 [16]. 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

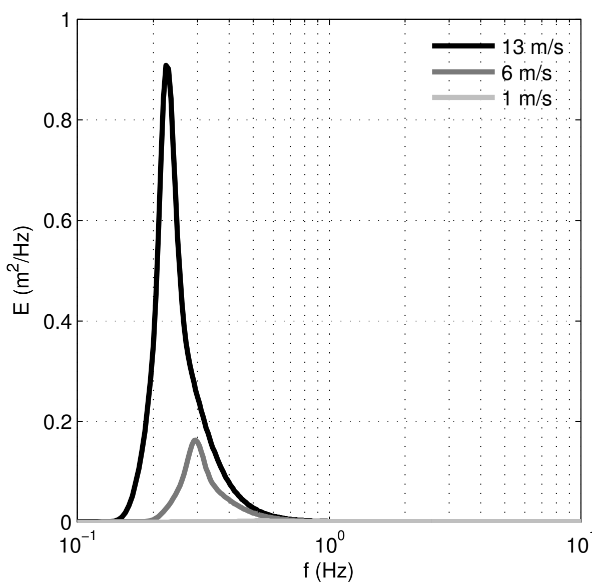

Fig. 2. Surface wave spectral modeling using TMA spectra with a fixed fetch (F = 30 km) and a shallow water depth (h = 15 m) for different wind speeds (U_{10} = 1, 6, 13 m/s).

sea surfaces was realized by a surface model [19]. The surface model converts a frequency-dependent wave spectrum to surface wave heights using Fourier transform pairs. Furthermore, due to the nature evolution of ocean waves, this problem is a time-evolving problem, where the following surface wave is related to the previous surface wave. For such wave evovlution, this model initializes random phases for the first surface; For following surface elevations, the model adpots Rung-Kutta integration alogrithm to step in time from the previous surface roughness [19]. 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.

Finally, acoustic pressure fields were constructed by a 2-D rough-surface parabolic equation (PE) model [15] with

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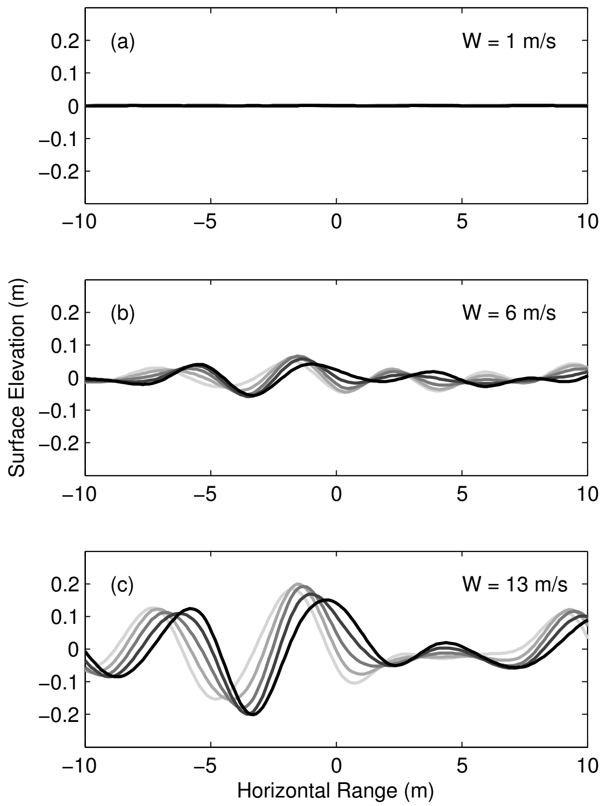

Fig. 3. Simulated time-evolving ocean surface waves from the TMA spectra as in Fig. 2.

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 [15]. 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 [15].

B. 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 [2], [5], [16]. 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) [5]. 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 [6]).

The QPSK system was demostrated in the box of Fig. 1. The transmittor 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: qudrature 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 (preset, known) is used to process the finetime sychronization 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. 1) between the whole transmitted signal, $s(t)$, and the channel impluse response, $h(t)$.

$$x_S(t) = (s * h)(t) = \int_0^T s(t) \cdot h(t-\tau) d\tau \qquad (1)$$

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

$$x_E(t) = \sum_{n=0}^{N} (s_n * h_n)(t) = \sum_{n=0}^{N} \int_0^T s_n(t) \cdot h_n(t-\tau) d\tau \quad (2)$$

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.

III. Modeling Results

In this section, QPSK system was tested with wind-impacted shallow-water acoustic channels using our proposed structure (Fig. 1). For each wind speed, we calculated one surface wave spectrum, generated a series of time-evovling surfaces, and simulated the associated acoustic channel responses. Then, with each acoustic channel response, we ran multiple communication tests with different SNRs.

A. Enrionmental and channel variability

Figure 2 shows surface wave spectra for three different wind speeds (1, 6, and 13 m/s) using the TMA model. For these

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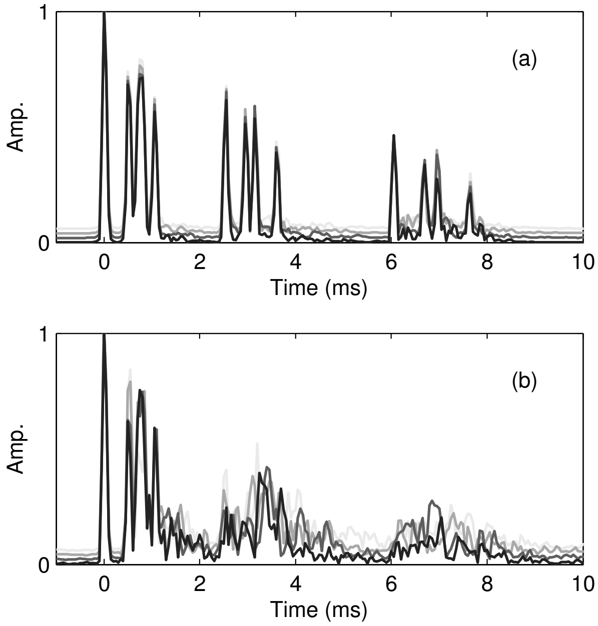

Fig. 4. Acoustic channel impulse responses from 2D rough-surface PE based on time evolving surfaces at different wind speeds: (a) W = 1 m/s, and (b) W = 13 m/s. The black line is the channel response for the original surface, while the line with lighter colors are those for consequential evolving surfaces. The time span for the evolving surface simulation is 0.2 s.

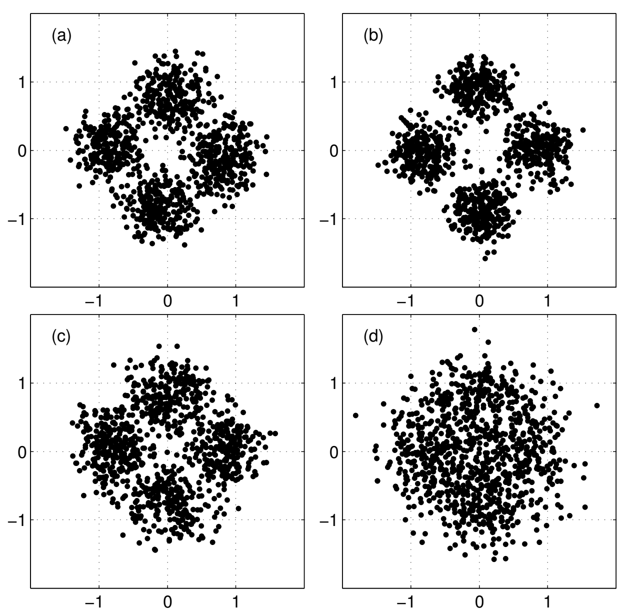

Fig. 5. Constellation of the QPSK demodulation. (a) W = 1 m/s, static scenario; (b) W = 13 m/s, static scenario; (c) W = 1 m/s, time-varying scenario; (d) W = 13 m/s, time-varying scenario. For these simulations, the QPSK bits rate of 500, and the SNR of 0 dB. For the time-varying scenario, the resolution between two surface is 0.2 s.

three cases, the wind fetch was 30 km and the water depth was 8 m. From Fig. 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 m^2/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 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. 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 surface evolutions, 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 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, the first peak is the direct path, while the following energy componets are all surface-related acoustic paths. Results showed that the surface paths have a relative high amplitude at low winds, and also, the fluctuation in time is relative 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.

B. *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. 5. For a static surface scenario, the high wind case has a better seperation in the constellation diagram than the low wind case [Figs. 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. 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. 5 (b) and (d)]. The demodulation constellation for a time-evovling surface become much worse than a static surface, even both scenarios had the same roughness level. In addition, comparying Figs. 5 (c) and (d), the demodulation was worse at high wind speed than at low wind speed when the surface evovlution in time was considered.

Figure 6 shows the bits error rate (BER) for two wind speeds (1 m/s and 13 m/s) in two surface scenarios with the

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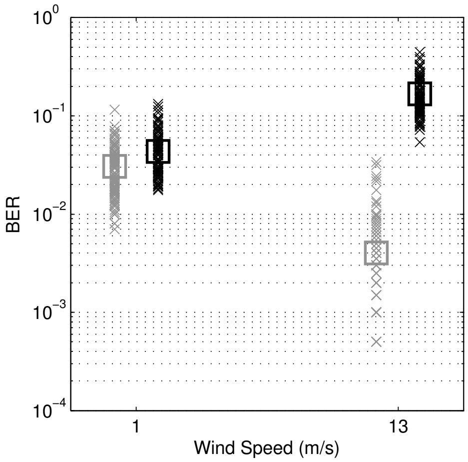

Fig. 6. Modeling results of QPSK system performance for two different wind speeds (1 m/s and 13 m/s) with two different surface scenarios. The grey color is for the static scenario; while the black color is for the time-varying scenario.

SNR of 0 dB. For low wind case, the BER for both surface scenarios are 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-evovling case had a degraded performance. The BER for the non-evolving surface was 0.010, and that for 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.

IV. Discussions

Modeling resutls indicated that, as wind speed increases, surface roughness and wave viariability increases (Figs. 2 and 3), and the acoustic channel exhibits decreasement in energy and increasement in variability for surface-related sound paths (Fig. 4). Also, the performance of acoustic coherent communication systems improves as increasing surface wind speed in static rough surface scenario; however, it decreases in time-varying rough surface scenario (Figs. 5 and 6).

Two completely opposite wind-dependent relationships were found from our numerical modeling resutls (Figs. 5 and 6). We proposed that the time-evolving approach was a more realistic scenario for underwater acoustic communications, e.g. Fig. 5 (c) and (d). On one hand, previous field experiment [20] 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 rough surface boundary, time-varying acoustic channel 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 increasing roughness does not degrade the performance of acoustic communication systems [Fig. 5 (a) and (b)]; Instead, it can improve the performance by providing an simplier multipath structure for underwater acoustic communication. Considering an extreme case, if the surface boundary is extremely rough and all surface energy are completely scatterred away, there will be very little surface return which leaves only a strong direct path component, which is perfect for communication system. The temporal variability, however, can degrade the system performance by failing the carrier recovery and channel equalization. For this reason, coherent communication system requires well-desgined channel adpative methods whose reaction time should be shorter than the coherence time of the physical channel [6]. 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 invevitable 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 [11], [16].

V. 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, 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.

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References

[1] D. B. Kilfoyle and a. B. Baggeroer, "The state of the art in underwater acoustic telemetry," *Oceanic Engineering, IEEE Journal of*, vol. 25, no. 1, pp. 4–27, 2000. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=820733

[2] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *Communications Magazine, IEEE*, vol. 47, no. 1, pp. 84–89, 2009.

[3] D. Rouseff, M. Badiey, and A. Song, "Effect of reflected and refracted signals on coherent underwater acoustic communication: results from the Kauai experiment (KauaiEx 2003)." *J. Acoust. Soc. Am.*, vol. 126, no. 5, pp. 2359–66, Nov. 2009.

[4] J. C. Preisig and G. B. Deane, "Surface wave focusing and acoustic communications in the surf zone," *J. Acoust. Soc. Am.*, vol. 116, no. 4, p. 2067, Oct. 2004.

[5] J. C. Preisig, "Performance analysis of adaptive equalization for coherent acoustic communications in the time-varying ocean environment," *J. Acoust. Soc. Am.*, vol. 118, no. 1, p. 263, 2005.

[6] L. Freitag, M. Stojanovic, S. Singh, and M. Johnson, "Analysis of channel effects on direct-sequence and frequency-hopped\nspread-spectrum acoustic communication," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 586–593, 2001.

[7] T. C. Yang, "Properties of underwater acoustic communication channels in shallow water." *The Journal of the Acoustical Society of America*, vol. 131, no. 1, pp. 129–45, 2012. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/22280578

[8] R. Stewart, *Introduction to Physical Oceanography*, 2008, no. September.

[9] L. Brekhovskikh and Y. Lysanov, *Fundamentals of ocean acoustics*, 2003.

[10] P. H. Dahl, "On bistatic sea surface scattering: Field measurements and modeling," *J. Acoust. Soc. Am.*, vol. 105, no. 4, p. 2155, 1999.

[11] ——, "High-frequency forward scattering from the sea surface: the characteristic scales of time and angle spreading," *IEEE J. Ocean. Eng.*, vol. 26, no. 1, pp. 141–151, 2001.

[12] G. B. Deane, J. C. Preisig, C. T. Tindle, A. Lavery, and M. D. Stokes, "Deterministic forward scatter from surface gravity waves." *J. Acoust. Soc. Am.*, vol. 132, no. 6, pp. 3673–86, Dec. 2012.

[13] M. Badiey, J. Simmen, and S. Forsythe, "Signal variability in shallow-water sound channels," *IEEE J. Ocean. Eng.*, vol. 25, no. 4, pp. 492–500, Oct. 2000.

[14] P. a. Van Walree, "Propagation and scattering effects in underwater acoustic communication channels," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 4, pp. 614–631, 2013.

[15] J. Senne, A. Song, M. Badiey, and K. B. Smith, "Parabolic equation modeling of high frequency acoustic transmission with an evolving sea surface." *J. Acoust. Soc. Am.*, vol. 132, no. 3, pp. 1311–8, Sep. 2012.

[16] Z. Zou and M. Badiey, "Effects of Wind Speed on Shallow-Water High-Frequency Acoustic Transmission," *IEEE Journal of Oceanic Engineering*, vol. in preparation, pp. 1–12, 2015.

[17] S. Hughes, "The TMA shallow-water spectrum description and applications," Tech. Rep., 1984.

[18] E. Bouws, H. Gonther, W. Rosenthal, and C. L. Vincent, "Similarity of the Wind Wave Spectrum in Finite Depth Water," *Journal of Geophysical Research: Oceans*, vol. 90, pp. 975–986, 1985.

[19] C. Bayindir, "Implementation of a computational model for random directional seas and underwater acoustics," Ph.D. dissertation, University of Delaware, 2009.

[20] P. A. van Walree, J. A. Neasham, and M. C. Schrijver, "Coherent acoustic communication in a tidal estuary with busy shipping traffic." *J. Acoust. Soc. Am.*, vol. 122, no. 6, pp. 3495–506, Dec. 2007.