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Analysis of acoustic channels with a time-evolving sinusoidal surface

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ABSTRACT

Sea-surface movement in the ocean induces a time-varying acoustic channel which affects underwater system including acoustic communication. For an investigation of surface movement effects on communication channel parameters (delay time, amplitude, etc.), acoustic transmission and reception experiments were conducted in the water tank. The delay time and amplitude of single surface bounce path from the measurement data show periodic time dependence, which is caused by a travelling periodic sinusoidal surface. A ray-based propagation model is applied to the experimental environment to estimate communication channel parameters. A comparison between measurement data and model result permit a physical interpretation of the communication channel parameters. The difference of single surface bounce path delay times from the model and measurement data are within small error bound. The delay times oscillate around the delay time of single surface bounce path when the surface is flat and show the periodic sine function. The amplitudes from the model are in agreement with those from the measurement data except at low amplitude region. Slight angle and frequency dependencies of source and receiver and noise in the water tank account for the disagreement in this region. Since the crest and trough of surface wave respectively make the acoustic energy emitted from the source converge and diverge, the amplitudes have high fluctuation and same phase with the delay time. The ray model is applied to an environment in the ocean. A striation pattern appears in surface reflected signal due to shadow zone on the surface.

1. Introduction

The ocean surface is irregular and is in constant motion, causing a time-varying acoustic channel with Doppler shift and is important for underwater acoustic communication. In particular, the arrival time and amplitude of surface reflected ray change as the sea surface evolves. In this work, to investigate moving surface effects on communication channel parameters, acoustic transmission and reception experiments were conducted at Seoul National University (SNU) water tank and time-varying acoustic channels are observed according to source frequencies, 20 kHz and 30 kHz. They are compared with ray model results.

Many studies on sea surface effects on acoustic channel have been performed. Randomly rough sea surface effects are investigated with scattering strength, which is evaluated through experiment or scattering theories [1,2]. Otherwise, measured or numerically simulated acoustic channels are used to study travelling sea surface effects. Parabolic equation is used to model high frequency acoustic transmission with an evolving sea surface [3]. Siderius and Porter [4] used a ray-based model to investigate the Doppler effect introduced by sound interacting with the moving surface. On the other hand, in situ data showed rapid changes of acoustic channels because of time-evolving regular surface wave, which acts as an acoustic lens and leads to focusing and caustics [5]. When the acoustic channels changed rapidly, signal estimation residual error increases and it becomes hard to operate these underwater acoustic communications systems. For operating the underwater system in an environment with travelling surface wave, time-varying acoustic channels, caused by the moving surface, need to be understood. Tindle et al. [6,7] developed a time domain wave front propagation model which is able to consider a regular surface wave and simulated focusing and caustics by the surface wave. Subsequently, small scale tank experiments were conducted to measure acoustic signals reflected by regular surface waves, which also show focusing and caustics as expected [8]. Even though the environment had an irregular surface gravity wave, focused arrivals from the surface existed [9]. Acoustic transmission and reception experiments were conducted in the ocean. Measurement data showed travelling surface wave caused Doppler and delay spreading in surface reflected signals [10]. Other in situ data also showed time-varying acoustic channels, which had striation patterns in surface reflected signals [11]. The striation patterns depended on the direction of acoustic propagation relative to the direction of surface wave. van Walree [12] conducted systematic measurements of shallow water acoustic channels to observe their

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features for applications in underwater communication. A definition of typical acoustic channels is difficult because of their varieties. Bubbles and turbulence effects as well as 3-D scattering in the ocean make acoustic channels more complicated and harder to predict [13]. Complexities and rapid variations of acoustic channels are detrimental to the operation of underwater system including acoustic communication. The underwater system performance considerably depends on the variability of acoustic channel [14] and continuous acoustic channel updates along with Doppler tracking are required in order to track channel fluctuations [15]. As mentioned above, simulated acoustic channels show features of measured time-varying acoustic channels and thus the system performance in time-varying environment are examined using the simulated acoustic channels. Peterson and Porter [16] developed ray-based acoustic propagation model considering motions of source/receiver and surface wave. Dol et al. [17] simulated acoustic channels characterized by wind-generated surface wave and bubbles.

In this work, acoustic signal transmission and reception experiments are conducted in a well-controlled water tank to investigate surface movement effects on communication channel parameters. The time-varying acoustic channels from the measurement data are compared with those from ray-based propagation model to analyze the surface movement effects. In Section 2, the environment of SNU water tank is described and the experimental results are shown. In Section 3, the features of ray theory and the formulation of ray tracing for a time-evolving surface wave are introduced. In Section 4, delay time and amplitude of single surface bounce path from the measurement data and moving surface ray model are compared; they directly reflect the effects of moving surface and these fluctuations cause the Doppler shift. The features of the time-varying acoustic channels (relation between the delay time and amplitude, frequency dependence of acoustic channels, etc.) are analyzed. Section 5 provides a summary of the present work.

2. The tank experiment

For an investigation of surface movement effects on communication channel parameters, acoustic transmission and reception experiments are conducted at SNU water tank at 20 kHz and 30 kHz source frequencies. Delay time/amplitude and frequency dependence of surface reflected signal are observed. The planar dimensions of tank is 8 m × 110 m. B&K 8105 and 8103 hydrophones were used as source and receiver respectively. Their depths are nominal 1.5 m and 1.1 m, respectively. The horizontal range between source and receiver is nominal 3 m. The water depth is 3.5 m and the sound speed is measured at 1427 m/s. Actual locations of the source and receiver are adjusted by analyzing the difference between delay times of direct and single surface bounce paths measured when the surface is flat. Under the current experimental condition, the single surface reflected signal was discernable from other reflected signals from either the bottom or side walls of the tank. Thus, the delay times and amplitudes of single surface reflected signals can be extracted from the measured acoustic channel impulse responses. During the experiments, a monochromatic and smooth surface wave representing a swell is generated referring to the work by Tindle et al. [8]. Its wave height, wavelength, and the period were 0.08 m, 3.51 m and 1.5 s, respectively.

20 kHz and 30 kHz binary phase shift keying (BPSK) signals were used as the source signals and transmitted continuously to observe time-varying acoustic channels. The received signal for each case was recorded for 5 s. The sampling frequency was 200 kHz. Matched filter is used to estimate the channel impulse responses. It is important to choose a symbol length of source (or source duration) which determines the longest delay time of channel impulse response. In the experiments, the symbol length of source was chosen as 511, which prevents signal distortion by previous channel impulse response.

Fig. 1 shows the channel impulse responses for the 20 kHz and 30 kHz. Channel impulse response for each ping is plotted vertically as a function of delay time. The horizontal axis represents transmission times of pings. Reference delay time of channel impulse responses is the mean arrival time of direct rays whereas acoustic channel amplitudes are normalized by the mean amplitude of direct rays. The delay times of direct and bottom bounce paths are constant along transmission ping times since the path lengths do not change. On the other hand, delay times and amplitudes of single surface bounce paths show periodic time dependence, which corresponds to that of the surface wave. Since the surface is smooth due to small wave steepness, no diffracted signals are observed. Bottom reflected signals are more dependent on the source frequency than the direct or surface reflected signals because of frequency dependence of bottom loss.

3. Ray tracing for a time-evolving sinusoidal surface

Ray theory is efficient and accurate at high frequency. At the frequency used in the water tank experiment, the smooth surface wave in the experiment can be considered as sloping line and the sound emitted from the source is reflected by the line. The travelling surface simply alters the direction of these surface reflected rays. Diffracted signals cannot be simulated with the ray model. However, in the ocean, a small roughness on smooth surface wave causes scattered and diffracted signals, and sound speed reduction of near-surface region owing to bubble layer and sound speed variation in the water layer exist. Since no diffracted signals are observed in the measurement data from the experiment and the experimental environment has isovelocity sound speed profile, modelling these effects are beyond the scope of present work.

For an analysis of the measurement data, a propagation model capable of treating moving surface is developed. A ray tracing algorithm is derived to simulate an acoustic channel with a moving surface, by taking a ray tracing algorithm for a frozen surface and modifying it to allow surface motion [18].

Assuming the water medium to be horizontally stratified, the Eikonal equation of ray theory is equivalent to Snell's law. In addition, the sound speed of each layer varies linearly, in which case the ray in the medium follows a circular trajectory as illustrated in Fig. 2(a). With these assumptions, the trajectory, travel time, and travel distance of the ray are calculated analytically for each water layer [19].

The surface wave is the upper bound of the first water layer and the lower bound is located just below the lowest point of the surface as shown in Fig. 2(a). The sound speed variation in this water layer can be ignored due to relatively small wave height of the surface wave. Thus, the ray trajectory $(r_{ray}(t), z_{ray}(t))$ in the first water layer follows a straight line and satisfies the following equation.

$$z_{ray} = m(r_{ray} - r_0) + z_0, \tag{1}$$

where r_0 and z_0 are the initial range and depth of the ray in the first water layer and m is the tangent of the ray.

In this work, the surface wave is considered as sinusoid and represented as follows.

$$z_{surf}(r_{surf}, t) = a \sin(kr_{surf} \pm \omega t + \phi), \tag{2}$$

where a, k, ω, and ϕ are the amplitude, wave number, angular frequency, and phase of the surface wave. k and ω satisfy surface wave