Conceptual development of a dynamic underwater acoustic channel simulator

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ABSTRACT

The underwater acoustic communication channel is characterised by transient signal fading across multiple propagation paths and much greater time spread between first and last arrivals than in terrestrial wireless systems. At useful transmission distances of a few kilometres the channel is significantly bandwidth-limited in the tens of kHz by absorption at higher frequencies, and unlike most terrestrial wireless radio-frequency channels, relative transmitter/receiver motion and sea-surface motion leads to significant signal Doppler effects. A dynamic underwater acoustic channel simulator is being developed to test and improve the effectiveness of point-to-point signal transmission by underwater acoustic modem systems. The simulator will enable testing of modems and signalling strategies in diverse transient acoustic propagation and background noise conditions in a cost-effective manner. The purpose of this paper is to outline the modelling challenges that are being addressed.

INTRODUCTION

A broad range of marine acoustic communication technologies are continuing to be developed that rely on the underwater environment as the data carrier, generally referred to as the underwater acoustic channel. To some degree this follows the lead from the natural world, where marine fauna make extensive use of the underwater acoustic channel across a wide range of distances, depths and environments, for acoustic communication, navigation and foraging purposes.

Examples of developing applications include using the underwater channel to replace the data umbilical between a boat and a Remotely Operated Vehicle (ROV), data transmission from a monitoring network to a base-station, and a network of acoustically communicating Autonomous Underwater Vehicles (AUVs) for subsea exploration (Freitag et al., 2001).

In marine ecology, the underwater channel is being increasingly utilised to help track/detect marine animals with acoustic transmitter tags, and to detect or infer the location or abundance of vocalising marine animals such as cetaceans and fish.

This paper is concerned with the development of a dynamic underwater acoustic channel simulator, to simulate the attenuation, distortion and superposition with ambient noise as an acoustic communication signal travelling through the ocean between a source and receiver location over distances of the order of one kilometre. This process is represented schematically in Figure 1.

The primary application of the simulator for this project is to enable the future prototyping of underwater communications systems. The 'dynamic' aspect of the simulator refers to the simulation of transient ocean phenomena that alter acoustic propagation during a data transmission, often leading to decoding errors.
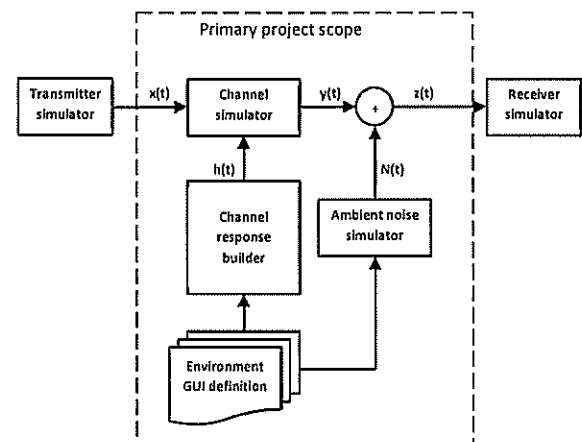

Figure 1. Schematic diagram for underwater acoustic channel simulator.

It is noteworthy however that a channel simulator may also be utilised as a tool to assist a wide range of ecological investigations, such as simulating the distortion/detection range of acoustic tag signals and mid to high frequency fauna vocalisations in diverse marine acoustic propagation environments. This is anticipated as an important additional application for the simulator beyond the current developmental stage project.

The remainder of this paper briefly outlines the underwater sound transmission phenomena that frame the underwater acoustic channel from a data-transmission perspective, and identifies those transient ocean phenomena that have been have been found problematic to the attainment of improved data rates and reliability of data transmission. Approaches to simulating these transient phenomena are discussed.

CHARACTERISTICS OF UNDERWATER ACOUSTIC CHANNEL FOR DATA TRANSMISSION

Sound speed and channel latency

Over a kilometre separation, a terrestrial RF transmission is delayed 3.33 microseconds by the medium propagation speed

of 3.0×10^8 m/s, compared with 0.667 seconds for a marine transmission over the same distance at 1500 m/s. Underwater sound channels are therefore described as having very high latency, which impacts on communication protocols involving signal acknowledgement from the receiver.

Ambient noise

Ambient noise levels in the ocean are highly variable in the dimensions of both space and time and significantly affect the detectability of data signals, by changing the ambient noise by a few orders of magnitude in the frequency range of interest.

The transient characteristics of ambient noise that need to be simulated include processes such as broad-band random high amplitude snapping shrimp noise emissions, diurnal fish chorus, transient broad-band noise from surface wave turbulence and surface bubble collapse, rain and high intensity propeller cavitation noise from vessel pass-bys.

Acoustic absorption

High acoustic absorption by bubble clouds associated with breaking surface waves can lead to significant transient attenuation of surface reflected acoustic waves. This begins to become significant for wind-driven waves at wind-speeds greater than 10m/s (Dahl, 2008), or for communications systems that operate in the surf zone (Farmer, 2001).

Whilst higher acoustic signal frequencies are generally able to transmit data more quickly due to the shorter modulation periods that are possible, the acoustic absorption in sea-water increases rapidly with sound frequency. Thus the selection of carrier frequency for a communication system is an optimisation between the benefits of a higher frequency for better data rates, and lower frequency for lower attenuation with distance.

Refraction and shadow zones

Unlike terrestrial radio-frequency (RF) systems, in the marine environment 'direct line of sight' between an acoustic transmitter and a receiver may not guarantee reliable reception. Warming of surface waters can produce a downward refracting depth dependent sound-speed profile on a seasonal or diurnal basis, resulting in a 'shadow' zone of poor reception relative to the transmitter. This zone may develop and disappear as the sound-speed profile evolves with time. An example sound speed profile for surface warming and the associated shadow zone, known as the "afternoon effect" during World War II, is illustrated in Figure 2.

Thus a simulator needs capability to model the influence of a time-evolving sound speed profile on the appearance and disappearance of reception shadow zones to enable evaluation of transmitter and receiver positions.

Changes to the sound speed profile over timescales of several hours have been reported to change the received signal strength as much as 10dB, as the signal field strength evolves with the sound speed profile (Siderius et al., 2007)
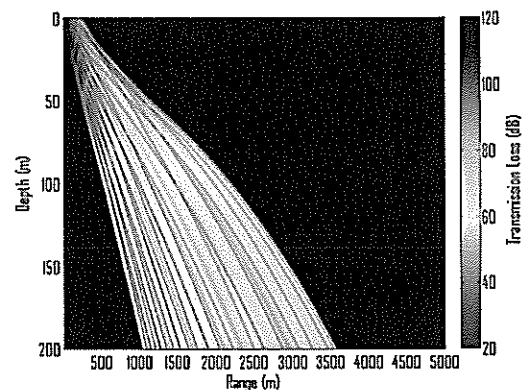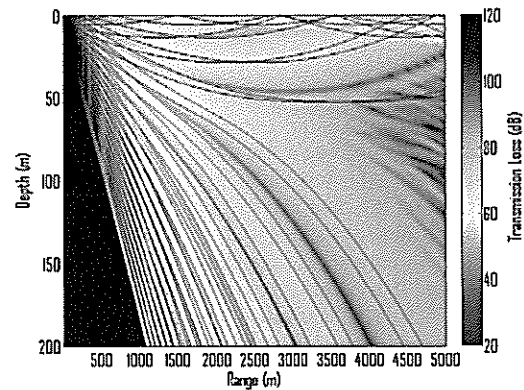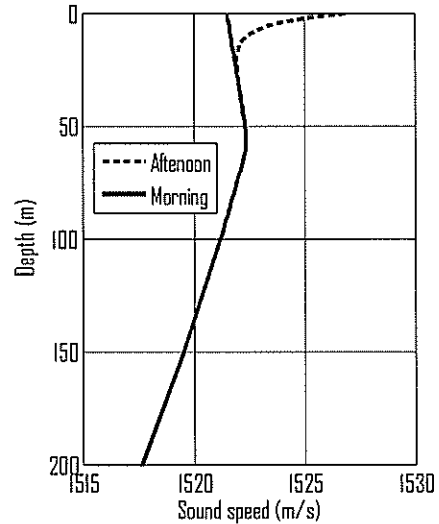

Figure 2. Top plot shows sound speed profiles for demonstrating the "Afternoon effect". The morning profile changes to the afternoon profile due to heating of the upper layer of water by sunlight. Middle plot is for the morning sound speed profile and shows the transmission loss as a function of range and depth for a source at 5m depth at a frequency of 10 kHz. Thin black lines are corresponding ray paths. Bottom plot is for the same situation but for the afternoon sound speed profile. Modelling was carried out using BELLHOP (Porter 2011).

Multi-path propagation delay spread

Surface and sea-bottom acoustic reflections in the ocean (shown schematically in Figure 3) creates the marine equiva-

lent of echoes down a canyon, but complicated by the fact that one 'wall' of the canyon is wobbling and rippling.
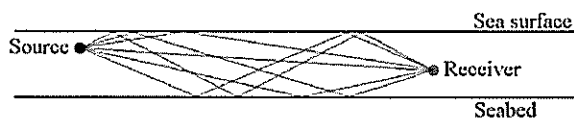

Figure 3. Schematic diagram showing propagation of sound from the transmitter to the receiver via a number of paths

The spread in arrival time of alternative multiple-reflected 'echo' paths can be quite considerable compared to the length of data symbols, particularly in shallower water. The tendency is for multiple 'copies' of the original message to become overlapped, making decoding more difficult.

Unlike echoes along a terrestrial canyon which exhibit static relative arrival times, in the marine environment the delay between arrivals of reflected 'copies' shifts as the surface moves and the total reflected path-length changes.

Addressing the time varying delay-spread exhibited by the underwater channel is an important capability of a dynamic simulator.

Transient signal fading

The underwater channel is characterised by multiple transmission paths with time overlap and with variable energy. This often generates transient fading of the received signal due to both variable attenuation along a single reflected path, and alternating phase-destructive and phase-constructive interference from multiple paths.

Transient Doppler frequency spread

The effects of moving surface waves not only cause time varying changes to the arrival-time structure of multiple reflected paths, they also cause the apparent received frequency to waver due to Doppler shift, as if the source was constantly changing speed. So instead of a received signal appearing as a discrete frequency, it may appear as a frequency that fluctuates of the order of 10 to 20Hz for a 10kHz carrier frequency.

This frequency spread tends to work counter to efficient detection algorithms, which generally try to filter the received signal as narrowly as possible to remove as much ambient noise as possible. A simulator must therefore be capable of reproducing transient Doppler shift.

Together with the spread in arrival delays, channels with Doppler spread are often described as doubly-spread channels (Eggen et al., 2000).

TRENDS IN UW CHANNEL SIGNALLING

Phase-incoherent signalling

The earliest underwater acoustic modem systems were developed primarily for control purposes where reliability was a higher design priority than data transmission rates. These systems normally utilised phase-incoherent signal modulation such as Frequency Shift Keying (FSK or MFSK for >2 multiple frequencies) (Eggen et al., 2000), with sufficient pauses between symbols to avoid overlap of successive symbols arriving via delay-spread multiple reflected paths. The delays between data symbols are made sufficiently generous to be insensitive to transient changes in the multipath signal delay

spread, and frequency filtering at receivers sufficiently coarse to achieve insensitivity to transient Doppler shifts. This type of signalling strategy could be built on a time-invariant propagation model utilising average properties for surface reflections, absorption and sound speed profile. Typical data rates using robust phase-incoherent signalling methods where reliability is paramount are in the approximate range of 50 to 500 bits per second over distances of the order of one kilometre.

Phase-coherent signalling

The quest for higher data transmission rates has led to the development of phase-coherent signal modulation methods that enable shorter symbol chips and shorter pauses between symbols. Phase coherent modulation utilises the third property of a wave, its phase, to distinguish successive chips or wavelets of data. Common phase coherent techniques include Phase Shift Keying (PSK – binary phases) and Quadrature Phase Shift Keying (QPSK – four phases)(Eggen et al., 2000). Data rates being sought are typically an order of magnitude higher than for phase-incoherent approaches, with rates in the tens of kb/second being achieved over distances of the order of one kilometre (Li et al., 2009).

Receiver equalisation schemes

Additional techniques are necessary to demodulate phase-coherent signals to counter the tendency of the multipath channel to scramble arrival times and phases of signal symbols. The distortion of the channel can be counteracted by including 'training' signals known to the receiver at the start of signal packets. The transfer function between the known training signal and the distorted received signal is estimated by the receiver DSP. This estimate is then used by the receiver to 'unscramble' or 'refocus' the multiple reflected replicas to obtain a stronger signal to demodulate.

The training signal approach is limited however by implicit assumption that the channel is static for the duration of a data packet. In reality the channel response is dynamically changing on timescales of less than one second, such that the channel estimate from the training signal is imperfect and increasingly 'out-dated' as the remainder of the signal packet is received (Preisig, 2007). The state of research has reached the point where the fine time-scale changes in the channel response from surface waves during a single symbol transmission are limiting the success of symbol decoding (Rodriguez et al., 2010).

Channel simulation research environment

Many teams from around the world are developing channel simulators to provide a test environment for improving and developing competitive signalling and demodulation schemes. Examples include the European Underwater Covert Acoustic Communications (UCAC) "Mime" simulator (van Walree et al., 2008), and the NARCISSUS-2005 simulator developed by Thales Underwater Systems (Cristol, 2005). Most simulators have been developed for military purposes and are unavailable for use by others.

Methods of quantifying transient channel transfer function

Direct measurement: The transient transfer function between two points may be measured directly in the field, as the time dependent complex cross-correlation between the source and received signal. This method has the advantage of cap-

turing the full range of transient phenomena for subsequent simulation testing of transmitters, but the substantial disadvantage of being site specific, and specific to the sea-state and sound-speed profile that prevailed during the tests.

Stochastic model: Whilst the underwater channel is generally deterministic in the sense that it would be predictable if enough environmental measurements of physical parameters were made, there are many UW communications applications, such as AUV's, where there is only very limited physical information. In this situation it is common for the communication system to be trialled or operated based on a stochastic channel transmission model that possesses the same statistical properties as channel transfer functions that have been determined by direct measurement in environments of interest. This type of model offers the same strengths as the direct measurement approach, but with the much greater computation efficiency that comes with a statistical representation of a large set of data. This type of model is often implemented in hardware that must work with channel response estimates in real-time, such as in receiver equalisation systems.

Deterministic model: The principal advantage of a physics-based or deterministic model of channel transfer function is that it may be made adaptable to a wide range of sites, ocean conditions and ambient noise environments. The draw-back as with all deterministic models is that the computational intensity increases with increased resolution in time and space. Modelling acoustic reflection effects for higher sea states and for rough normally unknown sea bottoms of uncertain composition is particularly problematic in this regard.

Blended model – The best of both worlds: Blended deterministic and stochastic models enable the best use of known site-specific factors, whilst achieving computational efficiency for random-like processes such as surface scattering and bottom scattering.

WORK IN PROGRESS - DYNAMIC CHANNEL SIMULATOR DEVELOPMENT

This project is concerned with simulating the propagation of communication signals of any arbitrary waveform that utilise carrier frequencies of the order of 5kHz-15kHz. This frequency range provides a reasonable compromise between distance absorption and data-rate capacity.

The UW channel simulator is being developed by a combination of physics-based propagation modelling and stochastic scattering models, and will be field-tested against direct measurements of transient channel transfer function for a limited range of test environments later in the project.

The Bellhop ray-tracing approach (Porter, 2011) is being modified to model transient Doppler shifts associated with moving surface waves and a moving transmitter platform, and to explore the range of surface wave conditions where energy from surface reflected paths is significant in comparison to direct and bottom-reflected paths. In these circumstances transient multi-path channel-fading and delay-spread are obstacles to better communication rates and the focus of simulation-based receiver evaluation. Specular and Gaussian models of Doppler shift from moving surface waves are being investigated.

At longer diurnal time-scales the transient development of the sound-speed profile may be modelled by interpolation of channel responses between successive speed profiles.

The discrete-time simulation environment has the advantage that the synthesis of the time-dependent channel response does not have to be computed in real-time. This will be exploited in the investigation of Doppler scattering effects associated with surface waves.

Whilst discrete-time signal-transmission simulations also do not need to be run real-time, it is intended that the simulator be adaptable to future hardware-based implementation, that may be interfaced with commercial transmitter and receiver systems. Such a hardware system does require real-time run capability. The efficiency of the transient channel response calculation is therefore being explored to enable future hardware implementation.

SUMMARY

The dynamic characteristics of the underwater acoustic channel are significant factors limiting high-rate and reliable underwater data communication links. In particular, the short time-scale transient effects of surface waves on multipath delay-spread and Doppler spread pose formidable challenges to the continued improvement of communication links that utilise channel equalisation techniques.

A dynamic channel simulator is being developed to enable simulation and investigation of the transient channel response in a wide range of sites, ocean conditions and ambient noise environments. The simulation is relevant to mid to high-frequency signals for which ray propagation theory is valid.

The simulator will be tested against field measurements of experimentally measured transient channel response.

ACKNOWLEDGEMENTS

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