EXPERIMENTAL STUDIES INTO ACOUSTIC TRANSMISSIONS ACROSS AN ESTUARY USING THE FORTHBASE FACILITY

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Abstract

Reliable acoustic communication is key to the development of collaborating AUV technology. Operation in shallow/littoral waters is a high priority for many military and civil applications. Such waters are however one of the most demanding environments for hydroacoustic communications systems, due to received signal distortion such as multipath time-spread. The temporal and spatial variability in shallow water acoustic channels disrupts coherence. High-resolution acoustic models are useful in estimating the operation of hydroacoustic equipment in such environments. However, even the best models have restrictions since their performance is chiefly reliant on the accuracy and resolution of the applied oceanographic data.

Of great benefit to the hydroacoustic communications research community is open access to real data from a complex dynamic channel, with the convenience and cost effectiveness associated with modelling. *ForthBase* is a hydroacoustic remote sensing facility set up in the Forth Estuary, Scotland, designed to collect real-time hydroacoustic and oceanographic data for acoustic communications studies. This site typifies the shallow-water turbulent flow conditions encountered in areas where, for example, naval security and surveillance are essential.

This paper includes the results of acoustic channel assessment experiments, carried out during neap and spring tidal periods. Transmissions were made periodically, while concurrent oceanographic measurements and observations were made. Stacked plots showing multipath arrival structure fluctuations over a range of time-scales are presented. Modelled and real data are compared for validation and further model outputs are presented to illustrate the effects of vertical transducer displacement on multipath structure.

Introduction

In the context of unmanned untethered submersible technology, the acoustic communications between an unmaned vehicle and a surface ship or buoy provides an essential control of the vehicle mission as well as telemetry of status information and sensor data. Such communication links are set to become even more vital as the move towards co-operating multiple vehicles (swarms) gain momentum in the military underwater battlespace context and the commercial exploration of the seabed [1].

The data rates that can be transmitted acoustically are dependent largely on the *in-situ* propagation characteristics. Within shallow waters/littoral zones, high multipath conditions are encountered. Temporal and spatial variabilities of oceanographic parameters lead to fluctuations in the acoustic channel response, hence disrupting coherence.

It can be argued that the greatest technical restriction to the future development of multiple communicating unmanned vehicles is the communications networks that will have to evolve to support their operation. Much work has been done in investigating diversity methods in underwater acoustics [2]. Spatial diversity can be employed in the form of multiple (2/3D) spaced hydrophones to improve system performance. In very shallow water the physical dimensions of a multiple transducer configuration that offers appropriate diversity may become impractical. This work therefore looks at single transducer communications as would be appropriate for use on small autonomous vehicles.

Shallow water with complex bathymetry

When signals are transmitted in water, stratification of the water column (sound-speed profile) and surface and bottom boundaries cause multipath effects that manifest themselves as multiple delayed copies of the transmitted signal. Since these copies arrive by independent paths, the received signal is subject to time spreading. For sequential data transmissions, this time spreading may result in inter-symbol interference (ISI). The effects of ISI are countered by incorporating error correction or introducing guard intervals, both of which impact data rates [2].

In many published papers typical scenarios for shallow water communications are as illustrated in Figure 1 (a), where the sea floor is flat. In this figure an acoustic transmitter and receiver pair are located at a depth of ~5.5m in a 20m deep channel with a separation range of 1km. The image is derived using a ray trace model where boundary interactions are simple reflections and ray curvature is determined by Snell's Law [3]. The sound speed profile (SSP) used in this model is indicated by background hue. Only the ray paths reaching the receiver, termed *eigenrays*, are shown.

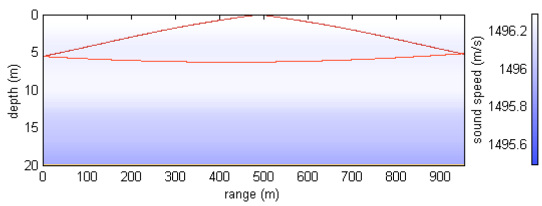


Figure 1. Flat bottom shallow water communications model

In this example, the simplicity of the bathymetry results in a trivial multipath structure, with a small number of eigenrays. When a more complex bathymetry is introduced, the eigenray count tends to rise and hence the received signal is subject to increased multipath distortion. Figure 2 shows a ray trace model output for a more complex bathymetric profile. The same SSP is used as for Figure 1.

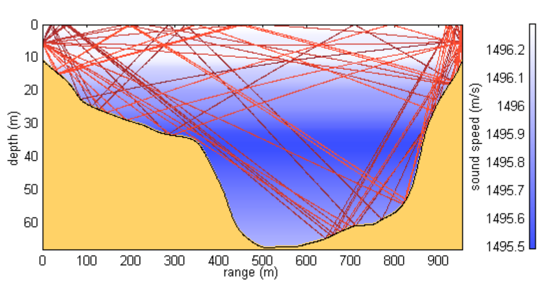


Figure 2. Complex bathymetry model output

From Figure 2, for hydroacoustic systems that are likely to operate in waters with complex bathymetry, a complex multipath structure should be expected.

The role of acoustic propagation models

Acoustic propagation models are an excellent way of investigating the nature of sound propagation in the sea [4]. They are, however, deterministic and give outputs that are primarily influenced by key oceanographic data inputs. Many models cannot cope with the complex bathymetries often encountered in shallow water scenarios.

Key to a model's performance is the oceanographic inputs. In reality, such data are difficult to collect due to both the temporal and spatial variability of such parameters in real waters. Oceanographic temporal variability encompasses all scales from sub-second, through tidal, to seasonal time scales and beyond. Relevant features inducing spatial variability range in scale from centimetres to many kilometres [5].

As an example of short time scale variability, sound speed measurement data collected in high flux environments at a static position and only minutes apart often show significantly different profiles (Figure 3). This degree of temporal variability infers a spatial dimension to such readings.

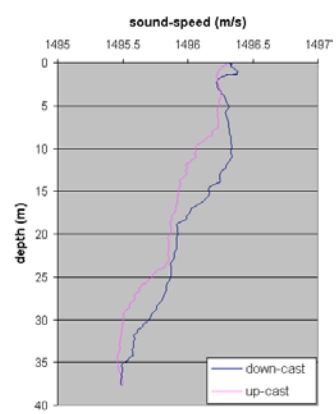


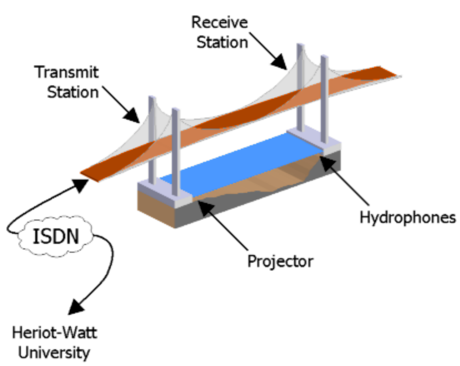
Figure 3. Sound speed up/down casts

Such effects indicate that oceanographic assessment can never be carried out with sufficient resolution to provide acoustic prediction models with good *real-time* input data. Thus acoustic propagation output data cannot be assumed "accurate", but rather can only act as a guide. Models do nevertheless represent a relatively low-cost and convenient method of estimating system performance.

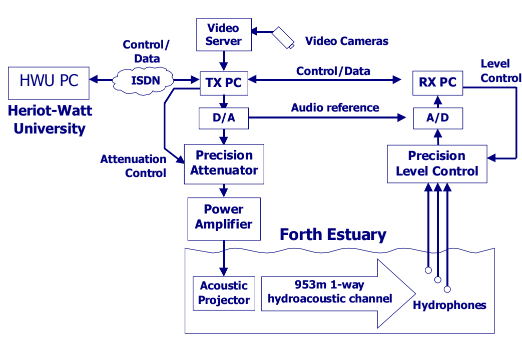
The *ForthBase* test range

The objective for the Heriot-Watt "*ForthBase*" project is to investigate hydroacoustic communications in a dynamic water channel [6]. Through a combination of modelling and real-time experimental data collection, temporal variability effects are being studied. It is intended that this work will lead towards optimal solutions for robust communication networks. The chosen area of water is the Forth Estuary, Scotland, a busy shipping channel populated with a variety of marine life. This macrotidal estuary has a mean tidal range of 4.5 m with mean peak speeds of 0.8 m/s on the ebb tide and 0.5 m/s on the flood.

The test equipment for the *ForthBase* range is located on the North and South tower pier defences of the Forth Road Bridge. The surface sediments beneath the road bridge are composed of sandy gravel near the north bank and sandy mud towards the south bank. Beneath the surface sediment is a layer of clay that is about 30-50m thick (estimated sound speed of 1,700 m/s) and beneath this lies carboniferous bedrock (estimated sound speed of 5,250 m/s). The depth at the range varies from approximately 8m relative to chart datum (//ACD) at the deployment sites to 65m//ACD at approximately mid channel. The range profile is that which is used for the ray trace example in Figure 2.



(a) *ForthBase* illustration



(b) System block diagram.

Figure 4. *ForthBase* hydroacoustic test facility

On the north pier defences are suspended a set of wideband hydrophones. At the south tower an audio-band acoustic projector can insonify the channel. The system is depicted in Figure 4 (a) and (b).

Acoustic channel variability

Acoustic communications between surface platforms and autonomous underwater vehicles dictates a time-varying channel. The extent to which channel parameters fluctuate depends largely on the location of operation and platform motion. Shallow, tidal waters inevitably incorporate significant spatial and temporal fluctuations in relevant oceanographic parameters and therefore represent a particularly demanding environment for AUV acoustic communications.

Platform movement through spatially varying water and temporal variations in the water column induce temporal acoustic channel fluctuations. Spatial variability of oceanographic parameters in deep water is mainly restricted to sound speed changes and multipath routes are relatively stable [7]. In many shallow water regions however, topographic features can strongly influence the multipath structure of received acoustic signals.

ForthBase channel variability experiments

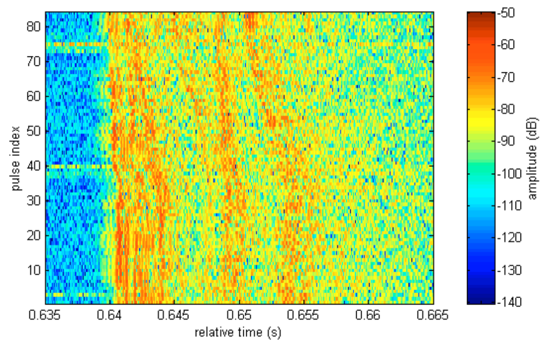
While many experiments have been carried out in flat seabed shallow water environments, what makes the *ForthBase* range so demanding for acoustic communications is the complexity of the bathymetry and the rapidity of fluctuations in oceanographic phenomena.

In 2002, experiments were conducted using the *ForthBase* range to investigate temporal and spatial acoustic channel variability in the Forth Estuary. Linear 1-8kHz, 1 second, frequency modulated chirps were transmitted at regular intervals across the ~1km channel over several tidal periods. Two horizontally separated hydrophones were used to receive the resulting signals.

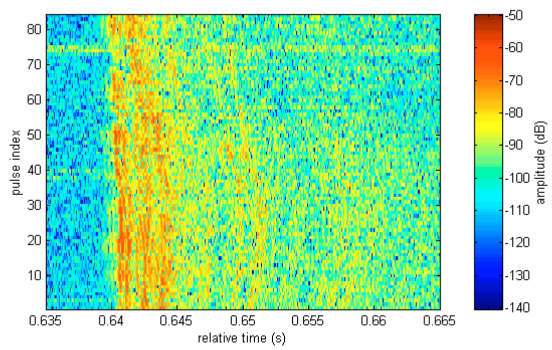
The following experimental and modelled results are intended to provide an insight into probable acoustic channel multipath fluctuations for a single transducer-pair communication link in such waters.

Spatial variability example

Figure 5 shows stacked plots of the matched filtered pulse arrival amplitudes at two closely spaced hydrophones over a 30ms time window for 84 transmissions. The x-axis represents relative time, the y-axis is pulse index and the received signal intensity normalised to transmit level is indicated by the colour bar. Immediately apparent is the complex structure of the multipath arrivals and the significant difference in the magnitudes of the multipath groups between the two hydrophones located 37m apart. For a vehicle travelling at 3kts it would take only 20s to track between these positions.



(a) East Hydrophone stacked plot.



(b) West Hydrophone stacked plot.

Figure 5. Matched filtered stacked plots

The difference in the two plots may be partially explained by the bathymetry at the hydrophone locations. A high-resolution bathymetric survey data indicates a large rocky outcrop some 10 metres from the west hydrophone position. Features such as this are likely to be encountered in many shallow water environments and can have a dramatic effect on received signal structure, as is seen above.

Temporal short-term variability example

To assess channel fluctuation on a time-scale for which tidal elevation variation can be ignored, experiments were performed with rapid transmission sequences and fixed transducers.

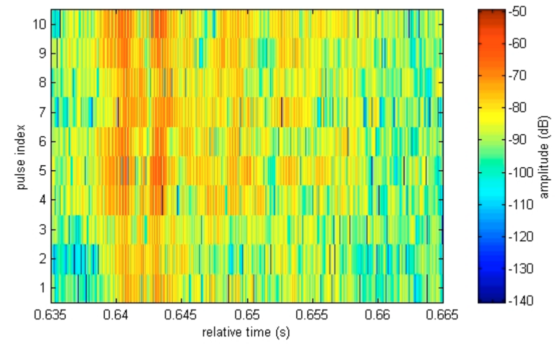


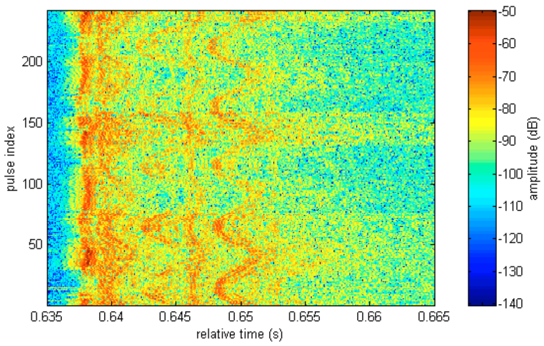
Figure 6. Short-term matched filtered stacked plot

Figure 6 shows the matched filter stacked plot for a sequence of 10 pings transmitted at 2-second intervals. This figure confirms that the multipath structure shows significant variation on a second-to-second basis.

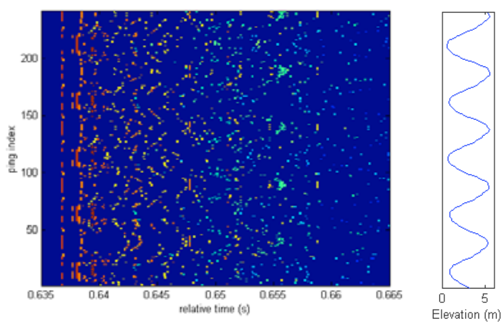
Temporal long-term (tidal) variability example

Trials were carried out during spring tides, over several tidal periods. 242 pings were transmitted at 15-minute intervals. Figure 7 (a) shows the matched filtered data and (b) shows the results from a range dependent ray-trace model. This model does not incorporate reverberation effects. Tidal elevation is shown to the right of Figure 7 (b). Both figures are time synchronised.

For the modelled plot, hue (z-axis) represents received amplitude. The sound speed profiles, tidal elevations and surface conditions used for the model were derived from measurement and observations concurrent with the acoustic data. Extreme break-up of the early multipath structure is clear from Figure 7(a). The model results shown in Figure 7(b) show a similar discontinuity. Later multipath groups clearly correlate with tidal elevation, with the 6th group having a correlation coefficient of 0.89.



(a) Real matched filtered data



(b) Modelled data and tidal elevations.

Figure 7. Stacked plots for several tidal cycles

Detailed raytrace analysis indicates that there are many occasions where no direct path exits between transmitter and receiver, hence the discontinuities observed in the first arrival groups for the real data. Also, the analysis has shown that the later multipath groups are the result of multiple interactions with the surface and bottom boundaries with a close relationship between arrival time and boundary interaction count.

The similarity in the behaviour of the model with the acoustic data for tidal elevation variation confirms the applicability of this model for illustrating multipath effects.

<u>*Vertical transducer displacement simulations*</u>

The experimental work dealt with fixed transducers and a fluctuating upper surface boundary elevation. For AUVs, short-term vertical elevation changes as a result of platform motion (heave, ascent/descent) are more relevant. To investigate the likely effects on received multipath structure for such vertical motion, the ray trace model was used to simulate the results by fixing the position of one transducer while displacing the other.

(a) Fixed transmitter, displaced receiver

The model was run using the oceanographic parameters from the previous experiments, but with a fixed tidal elevation of 3m. The modelled receiving transducer positions ranged from near surface (0.5m) to near bottom (10.5m) with a vertical resolution of 0.01m. Rays falling within ±0.5m in the vertical plane were considered as detected. Figure 8 shows the resulting simulated stacked plot, where in this case the y-axis represents receiver depth.

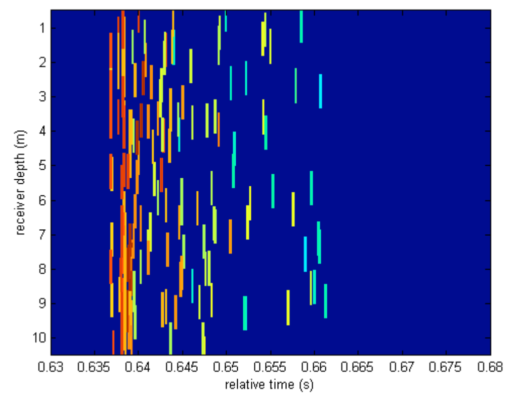


Figure 8. Simulation for vertical receiver displacement

(a) Fixed receiver, displaced transmitter

The model was also run for a range of transmitter displacements. In this scenario a range of depths were simulated, from 1m below to 1m above the projector position, in 0.02m increments. Figure 9 shows the resulting simulated stacked plot.

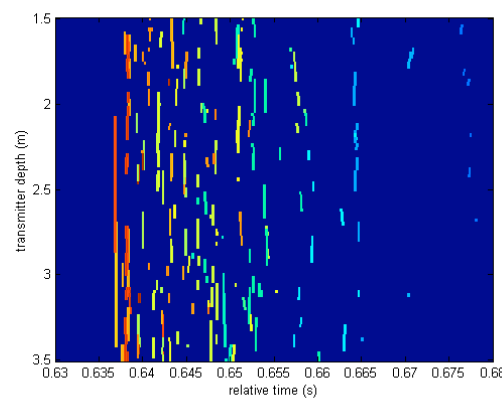


Figure 9. Simulation for vertical transmitter displacement

These model simulations illustrate the unpredictable nature of the received multipath structure for such conditions. The following multipath characteristics can be deduced for single element transmit/receive operation under the conditions as described:

- Consistency in early multipath group arrival time with vertical displacement cannot be expected, due to the discrete nature of the presence/absence of direct (no surface/bottom interaction) eigenrays.
- Multipath time spread varies significantly with vertical transducer position and fluctuations of the order of 15ms resulted from the model runs.
- The energy distribution within the multipath structure varies erratically with transducer depth.
- Figure 8 implies the order of the spatial sampling dimensions required for spatially diversity.

Discussion

This paper has looked at the effect of spatial and temporal variability on acoustic propagation in a shallow water dynamic estuary, with a particular emphasis on multipath. Through the use of the *ForthBase* hydroacoustic test facility we have illustrated the ease by which data can be collected, in timescales that vary from seconds to weeks. The multipath phenomenon in this estuary has been extensively studied experimentally for fixed transducer locations and our in-house ray trace model validated against the resulting experimental data. The model has been further used to simulate vertical transducer displacement, as may be experienced by underwater platforms. These results show that, for such waters, the received multipath structure may be unstable with transducer location on a fine scale.

Shallow water propagation in areas of demanding bathymetry is far more complex and presents a much greater challenge than would be encountered for a “flat bottom” scenario. Acoustic interactions with sloping bottom features are found to increase the likelihood of eigenray paths. Furthermore, perturbation in the stratification of the water column impacts on the stability of the eigenrays in a non-deterministic manner.

In the literature, methods of channel adaptation on a ping-to-ping basis are presented [8,9], whereby analysis of the previously received signal is used to adjust key system parameters. Channel adaptation based on such “acoustic probes” may well feature in future systems. However, the rapidity and stochastic nature of fine scale channel fluctuations will inevitably compromise the validity of adaptation parameters derived through such measurement techniques. Systems must therefore maximise all the possible advantages available through diversity. Such diversity can be spatial, or inherent in the transmitted waveform. If spatial diversity is limited or inappropriate, then an emphasis must be placed on time/frequency diversity.

Much underwater communications work concentrates on the exploitation of diversity through the implementation of specific processing techniques such as multicarrier modulation and adaptive beamforming [10]. To complement this type of activity, diversity can also be investigated at the more fundamental waveform level. Current work at the range is thus concerned with statistical studies relating to the stability of waveforms as a function of their key parameters (centre-frequency, bandwidth, duration). Such work currently involves comparisons between energy/bandwidth equivalent continuous-wave bursts and chirps.

ForthBase offers access to a complex shallow water channel for hydroacoustic studies. The authors encourage researchers to consider this open facility for collaborative studies.

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