AN INTRODUCTION TO THE "FORTHBASE" HYDROACOUSTIC TEST FACILITY

D McLaren Heriot-Watt University, Department of Computing and Electrical Engineering, Edinburgh, U.K.
R McHugh Heriot-Watt University, Department of Computing and Electrical Engineering, Edinburgh, U.K.

1. INTRODUCTION

In underwater acoustics the shallow water, medium to long range channel, which includes coastal regions, has long been identified as one of the most demanding environments in which to operate. Severe signal degradation can occur in such a channel due to multipath effects, which may include multiple interactions with the sea bottom and sea surface [1, 2, 3]. Temporal and spatial variability of the channel disrupts channel coherence and this is particularly noticeable in areas affected by strong tidal currents. The shallow water channel is however the very environment which is of particular interest to many research workers; in commercial applications arising from the needs of the oil and environmental agencies, in AUV development, and in equivalent Defence applications. Future designs for reliable shallow water acoustic communications equipment will require a better understanding of the channel and how environmental parameters effect propagation [4, 5].

A first application of such knowledge, which could significantly influence future sonar design, would be the adoption of a range of new robust, perhaps even eventually self-adapting, sonar signatures. Advances in sonar transmitter bandwidth capabilities makes all of this possible with today's technology. Wide bandwith and high power sources are also a potential acoustic *pollutant* to the local marine creatures, so all such signature specifications will have to be made "locals friendly".

In order to gain a better insight into acoustic communication in such complex shallow water environments, running realistic acoustic (and oceanographic) models can be extremely useful [6]. Nature is however a difficult act to emulate so even the best models inevitably have many restrictions. "Real data" collected from carefully monitored experiments is thus absolutely invaluable, both in the wealth of scientific understanding that it can reveal in its own right but also as test data for acoustic model validation [7]. However real data is "expensive" to acquire both in terms of personnel-time and boat hire time (and hence cost). Previous experience in hydroacoustic and oceanographic data collection experiments carried out by Heriot-Watt University (HWU) Ocean Systems Laboratory (OSL) has enabled us to automate the collection of experimental data using research vessels to some extent [8, 9]. However, the overriding cost will always be the platform hire.

Some 12 km to the north of the Heriot-Watt University campus is the Forth Estuary and located within the Estuary is an ideal *platform* for our equipment, namely the piers of the Forth Road Bridge. The "dream" of a setting up a permanent hydroacoustic test facility became even more attractive to us when we began to appreciate just what a complex and demanding channel (and to some extent a well documented channel) the Estuary presents. This idea developed into a research proposal. In August of 2001, thanks to EPSRC support, work began on implementing, what we call in-house, the "ForthBase" Hydroacoustic Test Range.

The project's overall aim is to establish a *remote sensing laboratory*, with transparent data connections back to the HWU campus for the purpose of long term research into *self adaptive acoustic communications* in shallow water channels through modelling and measurement. Thanks to the overwhelming support of the Forth Road Bridge Joint Board and their ever-helpful staff the "wiring -up" of the bridge is now complete. Remote presence is achieved by the use of an ISDN line. The acoustic channel is just short of 1 km in length, in a very active tidal current flow, and within a demanding shallow-water depth profile.

2. THE "FORTHBASE" FACILITY

2.1 The Estuary

The Firth of Forth, one of the major UK estuaries, is situated on the East Coast of central Scotland. It is 93 km long and has a 4655 km^2 drainage basin that includes several groups of large hills including the Pentland, Ochil and Lomond Hills. Morphologically, the Firth of Forth can be divided into two distinct regions. The firth extends from the North Sea, at the Isle of May, inland to the two bridges that join North and South Queensferry. It is roughly elliptic in shape with a major axis of 40km and a minor axis of 25km. The depths in the area are typically about 40m with occasional deeper channels. The tidal range within the firth is approximately 6m and the peak tidal currents in the region are 0.5 m/s, with residual and wind-induced surface currents having magnitudes of less than 10% of this value [10]. The Forth estuary is the inner part of the Firth area, extending from Stirling in the west to the Forth road and rail bridges in the east. It is a macrotidal estuary with a mean tidal range of 4.5 m and with mean peak speeds of 0.8 m/s on the ebb tide and 0.5 m/s on the flood. The depths in the estuary range from about 20 m off Rosyth (with depths up to 70 m under the two bridges) to less than 5 m in the upper estuary above Alloa. The freshwater inflow from the Forth, Teith and Allan rivers at Stirling is comparatively small, being on average 47 m^3/s[11].

2.2 The Test Range

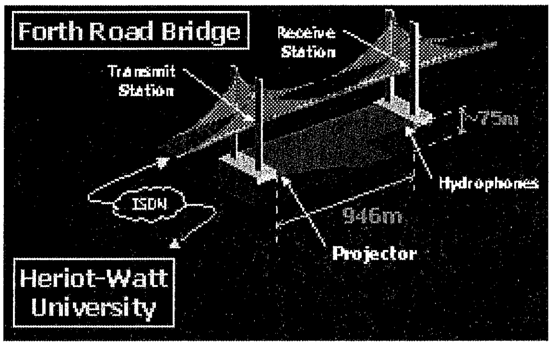
The Test Equipment for the ForthBase range is located on the North and South pier defences of the Forth Road Bridge (FRB). The pier defences were constructed in 1996 and are designed to defend the bridge against a collision from a passing vessel. The defences are constructed from a sequence of inter-linked circular reinforced cells in-filled with large rocks covering an area of approximately 1500 m^2. These defences are wrapped around the outer aspects of the North and South Bridge pile foundations, which support the main towers of the Forth Road Bridge structure. They are also, for the acoustics researcher, an ideal mid estuary location for attaching a variety of sensors.

(a) Hydrophone system *(b) West side camera view* *(c) East side camera view*

Figure 1.0 Views of the bridge pier defences, equipment fixing and camera views

On the north pier defences are suspended a set of three wideband (>200 kHz) hydrophones. At the south tower, an audio-band (500 Hz to 15 kHz) acoustic projector can insonify the channel. Also located at the south tower, slung under the roadway level, are cameras giving east/west visibility of traffic in the estuary. The control of all of this equipment is by means of two PC's directly connected to an ISDN line that has been specially installed into the south tower, at road level. The south tower PC controls the acoustic transmitter as well as collecting the camera images.

The north tower PC captures the hydrophone data using proprietary audio-studio equipment. This gives multiple channel 16 bit data acquisition at a 96kHz sampling rate. The digitised hydrophone signals are relayed over a dedicated 1km cable which links the north and south tower PC's and hence links to the ISDN line and HWU.



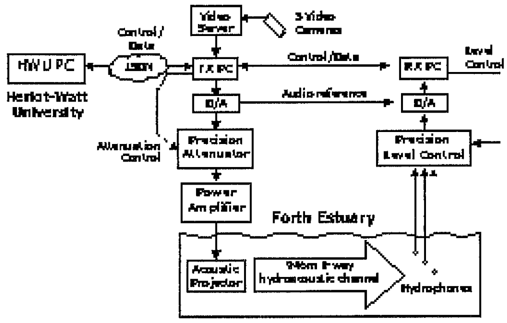


Figure 2(a) Diagram illustrating "ForthBase" link   Figure 2(b) Schematic of the "ForthBase" link

The underwater equipment is wired directly from the water edge, up the main bridge towers, to the control PC's located at road level. Using the PCs/ISDN line arrangement we have direct bi-directional control of all data flow to-and-from our equipment on the bridge from our laboratory at HWU. So, for example, we can send a .wav file from the HWU control PC to the transmitter PC in the south tower. We can control the level and timing of the transmit acoustic pulse, or sequence of pulses. At the receiving end the data acquisition system knows when to acquire data and for how long. The HWU link effectively "sees" the pc screens using Remote Administrator software.

The ForthBase channel is 946 m between the piers of the bridge and varies in depth from some 8m at the piers to extend to approximately 70m at the main north channel during high tide (Figure 3). The tidal flow is transverse to the acoustic path with flow rates of 0.5 ms^{-1} typical. Th tidal range can be in excess of 6m. The current flow in the estuary is fairly complex and is the subject of a parallel EPSRC project being run by the University of Wales (Bangor), Centre For Applied Oceanography, Marine Science Laboratories, Menai Bridge, Anglesey. Figure 4 shows a typical output from one of their current flow prediction models with a corresponding aerial bathymetry plot.

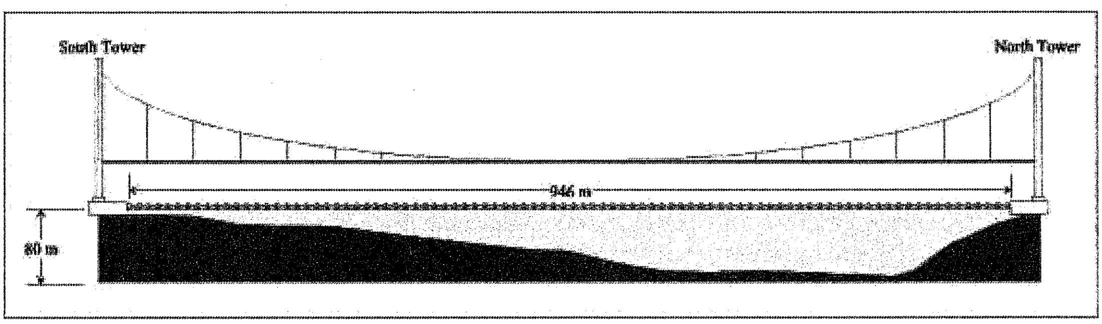


Figure 3 Channel Bathymetry between the piers of the Forth Road Bridge

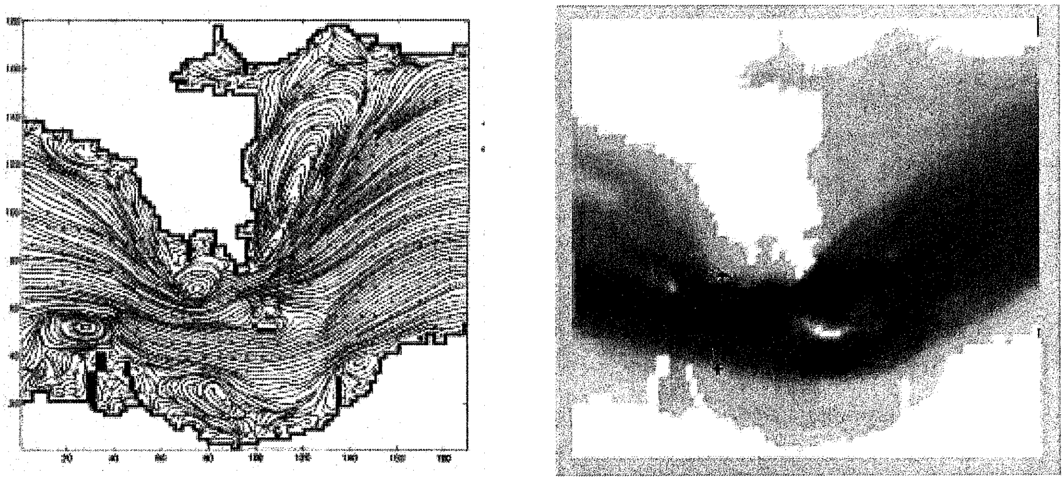


Figure 4 Typical water current flows (as predicted by the Bangor model), and bathymetry plot

2.3 Active and Passive Capabilties of the Range

The ForthBase facility can operate in essentially two modes of operation:

(a) a passive mode where the three spatially divergent hydrophones on the North pier defences act as listening stations for biological sounds or man-made traffic generated within the estuary, or
(b) as an active system in which the audio-band projector can insonify the channel and the receiving hydrophones monitor the signals arriving at the north pier after having traversed the tidal flow.

In terms of the passive applications, these include monitoring traffic noise (the east/west cameras give an indication of ship location) as well as the monitoring marine life. The Forth Estuary is regularly visited by harbour porpoise (Phocoena phocoena), bottlenose dolphins, grey seals, harbour seals, and occasionally minke whales (Balaenoptera acutorostrata). The three hydrophones could be used to track marine mammals passively and collect data on species abundance and movement patterns.

In terms of the active mode of operation, the audio-band acoustic source has a fully programmable electrical excitation waveform capability with direct control from the laboratory at HWU. Furthermore, the estuary hydrophone signals can be returned to HWU within a few seconds of reception. There is thus almost instantaneous feedback between transmit and receive signals across the estuary. It is thus intended to send a variety of acoustic signatures (in the 0.5 to 15 kHz band) across the channel. Comparisons of model predictions with experimental results will be made and the temporal variability of the channel will be assessed. A variety of modulation techniques including single or multiple chirps can be employed.

A ray trace model output and a Normal Mode model output are shown in figures 5 and 7 for the approximate bathymetry of the estuary channel.

2.4 Model Results for the ForthBase Range

In order to illustrate the type of multipath structure that might be expected for the ForthBase range, a sequence of model simulations are shown below.

Figure 5 shows the results from a ray-trace model. The figure shows a typical sound speed profile and the resultant ray-trace for a 2.5m deep, ±20° source . This ray-trace gives an indication of how the energy in the water column is distributed, and the figure shows many multipath arrivals with a significant amount of energy reaching the receiving hydrophone. Note that the plot does not have an equal aspect ratio.

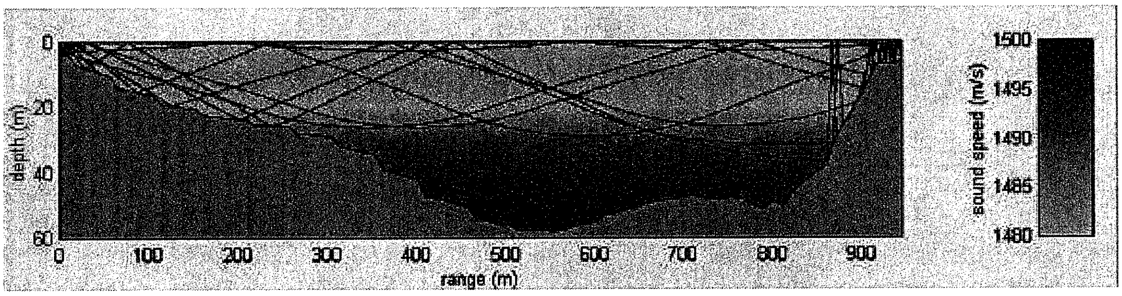


Figure 5 shows a ray trace model output with typical sound speed profile

Figure 7 shows the results using the PROSIM model. This is a normal mode model that was designed to predict the effects of a broadband audio frequency source (400Hz to 15 kHz), in shallow water acoustic channels. Figure 6 shows the input window with the sampled interpolated bathymetry. The source and receiver are set at 4m. The transmit waveform specifications are in this example: 1 second duration, 160 dBre 1μPa, 1 to 8 kHz Hanning weighted linear FM up-sweep, ± 40° elevation beamwidth.

Figure 7 shows the output from the PROSIM model. Figure 7 (a) shows the results using the sound speed profile as shown in Figure 6. Figure 7(b) shows the results for a constant sound speed profile of 1470 ms^{-1}. In this figure, the lower traces are the respective matched filter outputs. The matched filter gives a compression ratio of the order of 4,000 to 1. From a comparison of Figures 7(a) and (b) the sound speed profile does not appear to have a significant effect on the received signal. The multiples within all the received signals fall within a window which is only marginally wider than the 1 second transmit pulse width. Significant reverberation is not obvious from the model output.

Experimentation carried using ForthBase will involve the comparison of such model outputs with real data recorded at the range.

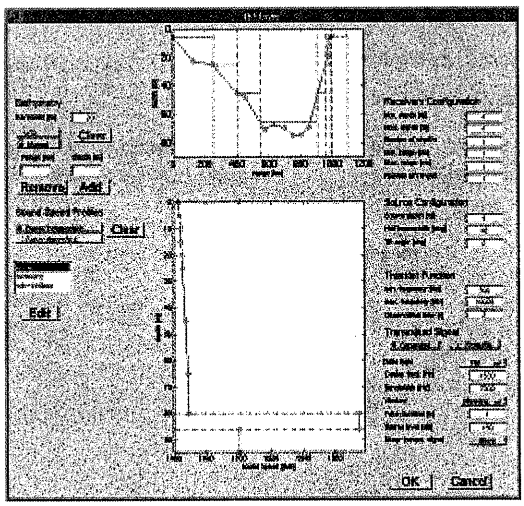
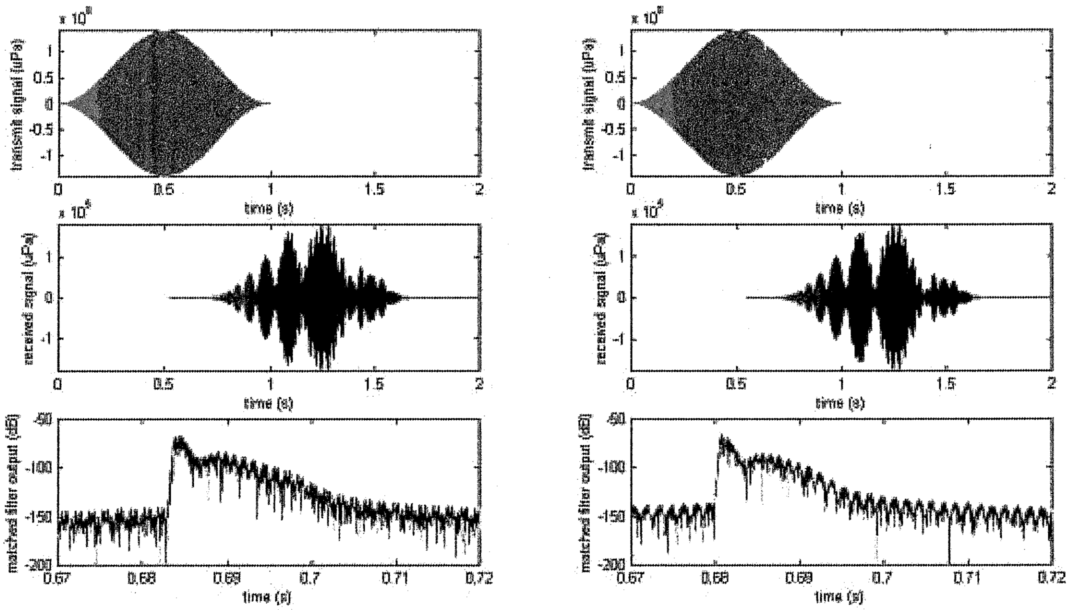


Figure 6 Input window for PROSIM model



(a) (b)

Figure 7 Shows broadband normal mode model (PROSIM) data for;
(a) typical sound speed profile and (b) linear sound speed profile (1470 m/s).
The top trace is the transmit waveform, the middle trace is the simulated received signal and the lower trace is the matched filtered output.

-

2.5 First Experiments

2.5.1 Passive Listening of Traffic within the Channel

A combination of the East/West cameras and the north pier hydrophones enable audio and visual monitoring of the channel for shipping. These facilities, as well as being necessary for monitoring estuary traffic during active trials, are also useful in their own right. Passive listening will allow time stamped measurements of estuary traffic, which is accompanied by corresponding video data. The vessels can be classified in terms of size and speed and prop-shaft rotational velocity. Figure 8 shows a typical section of recordings from a passing vessel.

(a)

(b)

(c)

(d)

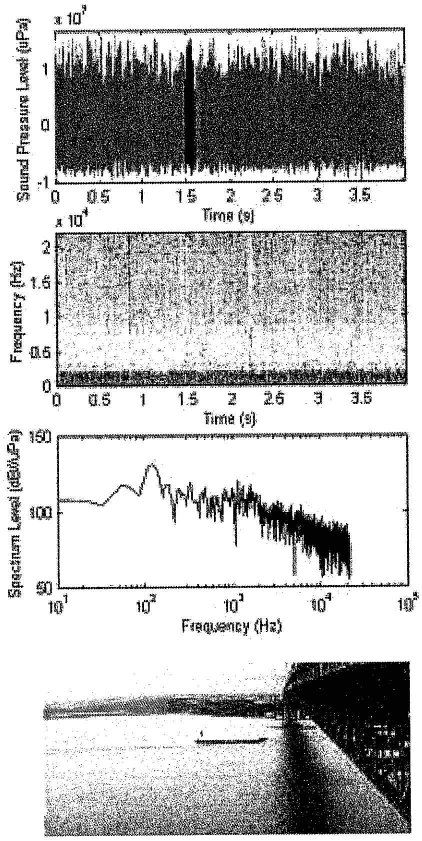


Figure 8 Forth Estuary ship signature
(a) time waveform (b) spectrogram
(c) fft (selection from (a)) (d) vessel recorded

The fact that cetaceans and seals use sounds very similar to those deemed most effective for underwater communication by engineers creates a potentially severe environmental problem. As an example, a recent interim report from NOAA Fisheries and the U.S. Navy concluded that mid-range tactical sonar were partially responsible for the stranding of seventeen Beaked Whales in the Bahamas. Issues of this nature are high on the agenda of environmental groups. The ForthBase capability to monitor passive noise measurements and cetacean activity make it an ideal facility for research into issues associated with acoustic source level and acoustic signature transmissions.

2.6 "ForthBase" The Future

ForthBase has been conceived as an open facility with external organisations able to "hire" the range for experimental purposes. Essentially a "customer" can give us a source file (.wav) and source level requirements and we will transmit the signature and supply back the hydrophone signals recorded. The tidal model can be used to give indicators of the channel water flow state during the experiments.

3 REFERENCES

[1] Zheng M., Experimental Study on Statistical Characteristics of Pulse Transmissions in the Shallow Water, Proceedings of the Institute of Acoustics 1993, Vol. 15, Pt 9, Pg. 142-15.1.
[2] Badiey M. Frequency dependence of broadband propagation in coastal regions, Journal Acoustic Soc Am,101(6), 1997, pp 3361-3370.

[3] Stojanovic M. Recent advances in high speed underwater acoustic communications, IEE Journal of Oceanic Engineering, Vol. 21, No 2, 1996, pp 125-136.
[4] Richards S.D. and Heatherside A.D. The effect of suspended particulate matter on sound attenuation in seawater J. Acoust. Soc. Am.100 (3) September 1996, pp 1447-1450.
[5] Richards S.D. The effect of temperature, pressure and salinity on sound attenuation in turbid seawater J. Acoust. Soc. Am.103 (1) Jan 1998, pp 205-211.
[6] Buckingham M.J., Ocean-acoustic propagation models, J.Acoustique, 1992, pp.223-287.
[7] Simons D. G., McHugh R., Snellen M., McCormick N. H. and Lawson E. A. 'Analysis of shallow-water experimental data including a comparison with a broad-band normal-mode-propagation model' IEEE Journal of Oceanic Engineering, Vol. 26, No.3, pp 308 - 323, July 2001.
[8] McHugh R., Lawson E. A. and Simons D. G. Automated Acoustic Data Collection Experiments 4^{th} European Conference on Underwater Acoustics, Rome, Italy, 21 to 25 September 1998, Vol 1, pp 483 – 488.
[9] van Dalen S., Simons D. G., McHugh R., and Jackson J.F.E. Validation of a broadband Normal-Mode propagation model using shallow water experimental data' 4^{th} European Conference on Underwater Acoustics, Rome, Italy, 21 to 25 September 1998, Vol 2, pp 661 – 666.
[10] Webb, A. J. and Metcalfe, A. P. (1987) Physical aspects, water movements and modelling studies of the Forth estuary, Scotland Proc. Roy. Soc. Edinburgh, 93B, pp 259-272.
[11] Elliott A.J., Clarke S. Shallow Water Tides in the Firth of Forth, The Hydrographic Journal, No. 87, January 1998, pp. 19-24.

4. ACKNOWLEDGEMENTS

The "ForthBase" project is funded by the Engineering and Physical Sciences Research Council (EPSRC). Figure 4 of this paper is thanks to Prof. Alan Elliott, Centre for Applied Oceanography, University of Wales (Bangor). We would like to thank the Forth Road Bridge Joint Board for their invaluable assistance in allowing us to do all sorts of crazy things within the bridge structure. In particular we are indebted to Chris Tracy, Alastair Andrew and the maintenance personnel on the Forth Road Bridge.