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Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Characterisation of underwater acoustic modem performance for real-time horizontal data transmission

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ABSTRACT

Offshore pipelines are integral to the oil and gas industry and vital for the transport of resources from subsea wells. As fields progress toward deeper water and more rugged terrain, an effective method of real-time monitoring of both environmental and pipeline conditions is essential for maintaining environmental and safety standards. This study seeks to assist in the development of real-time methods of data retrieval by characterising the horizontal performance of various underwater acoustic modems. Preliminary trials involve investigating performance of two commercially available modems in shallow water. In the first of these the system is found to have worked effectively, with reliable communications obtained at ranges up to 500m. Whilst this was less than the expected range for the modems, the characterisation of their performance gives an initial insight to the functionality of horizontal underwater communications in the varying oceanographic conditions.

INTRODUCTION

Background

As the offshore oil and gas industry progresses towards deeper wells and more rugged terrain, the pipelines that transport resources pose higher financial and environmental risks. Visions of the future suggest the implementation of completely submerged oil and gas extraction plants, “platform free fields”. This would place significant importance on reliable real-time monitoring of these systems and associated pipelines. There are several methods to consider for the transmission of crucial data including the use of umbilicals, Autonomous Underwater Vehicles (AUV)s and in particular, wireless underwater acoustic communication.

Umbilicals carrying electrical or fibre-optic cabling are a favourable option for high-bandwidth applications such as the control of remotely operated underwater vehicles (ROVs). Their weakness however is the significant cost in deploying, maintaining and repairing cabling for long-term or long distance deployments. Whilst AUV technnology is developing rapidly, their maintenance cost and associated risks suggest underwater acoustic communication is a viable alternative with a lesser financial burden.

Underwater acoustic communication is a fast growing industry with applications ranging from simple point-to-point communication to large underwater sensor networks for the offshore oil and gas industry. As the partial electrical conductivity of the sea significantly restricts RF communications, the emerging technologies for the oil and gas industry tend to be in fibre optics (Wright, 2000) and the use of underwater acoustic modems. In the case of stationary nodes positioned vertically apart, underwater acoustic modems are particularly suitable (Yu, 2000). Their applications are now widening to more sophisticated underwater networks, removing the need for communication cabling over short distances. With the integration of short-range optical communications, AUVs have also been integrated into some of these developments. (Vasilescu et al., 2005)

Despite great progress over the last decade, the dynamic ocean environment still provides many obstacles for fast and reliable underwater acoustic telemetry. In particular, the adaptation of RF based transmission protocols to underwater modems has been a slow and difficult process. This concern has been addressed using methods such as developing synthetic transmission channels, enhancing the ability to foresee problems in planned communications techniques. (Green and Rice, 2004)

A major contributor to the problems encountered by developers of communication protocols is the relatively high time delay experienced in underwater acoustics. The speed of sound in water is approximately $1.5\text{x}10^{3}$ ms^{-1} as opposed to RF communications with the speed of light at $3.8\text{x}10^{8}$ ms^{-1}. Further compounding the challenge, speed of sound in water can vary significantly due to variation in environmental parameters including temperature, salinity and depth shown below:

$$c = 1449.2 + 4.6T - 0.055T^{2} + (1.34 - 0.010T)(S - 35) + 0.016D$$

where T is temperature of the medium, S is salinity and D is depth. (Medwin, 1975)

A high variability in the speed of sound has the potential to create a lens effect within a water column, altering the path and concentration of acoustic energy throughout the medium. Figure 1 demonstrates a typical deep water scenario, showing the subsea deep sound channel created by the refraction of the acoustic path at different depths. This effect is much less significant in vertical transmission due to lack of multipath propagation. This makes acoustic modems a more favourable option for vertical or near-vertical applications.

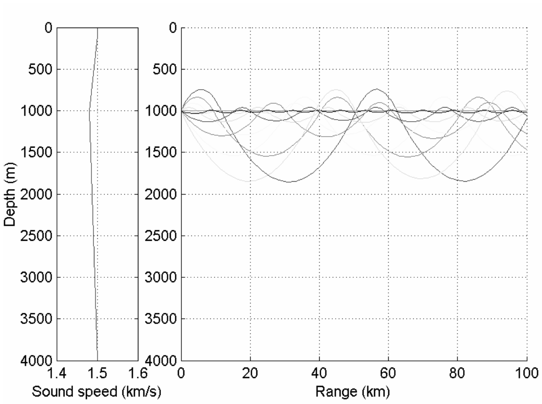

Figure 1. Acoustic ray paths in the deep sound channel. The sound speed profile (left) can distort the acoustic path, particularly in deep water (right). The transmitted signal over the given range is refracted around a specific depth rather than scattering from the sea surface and sea bed.

As communications tend to utilise the higher frequencies for increased bandwidth, it is generally acceptable to use ray theory to model the acoustic paths of the signal. This involves mapping the individual trajectories from the source:

$$\frac{dr}{ds} = c\xi(s), \qquad \frac{d\xi}{ds} = -\frac{1}{c^2}\frac{dc}{dr},$$

$$\frac{dz}{ds} = c\zeta(s), \qquad \frac{d\zeta}{ds} = -\frac{1}{c^2}\frac{dc}{dz}$$

Given the initial conditions:

$$r = r_s, \qquad \xi = \frac{\cos\theta}{c(0)}$$

$$z = z_s, \qquad \zeta = \frac{\sin\theta}{c(0)}$$

where θ is the ray launch angle with respect to the horizontal, c is the speed of sound in the medium and r and z are the range and depth co-ordinates respectively. The starting position is defined by r_s and z_s. (Jenson *et al.*, 2000)

Ray theory acoustic propagation modelling is much simpler to implement than methods required for low-frequency sources. It also allows a more intuitive way of interpreting the complex reflections from the sea surface, sea bed and other marine objects which can be treated similarly to light propagation models. (Brekhovskikh and Lysanov, 1982)

A final important factor for underwater acoustic communication is the ambient noise level in the specific environment of deployment. If the modems are in motion or in close proximity to a high marine traffic area, signal to noise ratio (SNR) considerations need to be addressed to prevent intermittent or even seasonal drop-outs in long-term deployments. This is particularly important for continuous transmissions where real-time monitoring is necessary such as environmental warning systems.

It becomes increasingly apparent that as the technology for underwater acoustic communication continues to progress, specific protocols will need to be tailored to suit the individual needs of the application. With this in mind, further challenges arise as interoperability problems between various devices can inhibit the performance. As with all methods of communication, an international standard will aid in not only the development of underwater acoustic communication techniques, but ensure their applications are compatible. (Jones, 2008)

Aims

The overall objective of this program is to determine the feasibility of utilising underwater acoustic modems for real-time sensor measurement retrieval along oil and gas pipelines. This is to be achieved by characterising the horizontal performance of various commercial modems and investigating the various mechanisms that affect the reliability of transmission.

To accomplish this, an added software layer will operate acoustic modems whilst implementing a high frequency noise logger to record ambient noise levels over the transmission bandwidth. Deployments will be performed in both shallow and deep water, with the anticipated final outcome demonstrating the feasibility of communication from deep ocean waters to the shore.

EXPERIMENTAL DESIGN

Recording and Control

In order to understand the various mechanisms affecting acoustic modem performance, an independent noise recorder was developed. A block diagram is shown in Figure 2. An integral component of the high sample rate recording system was a commercial portable Analogue to Digital Converter (ADC). With 16 bit sample rates up to 192kS/s, the ADC can output digital data in S/PDIF format via either a coaxial or fibre-optic link.

A Portable Digital Assistant (PDA) was used to receive the digital output from the ADC via a Compact Flash (CF) card. Software specifically developed for the PDA recorded the stream directly to on-board RAM or external disk. For most configurations, a 16GB portable USB drive was used. The recorder operated at 96kS/s at 16 bits, writing to disk in 20 minute (220MB) blocks.

Software developed for the PDA allowed for the custom scheduling of recording, and power management for any future long term deployments. This also provided the high level control of all components including the recorder and modems via an external low power device, the Modem Control Stack (MCS).

Designed using the Silicon Labs C8051F120 microcontroller, the MCS utilised two serial UARTs to simultaneously communicate with the PDA via Bluetooth and underwater acoustic modems via RS232. The MCS also routed power to all of the components of the recorder, becoming the hub for all power management stemming from the PDA. This provided comprehensive control of all components. With the software in its current configuration, it was possible to transmit interpretable commands over the acoustic link. These were capable of starting and stopping the recorder at the receiving end, gathering disk information or even shutting down the entire system.

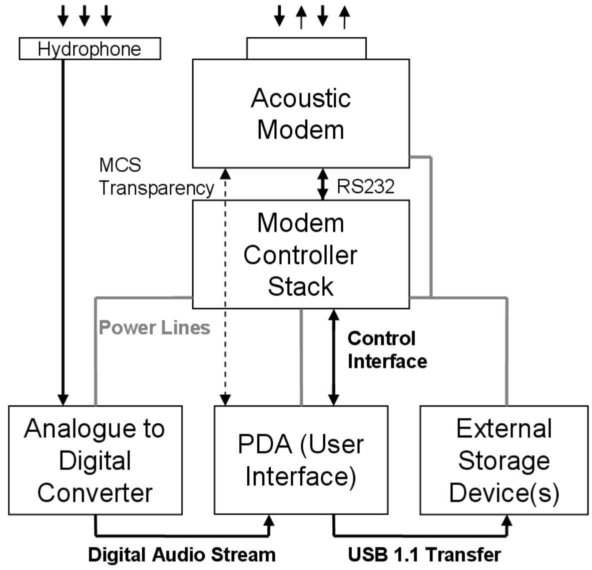

Figure 2. Block diagram of the components used to assess modem performance. With two communication interfaces, the Modem Controller Stack (MCS) can simultaneously communicate to the PDA and Modem, and also act as a transparent medium between the two for certain applications. Power management is also performed centrally, controlling all external devices.

Modem Connectivity Measurements

The first stage of experimentation involved preliminary testing of the equipment and basic modem connectivity measurements. For this deployment, a pair of short range high frequency acoustic modems was used for simple point-to-point transmission over various ranges. The modems operate over a bandwidth of 16-30 kHz and can communicate at up to 480bps. Range capabilities are documented by the manufacturer to be up to 3km depending on conditions.

When a successful transmission was received, the receiving modem sent an acknowledgement to the transmitter. For the purposes of this experiment, this acknowledgement did not affect the behaviour of the equipment during the trial, but was recorded to aid in post-deployment analysis. Furthermore, it was possible that whilst the reception of a packet may be successful, the corresponding acknowledgement signal was not decoded by the transmitter. For the preliminary analysis, the successful transmission of acknowledgement packets was assumed to correlate strongly with the quality of general telemetry and was therefore not considered.

Only the receiving modem was accompanied by a high frequency recorder. The apparatus shown in Figure 3 was laid on the sea-bed approximately 7km off the coast of Hillarys in Western Australia. It consisted of a deep water housing with the external hydrophone and modem transducer both facing upwards. The depth was approximately 22m at the deployment location.

The receiver was passive at all times until reception of the specific command “GETINFO”, after which a response containing the remaining disk space was transmitted back. This generally happened instantly, but in the event of a communication hold-up between the MCS and PDA, the time between the acknowledgement and the following data was several seconds.

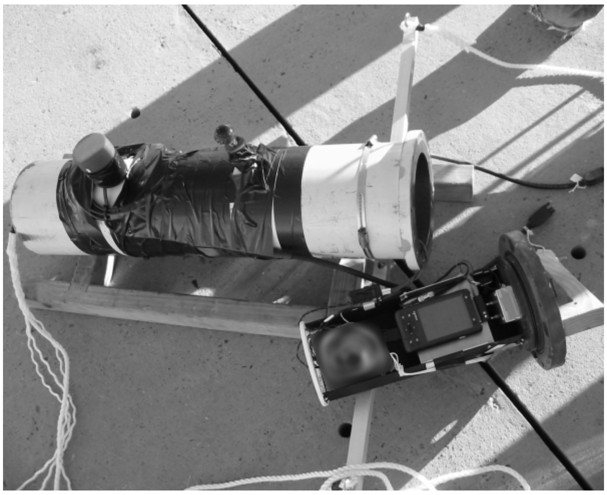

Figure 3. Deep sea housing (left) and associated recorder and modem receiver components (right).

The transmitting end of the modem pair was programmed to send two separate strings to the receiver every 30 seconds. The first of these was a test string with the maximum length of 99 bytes. The second, a modem command, prompted the receiving software to respond. Allowing the towing vessel and transmitter to drift southerly during each cast, the device was lowered in 5m increments starting approximately 10cm from the sea surface. The transmitter was bundled with a CTD probe to obtain a sound speed profile during each cast. All cast locations are marked in Figure 4. Transmitter movement was due only to vessel drift as the engine was shut off during each cast.

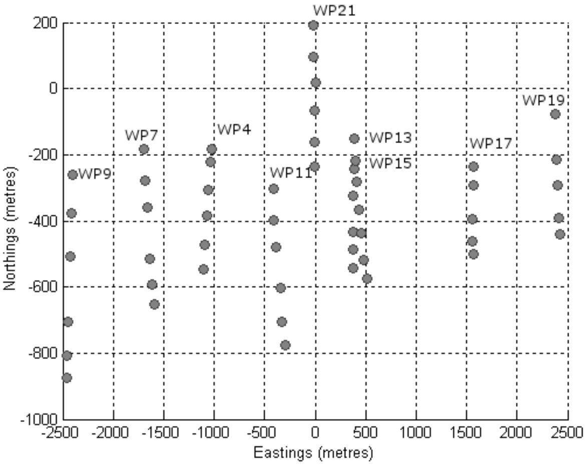

Figure 4. Positions of transmitter casts, occuring during southerly vessel drift. Each waypoint is accompanied by sub-positions denoting each 5m depth increment. Eastings and Northings are given with the origin denoting the expected position of the recorder.

PRELIMINARY RESULTS

The data showed that the hardware operated as required, although the transmission range of the modems was much less than the anticipated 3km. Specifically, correct modem operation was only observed during transects starting at WP11, WP13, WP15 and WP21 which were the four closest to the position of the recorder.

A likely cause of the low SNR over these ranges was the noisy shallow water environment where the modems were deployed. Snapping shrimp in particular were observed to be dominant sources of noise, producing a sharp “snap” capable of interfering with broadband communications (Versluis *et* *al.*, 2000). The lack of reception at longer ranges could also be attributed to an inadequate transmit power level setting of the modems or a lack of receive sensitivity.

Recorder Localisation

During the initial deployment of the recorder, the GPS co-ordinates of the vessel were documented by hand. Following the completion of the final transect, the position of the marker buoys was further south than originally recorded, including consideration of vessel drift. By determining the time delay between the modem pairs at various stages in the deployment, the position of the recorder could be numerically confirmed.

This involved assuming a homogenous horizontal channel at relatively long ranges to eliminate inclusion of depth. Considering only the initial direct acoustic path between the transmitter and receiver, the distance between the recorder and the position of the vessel, r can be determined:

$$r = \frac{(t_w - t_d).c_w}{2}$$

Here, t_w is the time between the falling edge of the transmitted packet and the rising edge of the received acknowledgement. The internal modem delay, t_d was measured to be about 0.25 seconds and speed of sound in water c_w, $1500ms^{-1}$.

By interpolating the position of the vessel's internal GPS co-ordinates, several measurements of the time delay at various waypoints can be used to further approximate the position of the recorder. Figure 5 demonstrates how circles of known radius confirm the location of the recorder to be 280m south of the documented position.

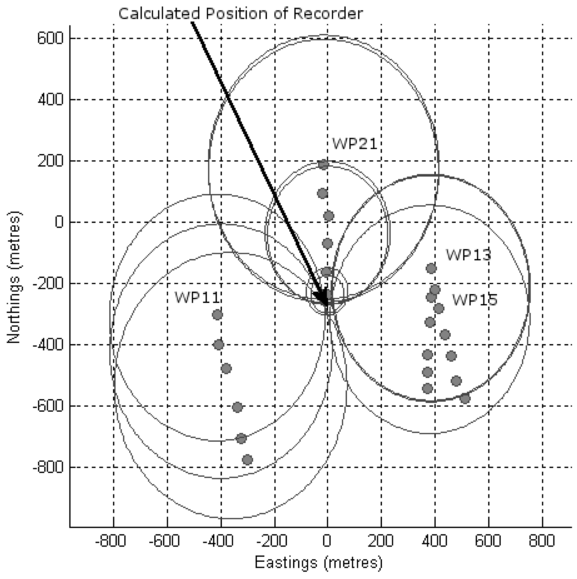

Figure 5. Localisation of the recorder. By determining the time delay of the modems at various points, circles of known radius successively approximate the position of the recorder using the point of convergence. The recorder was determined to be 280m south of the expected position, indicating the hand recorded GPS co-ordinates were incorrect.

Signal Strength

Although the quoted operational bandwidth of the modems was between 16 and 30 kHz, the recorder detected an acoustic signal occupying a frequency range of approximately 14 to 23 kHz. Figure 6 asserts this, demonstrating a typical sequence of transmission. This includes a long packet, followed by the "GETINFO" command and the associated responses of the receiver modem.

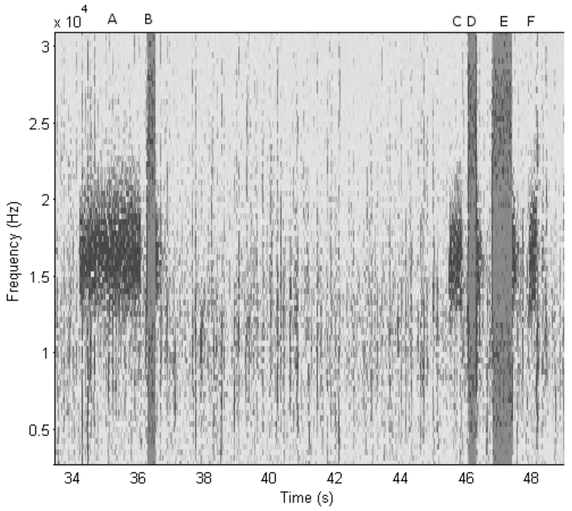

Figure 6. Spectrogram of various stages of modem communication. The observed clipping is due to the proximity of the receive hydrophone to the transducer. (A) Large test packet is received. (B) Acknowledgement is returned. (C) "GETINFO" Command received. (D) Acknowledgement returned. (E) Receiver returns requested information. (F) Transmitter returns acknowledgement.

By analysing the high frequency recorder data, the signal strength of the transmitter at various positions was determined. A 32 sample FFT was calculated over 5 millisecond blocks of data for the entire set. This produced three bins of interest with frequencies ranging between 15-24k Hz. By averaging these, the power level versus time over the frequencies of interest was obtained, shown in Figure 7. An algorithm was also developed to determine where a transmission had occurred and a marker placed at the location of the average acoustic power for that transmission. This was primarily useful for determining the received signal strength.

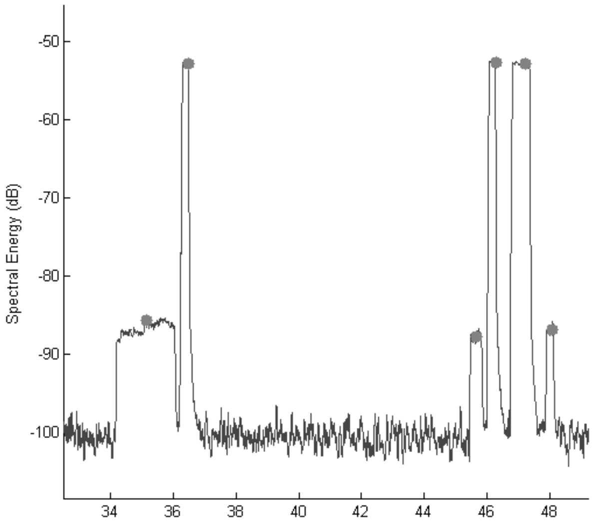

Figure 7. Power level versus time for typical communication sequence. From the same signal depicted in Figure 6, by averaging the power spectrum over frequencies of interest, the power level versus time illustrates the two way telemetry of the devices. Circular markers denote the software's signal detection algorithm.

The primary source of transmission loss over range, r in this deployment can best be approximated with spherical spreading (Jenson *et al.*, 2000). This is given by:

$$TL = 20\log_{10}(r)dB \qquad [1]$$

The modem separation distance for each detected signal was determined using the known GPS co-ordinates recorded electronically by the vessel. A compilation of signal strength observed by the recorder over the entire deployment was produced and the transmission loss compared to [1]. Figure 8 demonstrates good agreement with spherical spreading at short range, with a stronger than expected signal at longer ranges.

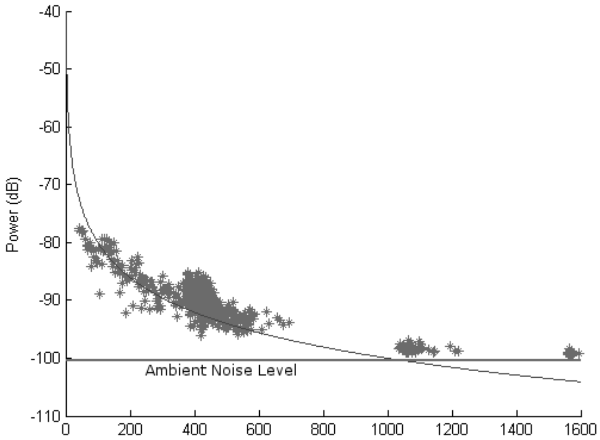

Figure 8. Signal strength as observed by the recorder. The observed transmission loss was also compared to the estimate for spherical spreading.

Modem Reception

When processing the modem response during the deployment, it was confirmed that the operating range was much shorter than expected. Analysis shows this was most likely due to the lack of sensitivity of the receiving modem combined with the lack of power from the transmitter. This would attribute the lack of performance to the signal strength rather than a complex multipath environment having an impact on the internal processing of the modem in this case. Displaying both the transmitter and receiver modem signal strength data, Figure 9(a) shows how the perceived signal strength was minimal towards ranges of 500m or more. In addition, the modem success rate can be shown to significantly decrease at this point, depicted in Figure 9(b).

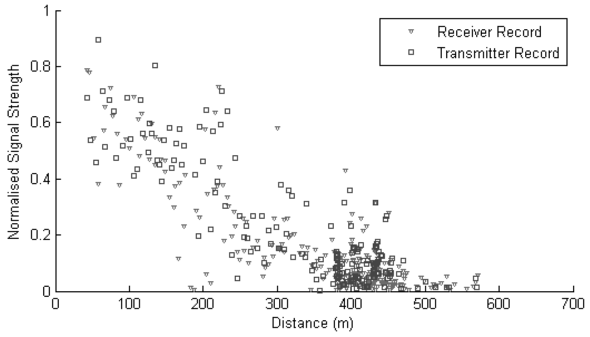

Figure 9(a). Signal strength as observed by the modems. The correlation between the transmitter and receiver illustrates similarity between the power of both modems, as well as confirming lack of a reception beyond 500m.

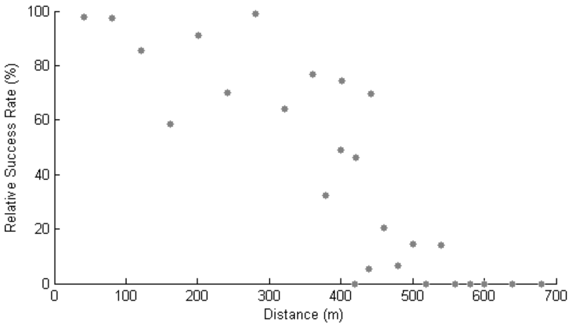

Figure 9(b). Relative success rate versus distance. By binning the success rate over 40 metre blocks, an observed steady reception rate dramatically decreased beyond 500m, correlating to the lack of signal strength shown in (a).

It was found that beyond 500 metres, the performance of the modems continued to drop. This corresponded to recorded signal strengths also falling to minimum levels. However, the high frequency recorder was able to detect signals at greater distances shown in Figure 8.

Data received by the modems was of high quality with no documented errors. However, this was most likely due to error correction techniques of the internal software. The error statistics could not be obtained for the specific modem used, although debugging information is expected to be available with the long distance modems that will be used for the second trial.

It was discovered that the internal software of the modems was unable to adequately process the reception of long ASCII strings. Whilst an acknowledgement packet was returned, data from the modem to the serial host was never received for the 99 byte packet. This test string was used to help assess the error rate of the modem during transmissions of a significant length.

Other small and unrepairable internal faults including host-modem communication errors occurred during other tests, further demonstrating the limitations of using commercial equipment. Nevertheless, these problems can usually be overcome with work-arounds such as high level packet control.

CONCLUSION

The first of several planned deployments, this trial has given insight into the shallow underwater performance of commercial acoustic modems. It has been determined that the reliability of communications in this specific case can not be accurately predicted due a large variance in the modem responses as well as some internal bugs. However, communications were still very effective within a range of approximately 500m. Measurements from the high frequency noise recorder also suggest that with more developed signal processing techniques, improved range may be achievable with the same output power.

Ultimately, the range of underwater acoustic modems is expected to be primarily dependant on the output power for most ocean-to-shore telemetry. In further trials, planned modification of this parameter will aid to better understand its impact on performance. Furthermore, the sensitivity levels of the modems will be varied; however, the signal strength measured from the modems themselves suggest modifying this parameter may not yield better results. In many circumstances such as noisy environments, this may further degrade the overall performance.

Although the initial deployment was planned only to test the recently developed hardware, the results have made a significant impact on future plans. Firstly, a technique to assess the performance of the modems in real-time during each transect will be programmed into the PDA or MCS software for the next field trial. This will help avoid wasted effort in deploying in an area where the apparent signal strength is below the noise floor, such as WP7, WP9 and WP19 in this trial.

It is expected that the next experiment will involve the use of long range modems designed specifically for horizontal underwater transmission. In addition, the anticipated working relationship with the modem manufacturer will greatly assist in post-deployment data analysis. Later in the program, it is hoped that simultaneous communications can be performed with both pairs of modems in a similar environment. This will start with a range test similar to this trial; and culminate in a long-term deployment of several days.

ACKNOWLEDGEMENT

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