Reliability in Underwater Acoustic Networks

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ABSTRACT

The concept of communications networks for underwater sensors and systems is emerging as a viable and relatively inexpensive method for relaying sub-sea data to the broader terrestrial network. The underwater environment however, presents an extremely challenging and variable communication channel, and has thus far prevented the widespread commercial realisation of underwater networks. This paper describes the major pitfalls of underwater communications and the methods and principles that have been applied by L-3 Nautronix to maximise reliability in underwater communications services.

INTRODUCTION

Underwater communications have advanced considerably during the last decades, and much effort has been applied to the improvement of the physical and data-link layers of the communications systems. Some of the improvements have benefitted from the application of technologies that have been proven in the rapidly advancing wireless systems used for consumer computer networks. However, many of the innovations in radio communications are not applicable to acoustic communications, due to (a) the slow propagation speeds and subsequent frequency dependent Doppler related issues, and (b) the high variability in noise conditions.

Some of the conditions that are specific to the underwater channel may be reasonably simulated in the laboratory, while for other factors, the uncertainty and variability remains less well defined. Predicting attenuation and available bandwidth for steady-state (idealised ocean) conditions is straightforward, whereas understanding the dynamic range of the noise environment or the dynamics of platform and surface motion and how that impacts the communications reliability requires physical testing to ensure defendable verification.

The concept of operations for the envisioned network may include a variety of different platforms, some of which for instance may be static and quiet and away from other noise sources, some may be moving and noisy, while others may be subject to the influence of highly variable noise fields. It is the variability of the environment that presents the greatest challenges in maximising the communications channel.

The tradeoffs between initial set-up costs, required throughput, network longevity (i.e. hours/days/years) and maintenance costs must be evaluated on a case-by-case basis.

POINT-TO-POINT RELIABILITY

Before attempting networked communications, reliable communications between two points should be established. Typically, this is initially demonstrated in simulation, followed by a series of experiments with gradually less constraints; starting in a laboratory (test-tank) environment and continuing until finally a system can be shown to be reliable, “out-of-the-box”, in a broad range of ocean conditions. A significant operating margin or performance headroom is sensible in order to maximise reliability in all conditions.

Uncertainty in the location of network nodes

Accurate positioning and rotation of subsea nodes is time consuming and expensive, and in many cases nodes may be mobile. Therefore it is highly advantageous to enable communications for arbitrary geometries (with obvious limitations for range). This can be achieved by (a) steering a narrow beam, or (b) using a wide beam. The former is more power efficient in acoustic transmission, and dramatically reduces problems associated with ambient noise and multipath reverberation, however it requires expensive multi-element hardware which requires beamforming and potentially multiple parallel demodulation processors. For systems that may not be recovered, omni-directional transducers present the simplest and most cost-effective solution. The problems associated with noise and reverberation shall be addressed here with the assumption that the transceivers are omni-directional.

Uncertainty in the noise environment

The underwater acoustic noise environment varies with surface condition, water depth, and the influence of mechanical and biological sources.

Biological noise from snapping shrimp (in shallow water) and propeller cavitation noise extends beyond 100 kHz, and may be highly localised, both temporally and spatially (as seen in the examples in Figure 1 and Figure 2). Choruses of snapping shrimp are very broadband and high in noise spectral density; 65 dB re 1 µPa^2/Hz at 10 kHz is common [Cato & Bell 1992], and in the vicinity of highly featured bottoms or pylons L-3 Nautronix have recorded noise densities approaching 90 dB re 1 µPa^2/Hz at around 10 kHz (for one second averages). Worse still, individual shrimp snaps may have source levels up to 170 dB re 1 µPa, which can temporarily saturate a nearby receiver and corrupt short sections of received data. The recovery time of the receiver may be significantly longer than the actual shrimp snap duration, which is less than 10 µs for the upper 10 dB of the signal envelope [Cato & Bell 1992].

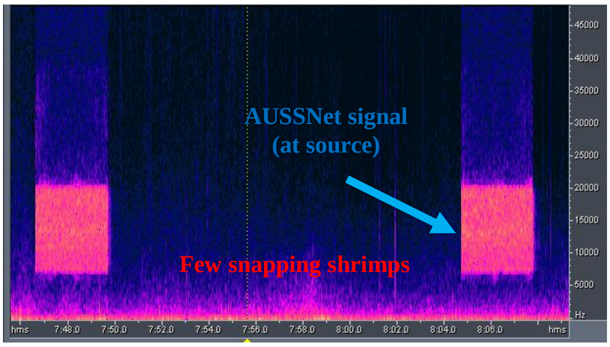

Figure 1. Shallow water Ambient Noise (Cockburn Sound, WA at 12:00 pm 24-Jun-09)

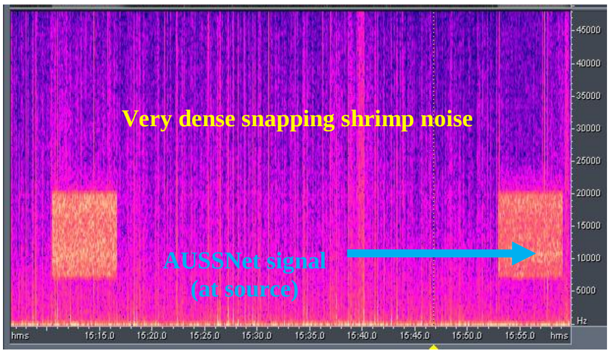

Figure 2. Shallow water Ambient Noise (Cockburn Sound, near armaments jetty WA, at 12:00 pm, 24-Jun-09)

Other noise sources

Surface conditions alone can vary the ambient noise by nearly 40 dB, considering the variations from from sea state zero (as low as 35 re 1 μPa^2/Hz at 10 kHz) to heavy rain (close to 75 μPa^2/Hz at 10 kHz).

Long range shipping noise is relatively benign in its impact on underwater communications, however the noise from a nearby vessel or platform may be highly variable, when the vessel is changing its condition (especially with dynamic positioning thrusters), and highly directional. The directivity of the vessel noise is also frequency, and vessel state dependent, and difficult to predict.

MITIGATING NOISE

Mitigating ambient noise fluctuations

By measuring the noise environment and the channel conditions, communication systems can be optimised for maximum reliable throughput in an acoustic channel without wasting power (and hence endurance). However, acoustic communications are slow, due to slow propagation speeds and limited bandwidth, and channel conditions may change considerably within the duration of a single transmission.

Due to the long propagation delays, continuous evaluation of the received signals and the environment and adjustment of the transmitted signal characteristics (e.g. packet by packet) is not possible. At best, long sections of communication signals may be optimised at transmission for data rate, power, and processing gain, and then analysed on a packet-by-packet basis on reception using a real-time *channel probe* and adapted accordingly. Many systems include a channel probe ahead of the main data transmission to assess the channel impulse response on reception of the channel probe, apply a single channel equalisation for the following data signal, and are compromised by the temporal channel variations that occur during a signal transmission.

The L-3 Nautronix modems include a dedicated channel which is tranmsmitted in parallel to the data and used for high accuracy timing synchronisation and for assessment of and compensation for the channel impulse response on a *symbol-by-symbol* basis.

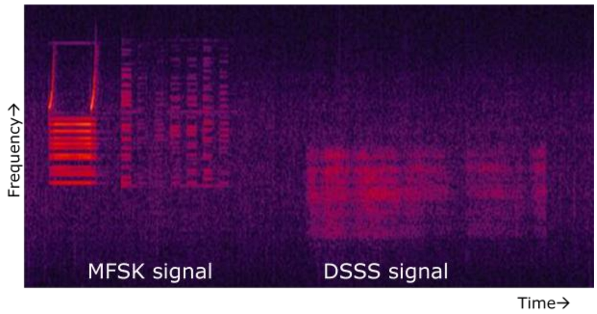

Figure 3. Channel probe followed by MFSK signal (left): received with many errors, and a DSSS signal with real-time channel probe (right): received with zero errors. Signals were recorded in 10 m water depth near Kiel, Germany. Range: 2-3 km

The L-3 Nautronix modems may also be utilised to optimise for data rate/processing gain (enabling reception at from -3 to -12 dB SNR) and power (from 160-192 dB re 1μPa) at *transmission*. Note that at the time of writing some of the decision making for optimising the signal transmissions must be relegated to the application layer software (i.e. external to the DSP modems). The process for optimisation at transmission is summarised below.

Firstly, signal power level, processing gain and data rate are autonomously adapted for a particular signal transmission using diagnostic information retrieved from previous transmission(s). Some SNR headroom is allowed for variability in noise levels that may be encountered within one signal transmission, based on the noise variation statistics of previous transmissions. This headroom is a combination of (a) signal power (limited by system and cavitation limits), and (b) by increasing the time-bandwidth product of the signal symbols, and thereby trading data rate for processing gain (i.e. utilising a wider bandwidth or a longer duration per symbol to increase processing gain). An implied benefit of this trade-off is covertness - high processing gain enables signal reception at low, even negative SNRs, and such signals are therefore more difficult to detect by non-cooperating receivers. Figure 4 shows a signal received at very low SNR by virtue of high processing gain.

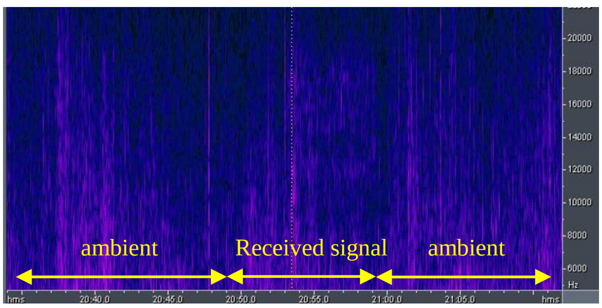

Figure 4. AUSSNet signals received at very low SNR (Cockburn Sound, WA on 24-Jun-09)

Mitigating self-noise

Given that a system has adequate signal power to operate in a particular channel, the communications reliability of an otherwise operational system is limited by self noise; coherent and incoherent multipath reverberation. Incoherent multipath may be treated as any other noise source, and mitigated by processing gain, which can be achieved by a number of methods, including the integration of coherent communication signals (e.g. by using coded sequences). Coherent multipath (distinct echoes) presents a slightly deeper problem, particularly when the multipath signal is strong, and the delay is long compared to the duration of an information symbol.

A useful analytical model for approximating the relative levels of coherent and incoherent multipath reverberation is given in the [APL-UW, 1994] wherein the coherence of the reflected signals is expressed as *pulse elongation.* Understanding delay spread and the relative level of multipath reverberation for the deployed environment of interest is crucial to avoiding multipath induced *Inter-Symbol Interference (ISI)*, which is a key inhibitor of acoustic communications. The APL method is repeated here:

$$L = \frac{2r_1 r_2}{r_1 + r_2}\frac{s^2}{c}\left(1 - e^{-\frac{\theta}{\gamma_0}}\right)$$

Where

L is the pulse elongation (s)

r_1, r_2 are the incident and reflected specular path lengths (m)

s is the rms surface slope (m)

c is the sound velocity (m/s)

θ is the grazing angle (radians)

$\gamma_0 = \tan^{-1}(s)$

The pulse elongation L gives an indication of the coherence and the coherence bandwidth ($1/L$) of the surface reflection.

The envelope of the reflected intensity for a single specular surface interaction and associated reverberations may be estimated, based on the equation above and assuming a generic rough scattering model $R'(\theta) = R(\theta)e^{-0.5\Gamma^2}$ for the reflection coefficient $R(\theta)$ with Rayleigh roughness parameter Γ less than 2:

$$I(\tau) = \frac{I_0 A_0}{(r_1 + r_2)^2}\left| R'(\theta) + \begin{cases} 0 & \tau \le 0 \\ \Phi\left(\sqrt{\frac{\tau}{L}}\right) & 0 \le \tau \le \tau_0 \\ \Phi\left(\sqrt{\frac{\tau}{L}}\right) - \Phi\left(\sqrt{\frac{\tau - \tau_0}{L}}\right) & 0 \le \tau \le \tau_0 \end{cases} \right|$$

Where

$\tau = t - t_s$ (s)

t_s is the specular path time-of-flight (s)

τ_0 is the signal pulse length (i.e. symbol length) (s)

I_0 is the transmit pulse intensity

A_0 = unit area

$\Phi(x)$ is a probability function defined by

$$\Phi(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

Applying these expressions and assuming a low sea surface roughness (obtained from windspeed derived estimates using the Pierson-Moskowitz Sea spectrum), it is evident that surface reflections may be very strong and coherent, as in the model shown in Figure 5.

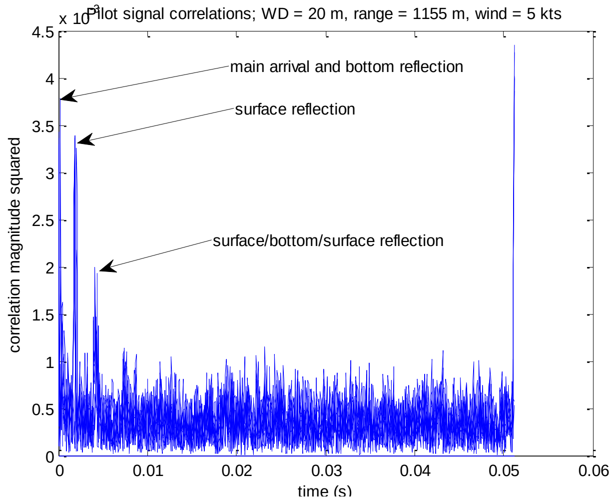

Figure 5. Multipath reverberations, shown as received signal correlator output modelled for a shallow water case, with windspeed set to 5 knots: Multipath is strong and coherent.

Repeating these simulations for a variety of environments provides an indication of the multipath delay spread that could be expected for those environments, and sets guidelines for the symbol rate of a potential communications system. Figure 6 shows the predicted multipath delay spread for the same environment as used in Figure 5, but with variation in the rms surface slope (due to windspeed). Note that increasing the windspeed reduces the delay spread.

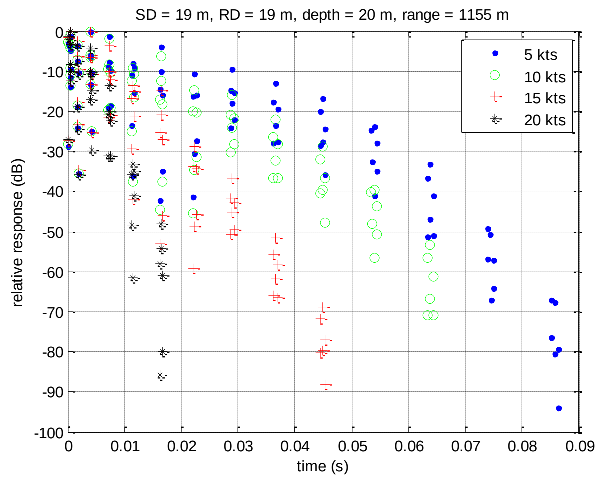

Figure 6. Modelled shallow water multipath level and delay spread variation with surface conditions (wind speed in kts)

Multipath signals that are of comparable level (i.e. within 3 dB) to the first arrival are shown in Table 1 for selected water depths and communication ranges.

Table 1. Modelled Multipath spread for bottom mounted transceivers

Water Depth (m)	*Range* (km)	*channel spread* (ms)
20	1	5
20	2	5
150	1	25
150	2	15

Improving the data rate

Considering that ISI can be avoided by setting the symbol rate longer than the channel multipath delay spread, the modelled examples above imply that the maximum symbol rate is somewhere between 40 and 200 symbols per second. This is obviously very slow, but it can be improved significantly by use of modulation techniques that make efficeint use of the transmission bandwidth. A short selection of contemporary techniques is summarised as follows.

Orthogonal frequency division multiplexing (ODFM) systems allocate portions of the bandwidth to separate carriers; this method is common in RF and wired communications and is very bandwidth efficient (carriers may theoretically be separated as closely as $1/\tau_0$Hz, where τ_0 is the symbol duration). However, ODFM is sensitive to the frequency selective nature of multipath induced fading that is typical in horizontal underwater acoustic propagation channels; some bandwidth allocations will perform better than others in a way that is very sensitive to the relative geometries of source and receiver, and water depth. For reliability in multipath affected channels, OFDM requires striping of data across multiple bandwidth allocations [Chitre *et al*, 2008], which adds complexity and reduces the data rate. Also, a Doppler affected signal will require separate corrections for each sub-band, which add significantly to the processing load.

Swept-carrier modulation is a technique which can be used to effectively mitigate multipath interference problems with relatively high bandwidth efficiency. The carrier over which the information is modulated is shifted constantly (swept), so that the signals received from direct arrivals are separated in frequency from the multipath arrivals. If the sweep rate is chosen carefully, multipath reflections will arrive at the receiver outside of the (shifting) band of interest, as the demodulating carrier is swept to match the carrier frequency at transmission [Cook 1999]. A method of phase shift keyed (PSK) encoding, using a swept carrier (i.e. Sweep Spread Carrier S2C) has been implemented by Evo-Logics since 1999 [Kebkal & Bannasch, 2002]. The resistance of swept-carrier modulation signalling to bandwidth specific or impulsive noise may be improved at the expense of efficiency (data rate) by increasing the channel coding overhead, and effectively spreading the length of the symbols in time (and therefore, by virtue of the swept carrier, in frequency also).

Alternatively, signals can be made resistant at the physical layer to impulsive noise, coherent multipath, frequency selective fading, and overall low SNR at the receiver, by use of direct sequence spread spectrum (DSSS) signalling.

Using DSSS signalling, the symbols are PSK encoded as long bipolar pseudo-random number sequences (codes) over a single, constant frequency carrier. Each information bit is spread over the entire transmission bandwidth, and the fading or blocking of particular frequency bands has the comparatively benign effect of proportionally lowering the overall processing gain. For example, if only half of the bandwidth of the transmitted signal arrives at the receiver (e.g. which could be due to multipath fading or noise), the net processing gain is reduced by 3 dB.

The DSSS data rate may be improved using a variation of *code division multiple access*; transmitting multiple codes in parallel. This is the method predominantly used by L-3 Nautronix, and has thus far enabled data rates of the order of 1 kbps to be transmitted reliably over up to around 10 km in shallow water, high noise environments. The L-3 Nautronix modems also hold the record for the deepest operating digital communications system, between a noisy surface ship, and the bottom of the Mariana Trench (10.9 km deep), in March 2012. [Roberts *et al*, 2012].

RELIABILITY IN UNDERWATER ACOUSTIC NETWORKS

If a point-to-point communication fails, the necessary retry event imposes a significant throughput penalty due to the long propagation delays. This penalty is compounded with the inclusion of multiple nodes, having the net effect of futher reducing the overall throughput. Also, the broadcast nature of omni-directional transmission may be expected to result in potentially interfering node pairs. Interference can be mitigated by time, frequency, or code diversity, at the cost of futher reductions in overall throughput. Constraining a network to the simplest and smallest topology that satisfies the operational requirements therefore is a sensible approach for minimising cost and complexity and maximising data throughput.

One such simple network topology is the *star*, or *clustered network*, as demonstrated by the Autonomous Underwater Surveillence Sensor Network Capability Technology Demonstrator (AUSSNet CTD system) [Ghiotto & Roberts, 2011], and illustrated in Figure 7.

Cluster Network Topology Example - AUSSNet

Control of the AUSSNet cluster network is maintained by a master node, or Access Node. This node operates autonomously and may be interrogated by a human operator, over either a SATCOM or acoustic communications link. All peripheral nodes communicate directly with the Access Node. Zero probability of network collisions may be easily achieved by mandating that all communications involving the peripheral nodes must be solicited by the Access Node.

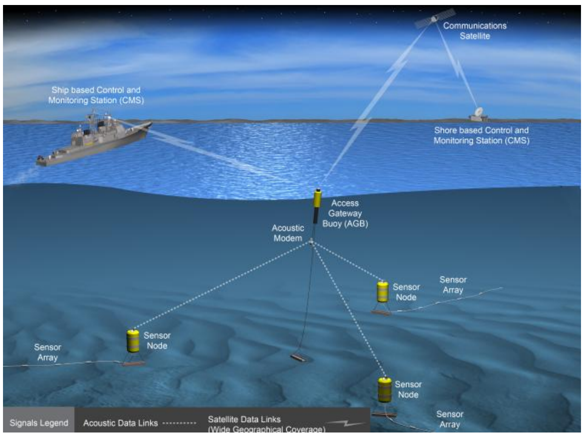

Figure 7. Star network example - AUSSNet

The acoustic reliability and effectiveness of AUSSNet has been demonstrated in conjunction with a number of high profile military exercises including the large scale US-Australian joint exercise *Talisman Sabre 2011 (TS11)*, during which AUSSNet acoustically relayed the captured signatures and geospatial tracks of navy and merchant vessels and test vehicles that had been autonomously detected and processed by the AUSSNet Sensor Nodes.

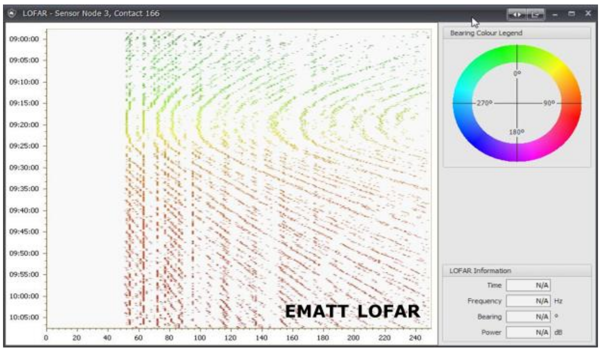

Figure 8. Example of processed sonar data of AUSSNet detected target at TS11, acoustically relayed.

Cluster Network limitations

The star network, does however present the Access Node as a risk of a *Single Point of Failure.* Redundancy in the Access Node with (a) the use of multiple, mobile Access Nodes, or (b) rapidly deployable Access Nodes is potentially a method for reducing this risk.

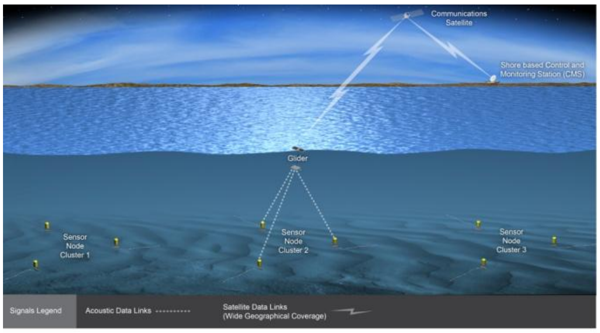

Figure 9. Cluster Network Access Node redundancy with multiple mobile gateways.

Acoustic network scalability

The cluster network is ideal for small numbers of nodes, however for installations where the geographic coverage requires a large number of nodes, it is likely that some nodes will be significantly further from an Access Node than others. The example in Figure 10 shows a sensor network that might be deployed for surveillance of a coastal area, requiring multiple nodes deployed in a ‘string’. In this case, a cluster network is not appropriate, and multi-hop communication provides the most power and data rate efficient method for acoustic communication over the length of the ‘string’ [Benson *et al*, 2007]. Networks utilising multi-hop communications require routing redundancy in order to avoid single points of failure at any particular node. For a ‘string’ network, routing redundancy requires signal transmission over significantly longer distances than that between neighbouring nodes; a mode that is best reserved for operation only when node failure occurs.

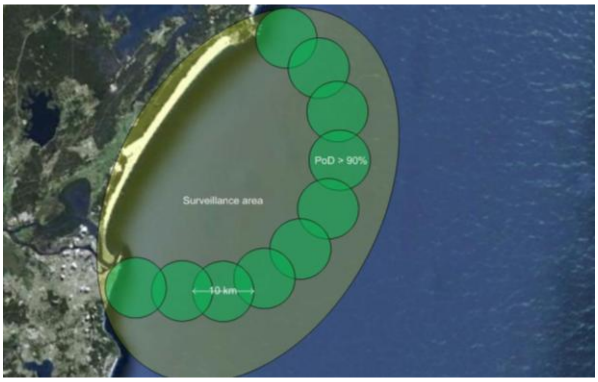

Figure 10. Sensor Network deployment for coastal surveillance in a ‘string’ network.

Intriniscally redundant network topologies

More sophisticated network topologies, such as the *mesh* networks used in Mobile Ad-hoc Networks (MANET) include redundant paths between nodes at the expense of extra network traffic and higher routing complexity. While they hold promise, underwater acoustic mesh networks at this stage remain a subject of research and development, and demonstration may be limited by the costs of production, deployment and recovery of the large number of nodes (compared to simpler networks) required to demonstrate the benefits of such topologies.

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REFERENCES

Cato D H and Bell M J, *“Ultrasonic Ambient Noise in Australian Waters up to 200 kHz”,* MRL-TL-91923 Materials Research Laboratory DSTO 1992

“*APL-UW High-Frequency Ocean Environmental Acoustic Models Handbook, 1994”,* Technical Report APL-UW TR 9407 Applied Physics Laboratory, University of Washington, October 1994

Chitre M, Shahabudeen S, Frietag L & Stojanovic M, *“Recent Advances in Underwater Communications and Networking”,* 978-1-4244-2620-1/08 IEEE 2008

Cook G, *“A Swept-Carrier Technique for Underwater Acoustic Communications”*, PhD Thesis, University of Western Australia, Australia 1999.

Konstantin G Kebkal, Rudolf Bannasch, *“Sweep-spread carrier for underwater communication over acoustic channels with strong multipath propagation”,* J Acoust Soc Am. 2002 Nov; 112 (5 Pt 1):2043-52 12430816

Roberts P, Andronis N, & Ghiotto A, *“Voices from the Deep – Acoustic Communications with a submarine at the bottom of the Mariana Trench”* L-3 Nautronix, Australian Acoustical Society Conference (Acoustics 2012) (2012)

Ghiotto, A & Roberts P 2011, “*AUSSNet Talisman Sabre 2011 Final Report”*, L-3 Nautronix, Fremantle WA, 2011

Benson C, Ryan M, Frater M, *“High-Capacity Underwater Communications”,* MILCIS2007, Canberra, ACT, 2007