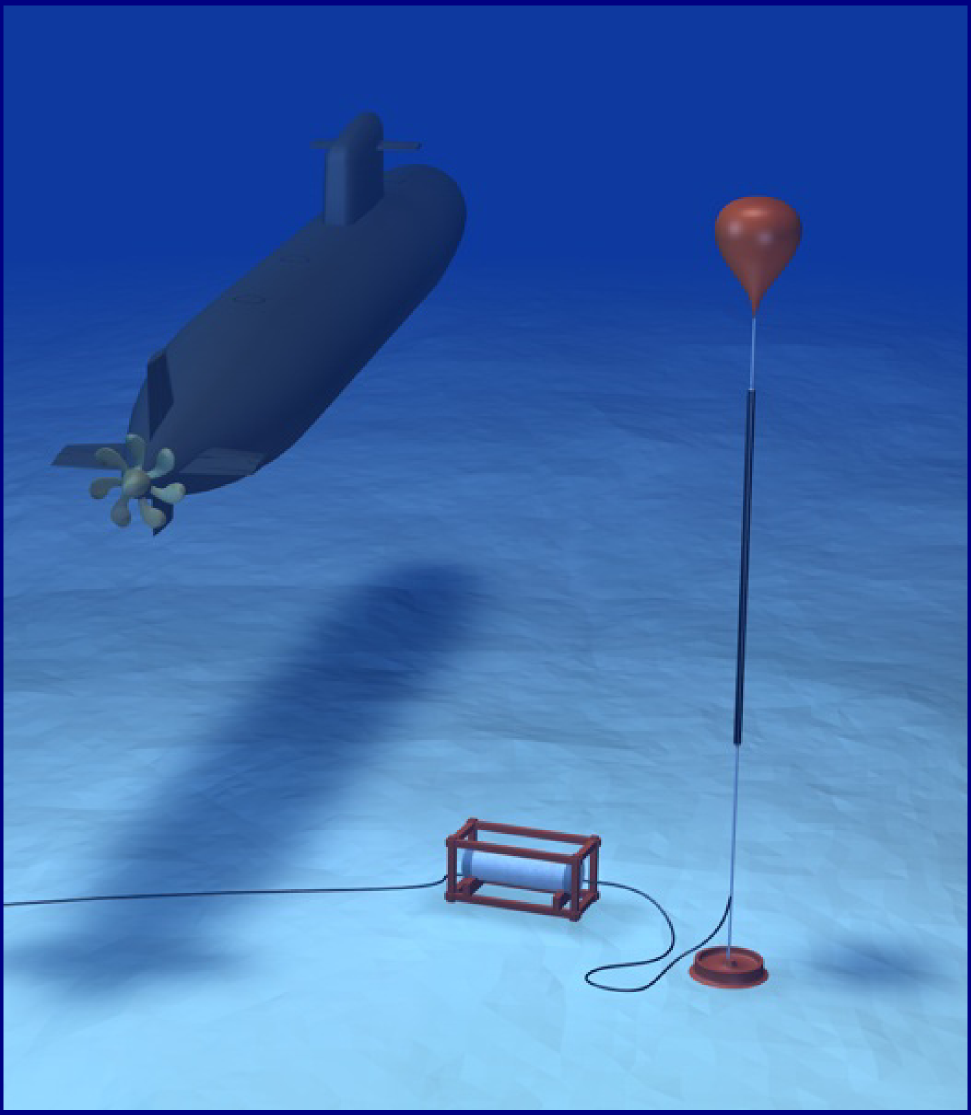
RADIATED NOISE RANGING FOR SUBMARINES



A DISCUSSION PAPER ON THE PRINCIPLES OF NOISE RANGING AND SYSTEM IMPLEMENTATIONS

XENTHOS

COMMERCIAL IN CONFIDENCE

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1 INTRODUCTION

With a continuing emphasis on the detection of submarines by acoustic means, the evaluation of the radiated and passive signature of the submarine has been an enduring activity. Indeed, as early as 1917, the Royal Navy (RN) employed sea lions in an experiment to assess their ability to detect enemy submarines. Whilst that experiment may not have been a particularly rigorous scientific effort, the period since the Second World War has seen a continuous leapfrogging of detection and noise reduction technologies. Today's technologies represent the efforts of some 50 years of concerted development across the industrialised world. A modern submarine will radiate less than 10 to 20 parts per million of its total shaft horsepower power as noise[1] and present a signature which is commensurate in many cases to the surrounding environmental noise. Detection of such a vessel requires an equally advanced capability in underwater acoustics; very high gain arrays of sensors and an associated processing facility that exploits every statistical aspect of the radiated noise signature.

Today, the management of acoustic stealth and noise hygiene is an essential part of submarine operations and management. In order to be able to quantify and determine the success and efficiency of those noise management efforts, it is necessary to have the capability to measure the radiated noise signature under conditions that will provide both repeatable and transportable results. Furthermore, in order to evaluate the operational vulnerabilities of the vessel it is necessary to possess a full knowledge of the behaviour of the acoustic signature under the full range of vessel operating conditions.

However, in an era when the large capital expenditures that were common during the cold war period are no longer available, there is an ongoing requirement to be able to reduce the cost of vessel operations and support whilst still maintaining the same capabilities. Thus, today's submarine operator is facing the invidious situation of being required to provide more capabilities with less money. Under these circumstances the operators must seek out lateral solutions to achieve their objectives.

This document describes some of the issues associated with acoustic ranging and proposes a number of 'lateral solution' affordable options available to the submarine navies to achieve a baseline measurement capability.

[1] "Hide and Seek, The 1995 Mike Adye Lecture", Peter Ewins, Chief Scientist – UKMOD. Journal of Defence Science, Vol 1 No. 4 October 1996.

2 SUBMARINE ACOUSTIC RANGING

In seeking a technical solution to any complex technical issue it is imperative that the requirement be well understood by both the client and the system designer. Underwater acoustics certainly qualifies as a complex technical issue and the imperative is well placed.

In evaluating the radiated noise signature of a submarine a number of motivating requirements recur. While not exclusive, they include:

- Contract Acceptance
- Routine Hygiene
- Baseline Measurement
- Signature Reduction Efforts
- Vulnerability Assessment
- Each of these requirements has a different scope

2.1 SYSTEM DESIGN

In assessing the viability of any radiated noise measurement system it is necessary to evaluate the system figure of merit (FOM). The FOM is defined by the modified sonar equation

$$FOM = SL + TL + DI - DT - NL$$

Equation 1

Equation 1 defines the system Figure Of Merit (FOM) as a function of the source level (SL), path transmission loss (TL), directivity index of the receiver (DI), detection threshold (DT) and ambient noise level (NL).

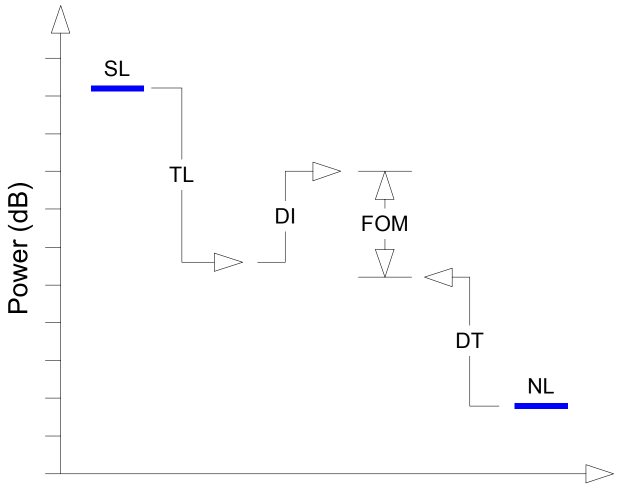

Figure 1 - Conceptual view of modified sonar range equation

A conceptual view of the modified sonar range equation, as it applies to radiated noise measurement is depicted in Figure 1. The source level radiated by the target vessel is attenuated by the transmission loss inherent in the propagation path to the receiver. The receiver may include some gain component over the ambient noise denoted as the directivity index. The noise level at the receiver must be exceeded by some amount, the detection threshold to guarantee reliable

measurement. The difference between the two described quantities is then described as the figure of merit. Obviously the greater the figure of merit, the more reliable the operation of the system will be. This section includes a brief discussion on each of the constituent components of the modified sonar equation in relation to acoustic noise ranging.

2.1.1 RADIATED NOISE SIGNATURE (SL)

The radiated noise signature or source level comprises three components, namely transients, tonals and broadband noise. Each of the three components has a different causative mechanism(s) and there are no strict differentiation criteria between each of the three components:

- Tonals – Narrow band components with extended temporal coherence time. Commonly derived from electronic components, pumps, fans etc with constant speed excitation. Not commonly generated from diesels or internal combustion engines due to the reciprocating action of the engine. At very low frequencies, tonals can be generated at the propeller blade rate frequency.
- Broadband - The main causative mechanism for the broadband component of the signature is machinery noise but broadband components are also generated by turbulent flow over the hull, boundary layer noise, and vortex shedding. Broadband components can generally be traced to complex turbulent phenomena, either internal or external to the pressure hull.
- Transients - Transients are by definition of short time duration and are often a function of the operation of the vessel, eg depth changes and the resultant structural compensation; movement of manoeuvring planes; opening of bow caps; transgressions of noise hygiene practice; etc

It is not possible to describe all the possible causative mechanisms for each of the signature components within the scope of this document and there is considerable overlap between the definitions. However, while only very limited information is available in the public domain on acoustic signature levels, the general nature of a submarine signature can be derived from first principles and references.

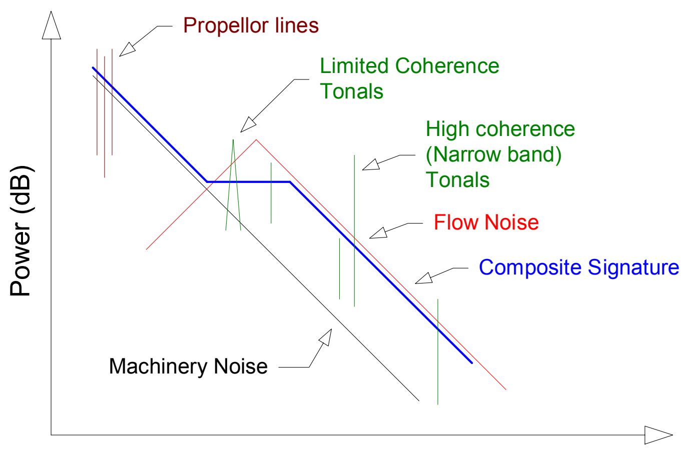

Figure 2 - Conceptual view of generic submarine signature

Figure 2 shows a conceptual view of a generic submarine signature. It is not representative of any class of vessel and is a composite of material

that is available in the public domain. The general form of the signature is a peak at low frequencies representing the machinery noise with a break point introduced by the increasingly dominant presence of flow noise at a frequency of a few hundred Hertz. The signature tends to flatten at frequencies greater than the break point and then tapers off relatively rapidly at the higher frequencies. Of note are the tonal components, generated at low frequencies by the blade rate and at mid frequencies by various equipment sources. Note that tonals can also be present at high frequencies and, depending on their frequency and propagation viability, can represent a serious threat to vessel vulnerability.

It would be some measure of understatement to say that the radiated noise signature of a submarine is highly variable (to just about everything). However, it is particularly sensitive to the speed of the vessel. Ross[2] reports that the cumulative radiated noise for a surface ship in the range of 500 Hz to 1 kHz increases as a function of U^5 to U^6 (where U is the speed of advance). It is suggested that the causative mechanisms are as broadly applicable to submarines as they are to surface ships. Hence, in specifying the requirements of any radiated noise and signature measurement system, the operating profile of the vessel must be considered in light of the cost penalty of a system needed to be able to measure the signature. Specifying a system that must be able to measure the Ultra Quiet State (UQS) signature of the vessel in anything but the most favourable environmental (weather) conditions can necessitate the construction of a very long, fixed array based installation with the associated cost penalties.

It should also be noted that the speed of the vessel and its operating depth also determines whether the pressure differences across the propeller surface are sufficient to induce cavitation. The examples provided above assume the non-cavitating state.

2.1.2 TRANSMISSION LOSS (TL)

Transmission loss is an important aspect of any signature measurement system. Signature levels are always referenced to one metre (1 m) so as to provide comparable values between systems and vessels. Therefore, inherent in the translation of the measurements from the levels received at the hydrophones, is the compensation for the transmission loss. In a free field environment, ie one without boundaries, the transmission loss is simply a matter of spherical spreading and thus defined by

$$TL_{spherical} = 20 \cdot \log_{10}(r)$$

Equation 2

However, and somewhat unfortunately, the underwater environment can rarely be described as free-field. The environment is dominated by the sea surface and sea bed discontinuities and, depending on the frequency of interest, has its own set of characteristics. In a somewhat simplistic approach, Urick[3] describes the transmission loss in a surface and bed-bounded environment as cylindrical spreading and proportional to

[2] "Mechanics of Underwater Noise", Donald Ross. Peninsula Publishing, Los Altos California 1987. ISBN 0 932146 16-3.
[3] "Principles of Underwater Sound", Robert J, Urick, 3rd Edition. McGraw Hill Book Company, 1983. ISBN 0-07-066087-5.

$$TL_{cylindrical} = 10 \cdot \log_{10}(r)$$

Equation 3

In practice, neither is wholly correct and the situation needs to be considered in more detail.

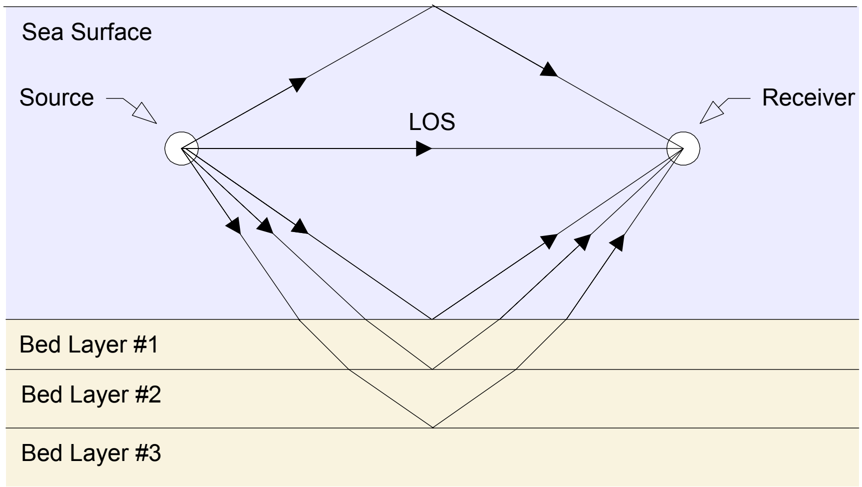

Figure 3 - Conceptual cross section of acoustic channel

Figure 3 depicts a simplified conceptual view of the channel between the source and the receiver. A line of sight (LOS) propagation path exists between the source and receiver and is subject to spherical spreading (assuming the wavelength is not so long that it is comparable to the depth of water). A surface reflection is generated by the high reflectivity surface interface and a number of bed reflections are generated from the different sea bed density layers. At low frequencies, and depending on the angle of incidence, both the surface and bed interfaces can be good reflectors. At higher frequencies the increased surface roughness due to its scaling with wavelength tends to decorrelate and scatter the incident energy. While many propagation loss models then provide an estimate of the channel transfer function by incoherently summing the incident power received at the hydrophone, the reality is that the signals may combine either constructively or destructively depending on the effective path length and phase shift.

Significant research has been conducted in the calibration of the transmission loss for an acoustic range by both industry and academic agencies[4,5] but little success has been reported. Given the complexity of the phenomena, channel modelling probably has some potential at low frequencies i.e. less than 500 Hz, but at frequencies higher than this the nature and complexity of the environment virtually precludes modelling and channel compensation.

Fortunately a number of strategies can be employed which can ameliorate some of the consequences of the presence of the interfaces.

[4] "Performance of a Fixed Acoustic Range in a Shallow water Environment", P. J. Enoch and S Lawrence McGowan, Ultra Electronics. Undersea Defence Technology Conference Proceedings, 1996 Page 409 415.
[5] "Acoustic Noise Range Calibration", R. S Appleby, D. K. Waymont, S. Foale, Smith System, Engineering. Undersea Defence Technology Conference Proceedings, 1997 Page 497 501.

The most obvious strategy is to provide as much distance as possible between the interfaces and the source and receiver thereby maximising the spreading loss of the multi path components. Hence measurements in deep water are always preferred over the shallow water equivalent.

Unfortunately, it is not so easy to ensure an adequate propagation loss for the surface reflection. However, common practice is to make use of extensive averaging to reduce the consequent interference effects. Again, at the higher frequencies, surface motion tends to reduce the coherence of the surface reflection and aid in the averaging process.

2.1.3 DIRECTIVITY INDEX (DI)

The directivity index (DI) refers to the gain that is provided by the acoustic system for the detection of signature components of the target noise source over the ambient noise. Traditionally, this parameter is called the directivity index since it refers to the gain realised by utilising an array of hydrophones to steer (direct) a beam towards the target therefore achieving a directivity based gain over the ambient noise. However, it is not the only way of achieving gain and a more generic approach is appropriate.

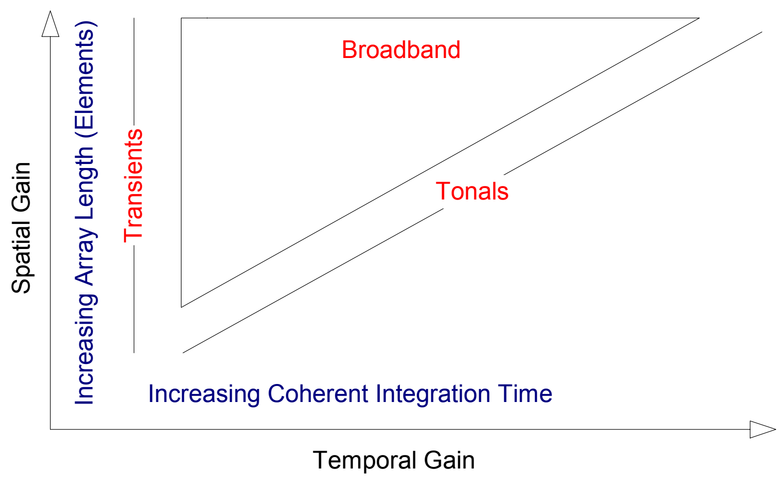

Figure 4 - Processing gain methods and signature components

Figure 4 depicts a conceptual view of the two orthogonal dimensions by which processing gain can be achieved, either spatially by distributing and coherently combining the signal from sensors distributed throughout the propagation medium (i.e. an array); or temporally, by observing and coherently integrating the radiated noise signature over time. The two processing gain dimensions have differing applicability to the signature components. A transient with limited temporal coherence can be integrated only in the spatial domain while a broadband component, depending on its temporal coherence, can be integrated spatially and to some extent temporally, while a tonal component can be integrated both temporally and spatially.

Common practice is to provide noise signatures in ⅓ or ⅛ octave resolution. The lower resolutions provide significantly smaller data sets with consequent reductions in data storage, transport requirements, etc. Moreover, the considerable reduction in the complexity of the plots aids subsequent interpretation. However it is considered that routinely providing ⅓ or ⅛ octave resolution for the signature can be seriously misleading. Low-resolution presentation of the signature can be

particularly undesirable when considering tonal components. The incoherent averaging process applied over the fractional octave intervals can hide the presence of narrow band tonals. However, narrow band tonals, and the ability of an opponent to integrate them coherently over time can present serious vulnerability issues to the vessel. It is therefore strongly recommended that the use of fractional octave representation of the acoustic signature be discouraged.

2.1.4 DETECTION THRESHOLD (DT)

The detection threshold is that signal excess over the ambient noise that is required for an acoustic measurement sensor to reliably detect and measure the vessel signature. Note that detection and measurement are two different processes. The detection threshold is particularly relevant to the broadband signature since no amount of coherent temporal averaging will result in any processing gain on the broadband components. The detection threshold for optimum results would be set at 10 dB or more[6], thereby ensuring that the ambient noise has no significant impact on the variance of the signature estimates. Depending on the target vessel signature, its operating state and the ambient noise levels, values as low as 3-4 dB can be tolerated.

2.1.5 ENVIRONMENTAL NOISE (NL)

In radiated noise measurement, the ambient noise field (sometimes known as background noise) must be such that an appropriate figure of merit (FOM) is provided by the modified sonar equation. The topic of ambient ocean noise is a specialisation in itself, covering mechanisms from the purely physical, such as wind, rain and seismic, to biological sources such as whales, dolphins and shrimp. However, while several modelling tools are available for predictions of the environmental noise, often of greater significance in radiated noise measurements are the man made components. These components can include commercial and recreational shipping and, depending on the configuration of the range, the radiated noise of support vessels or aircraft used in the ranging. In looking at the lowest values of the radiated noise signature, the choice or even presence of a support vessel needs to be considered closely. To ensure the quietest acoustic environment may necessitate shutting down as many systems as possible on board the support vessel. However, this option may be highly undesirable or not possible. Any anticipated mooring of the support vessel must also be planned carefully, as chains cannot be used on the moorings because of their potential to generate transient noise.

[6] "Sound Pressure Measurements Using a Single Hydrophone", Darryl McMahon, Maritime Operations Division. Defence Science and Technology Organisation.

3 ESTABLISHING A NATIONAL ACOUSTIC RANGING CAPABILITY

Establishing a national ranging capability can be a major undertaking depending on the scope of requirements. In particular, establishing a capability where no previous experience or infrastructure exists can require considerable investment and expertise. This section examines the issues presented by the development of a classical array based capability in contrast to a more basic sonobuoy-based approach.

3.1 CONVENTIONAL ACOUSTIC RANGING

Historically, the textbook approach to acoustic ranging has been to locate a site with deep water that is relatively remote and therefore distant from either commercial shipping, fishing or recreational vessel use. The site will preferably be sheltered from the wind and rain and be of adequate width and depth so that the full range of submarine operations can be conducted in complete safety. The site will be provided with an in-water array of some complexity and orientation and cabled to a fixed location, on shore facility. The onshore facility will be set up with a suite of data collection and analysis equipment in addition to a comprehensive set of communications facilities for operations with the vessel being ranged. The on-shore facility will also be capable of housing several ranging staff, plus the support crew for a period of anything up to a week.

Unfortunately the textbook approach is rarely realised. Many countries simply lack the ideal geographic environment and compromise has to be made in the location of the facility. For instance, ranging locations in Australia are restricted by the limited availability of deep water within reasonable distance from the coast and, being geologically old, it lacks the inlets sheltered from the wind by surrounding mountains that are available to many nations in the northern hemisphere. More importantly, the funds that were available for naval support facilities have been reduced for nearly every submarine operating nation, almost without exception.

Costs become important when considering the various system components. The in-water array can be expected, at a minimum, to cost at least US $50k and with even moderate frequency coverage and gain, is more likely to cost around US $250-300k. An in-water data acquisition system and its associated cabling would be US $500k upwards, depending on the length of the cable and the depth and nature of the cable path. Floating cables have been utilised at some facilities, thereby avoiding the costs associated with the necessity to lay the cable on the bed and also retain access but have not met with wide acceptance. An RF link (digital) is the obvious alternative to a cable deployment, having the advantages of being immune to damage from fishing and commercial shipping and little sensitivity to operating range. However, any RF link associated with acoustic ranging has to be of considerable bandwidth, will require some form of telemetry buoy and is of course vulnerable to interception. Encryption of the link is possible but again adds complexity and cost. The cost of the onshore facility is purely a function of the location. The Royal Australian Navy range shore facility in South Australia is simply a converted and fitted standard length, shipping container thereby representing a minimum in cost and complexity. With the appropriate level of fit, a shipping container can be made very comfortable and suitable for several days of ranging but it is only capable of accommodating limited (2-3) staff numbers. It is not suitable for

overnight accommodation and therefore additional premises must be provided for extended ranging exercises.

The cost of the on-shore processing facility is constantly reducing due to commensurate reductions in the costs of computer equipment. The data-processing requirement from an in-water array has not changed substantially over the last twenty years or so but the cost of the requisite hardware capability has dropped dramatically. Early ranging installations have previously employed mainframe VAX's or similar configuration mini-computers with arrays of disc packs and tapes. The same configuration today can be achieved with a few high end server configuration PC's. Data storage is always an issue but the recent Mammoth DLT format tape drives have alleviated the necessity to transport large numbers of tapes or disc packs. The development of high-density tape storage formats to meet the requirements of the commercial digital video camera promise to deliver even higher data storage densities.

All of the costs described so far are relatively fixed i.e. they are 'one-off' costs incurred only when the facility is established. However, labour costs are incurred every time a ranging is conducted and often represent the largest proportion of the annual ongoing cost. The availability of the vessel to be ranged is inevitably limited and expensive. Thus the frequency and duration of the ranging exercise is an important consideration when evaluating the annual cost of a ranging facility.

It should be noted that the figures quoted here are representative only and cannot be interpreted to suggest any projected cost. Depending on the performance requirements of the proposed ranging capability, it is not unrealistic to say that there is no upper limit that could be reasonably set. Furthermore the requirement for very large expenditures can result from what seem relatively innocuous features in the environment or requirements. For instance, cable deployments can be particularly sensitive to the parameters of the projected run, i.e. depth, bottom type, length etc and variations in costs of orders of magnitude are common.

Whilst not strictly a cost related component, the development, construction, deployment and training time associated with establishing a ranging facility can be considerable. Site surveys are almost mandatory and it may be necessary to deploy the in-water components and lay the cable at particular times of the year. Earthworks may be required for the shore facility and, given that the location is usually remote, presents a particular problem in transporting heavy and expensive earthmoving equipment.

Given the expenditures and expertise required to establish and run a ranging facility many countries are looking at options to reduce the cost.

3.2 SONOBUOY RANGING

The use of sonobuoys in the anti submarine warfare (ASW) role is well established. However, employing sonobuoys for radiated noise measurement rather than the more conventional vessel detection and tracking role has a number of important issues that need to be addressed.

It is perhaps obvious that national agencies would not invest in ranging systems with complex and expensive hydrophone arrays if those systems were not absolutely necessary. Hence, what can a single sonobuoy-based

system achieve and is it feasible to even consider it as a possible alternative? It needs to be stated clearly that a single hydrophone system will never achieve the performance levels available from a vertical or horizontal array. The linear array achieves a processing gain that is theoretically proportional to the number of elements in the array octave; a ten-element array will therefore have 10 dB of gain over isotropic noise. A single hydrophone from a sonobuoy (assuming no directivity is available) provides no gain over the ambient noise.

The answer, not surprisingly, relates to the processing gain required as a consequence of the ambient (background) noise and the anticipated source level (how quiet is the vessel which is to be ranged?) according to the modified sonar range equation. Given that sonobuoy measurements can be made safely at distances of 100 m or less, will the resultant signature level at the sonobuoy be adequate to ensure a sufficiently positive Figure of Merit (FOM)? As noted earlier, the radiated noise of a submarine or surface ship is very sensitive to vessel speed and therefore the modified sonar range equation needs to be evaluated in conjunction with environmental noise levels and the operational profile of the vessel to establish the likely success of the method. A sonobuoy based ranging system is obviously a compromise when compared to a full array capability; however it is a judgement call as to whether the capabilities provided are adequate for the requirement, and whether the consequent saving in cost offsets the more restricted performance capability.

Submarine manoeuvrability is often restricted on fixed acoustic ranges owing to water depth and/or the geography of the site. However, sonobuoy-based ranging in deep ocean areas allows submarines to manoeuvre over their full automobile envelope, in speed, depth and operating state.

3.2.1 TRACKING SYSTEM REQUIREMENTS

The most obvious differentiator between the application of sonobuoys in an ASW role and in a radiated noise signature application is the requirement for measurement of the exact acoustic path length between the sonobuoy and the target vessel in the radiated noise assessment process. As noted earlier, all absolute sound pressure levels are referenced to 1 m and any proposed use of sonobuoys for radiated noise ranging must include some method of providing the radial range to the target vessel for the subsequent range correction. Hence, some form of tracking of the target vessel is required.

In addition to tracking the target vessel it is also necessary to be able to accurately assess the bearing of the vessel and its depth. All are necessary to achieve a full understanding of the orientation of the vessel relative to the sonobuoy hydrophone.

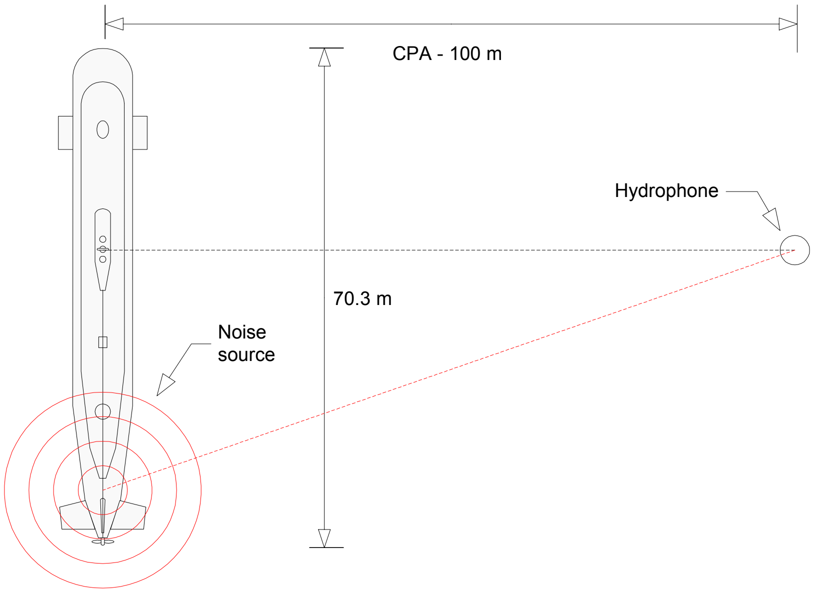

Figure 5 - Conceptual view of submarine transiting past hydrophone

Figure 5 shows a scaled and conceptual view of a submarine transiting past a hydrophone with a closest point of approach (CPA) of 100 m. Setting the closest point of approach to 100 m is standard practice and is an accepted compromise between minimising the spreading loss with range and any near field effects caused by the size of the submarine relative to the CPA. Unfortunately, even for a CPA of 100 m, the dimensions of the submarine need to be considered in any signature measurement exercise. The submarine cannot be considered to be a point source. As can be seen from Figure 5 the submarine depicted subtends a field of view of some 38° at CPA. Given that the dominant noise sources for a submarine are often localized around the propulsion equipment in the stern, an error of 0.5 dB is easily introduced into the subsequent measurement if the vessel is not considered to be a number of distributed sources.

The resultant errors can be even more serious for measurements closer to bow or stern aspect. The standard definitions for aspect measurements, as used by the Naval Surface Warfare Center (NSWC), are included in Figure 6 for reference.

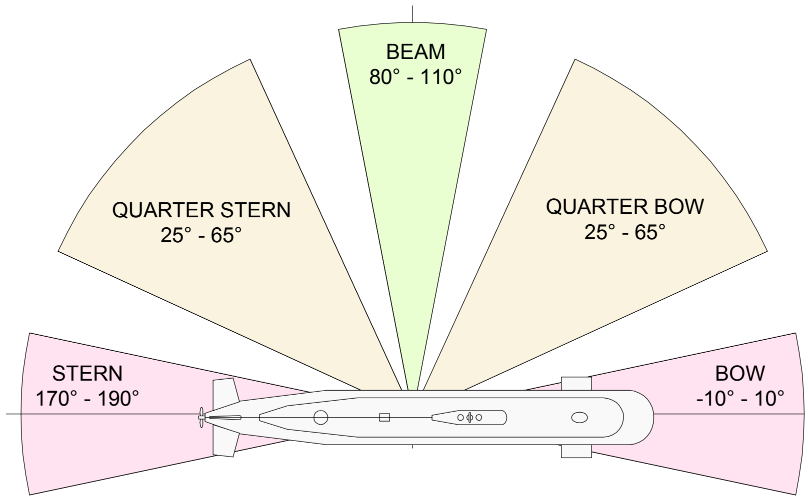

Figure 6 - Standard definitions of vessel aspect

The measurement can be further complicated by the likelihood that the vessel heading is not orthogonal at CPA. In the presence of currents the vessel heading is not necessarily the same as the direction of travel, further accentuating any measurement problems. The situation is depicted in Figure 7.

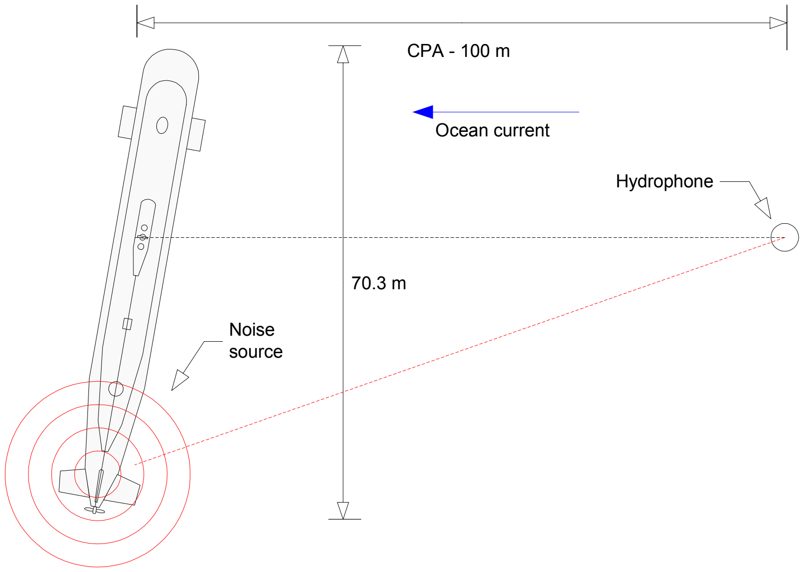

Figure 7 - Conceptual view of submarine transiting past hydrophone with prevailing current

The target vessel will rarely be able to reliably achieve a CPA of 100 m, and the tracking system must be able to estimate the true CPA to an accuracy of a few metres.

Finally, while not depicted in the conceptual figures, the target vessel depth represents an additional degree of freedom that needs to be included in the radiated noise estimation process. While the depth of the sonobuoy hydrophone is presumed to be known, the target vessel depth may not necessarily be the same as that of the deployed sonobuoy hydrophone.

In summary, the target vessel tracking system needs to be able to provide in real-time, and as a minimum, the following parameters:

- The radial range to a pre-ordained point on the target vessel
- The vessel aspect relative to the receiving hydrophone
- The depth of the target vessel.

3.2.2 TRACKING SYSTEM CONFIGURATIONS

Tracking system implementations can be divided into two broad categories, passive and active. The categorisation refers to whether the system uses components of the radiated noise signature of the vessel for tracking or whether it utilises an additional signal over and above the radiated noise.

Passive tracking systems require two or more sonobuoys to form a baseline from which the location of the vessel is estimated by a triangulation and least squares approach. Passive tracking has the

advantage that no additional energy is introduced into the environment during the ranging process and therefore there is no risk of compromising the signature measurement process. To form a baseline the sonobuoys need some form of position referencing which could be provided (foe example) by the GPS equipped SSQ53E, recently described and tested constructed by Ultra (Hermes) Electronics and the Defence Research Establishment Atlantic[7]. However, passive ranging relies on a sufficiently strong and stable (narrowband) signature component that can be exploited by the subsequent processing (and tracking) system. Given that the exercise is to minimise the radiated noise signature such a component may not be available. Furthermore, the burden involved in post processing the results can be considerable. The US employs this passive tracking in some of its noise ranging operations and the subsequent analysis of the data to reconstruct vessel tracks is very labour intensive, frequently taking many weeks to prepare the results. It is suggested that a passive tracking system is not an ideal solution and that an alternative approach be considered.

Active tracking systems can be divided into two categories:

1. those for which little effort is made to provide diversity between the tracking system signal and the radiated noise signature; and
2. those for which the tracking signal is designed so as not to interfere with the radiated noise signature.

The first category is obviously the simplest to implement and can utilise (for example) the standard 13.5 kHz range pinger employed by many tracking range facilities. In order to remove the spectral pollution of the submarine signature, the data record is edited in the time domain (post exercise) and the polluted sections of the data record removed. This practice is perfectly legitimate and standard practice at some facilities but is considered to be inordinately time consuming due to the difficulties of automating the task and the subsequent reliance on manual processing. A tracking system in which the transmissions are designed not to pollute the radiated noise signature of the target vessel is more difficult to design but can offer substantial improvements in performance. Moreover, with improvements in signal processing and hardware capabilities many of the perceived implementation difficulties are now much less significant than they were in the past. With the capability to monitor the position of the submarine simultaneously with the conduct of the ranging exercise the system offers considerable advantage over a passive tracking system or a system in which the data record has to be edited post-exercise.

3.2.3 TRACKING SYSTEM IMPLEMENTATION

A proposed tracking system that would realise the requirements of section 3.2.1 can be described in broad terms. Detailed design specification is well beyond the scope of this document and would be of little value without input from the end-user but some salient points can be summarised for further discussion.

The requirement to be able to ascertain the aspect of the target vessel relative to the sonobuoy hydrophone can be realised by locating two beacons on the target vessel, preferably at bow and stern locations of opportunity to maximise the baseline length. The precise location is not important but it will be necessary to have the beacons "surveyed in" so

[7] "GPS Equipped Sonobuoy", Gregory J. Baker and T. R. M. Bonin. Defence Research Establishment Canada and Ultra Electronics, Dartmouth, Nova Scotia Canada.

that an acoustic baseline can be created. The beacons should be self-powered by rechargeable batteries and capable of operation for at least 8 hours, the predicted duration of a ranging exercise.

It is proposed that the beacons be self contained, not utilising any through-hull penetrators, to minimise cost and to facilitate deployment. The beacons will be synchronised prior to mounting on the hull or the ranging exercise through the use of a portable time reference. The time reference would derive its time signal from a GPS receiver and should be able to be operated by untrained personnel. Microprocessor controlled crystal oscillators with sufficiently low drift to ensure operation for the full duration of the day's ranging exercise are now commercially available. The oscillators would be sufficiently stable to rely on the beacons effectively "free wheeling" without any consequent loss of tracking accuracy. It is proposed that the beacons would be constructed without any external physical connection, hence improving their physical integrity. Battery charging can be achieved with an inductive loop while clock synchronisation and activation can be provided with an infra red connection. The beacons are envisaged to be sufficiently small to not necessitate any substantial mounting hardware and may be mounted either in or outside the casing, depending on the end user's preferences and the physical locations available.

The precise nature of the through-water acoustic beacon signalling would need to be discussed with the end user. However, it is suggested that whatever scheme is employed, the signalling needs to include a depth component to provide the depth of the target vessel. Various modulation schemes can be employed with varying performance trade offs but a variety of schemes are already employed and available in the public domain.

3.2.4 SONOBUOY REQUIREMENTS

In assessing the requirements of a sonobuoy suitable for a sonobuoy-based ranging system a number of parameters are of immediate relevance

- Acoustic bandwidth and dynamic range
- Spatial location capability
- Digital/Analogue link

The bandwidth of the sonobuoy needs to support the bandwidth requirements of the ranging exercise (inclusive of the tracking signals radiated by beacons on the target vessel). Many sonobuoys are restricted in bandwidth to that required by the ASW application and would be unsuitable for the wider bandwidth usually required for an acoustic ranging exercise.

A sonobuoy equipped with a GPS engine is of considerable advantage in any ranging exercise since it provides so much more relevant information to the operators; information which is essential in the subsequent post-ranging analysis. After deployment the sonobuoy constellation will inevitably drift and the location of the sonobuoy receivers needs to be relayed to the target vessel. If a communications channel is available the drift position of the sonobuoys can be reported via an Underwater Telephone (UWT) link. Alternatively, a moored sonobuoy configuration may be useful depending on the specific operational scenario.

In assessing the use of sonobuoys it should be noted that the RF beam pattern of sonobuoys is optimised for reception by aircraft circling in the immediate vicinity or usually within line of site range. However, depending on the sea-state, the RF beam pattern may not be suitable for reception by a support vessel that has limited visibility to the sonobuoy antenna. Thus modifications, to the sonobuoy antenna (a relatively minor modification) may be required if a support vessel is employed rather than an airborne platform. The need to minimise any increases in ambient noise due to the presence of support units is important.

3.2.5 PROCESSING SYSTEM REQUIREMENTS

Requirements for the processing system are often over specified. In essence the processing system can be segmented into two categories, the ranging operations system and the post-processing and report generation software.

The range operations software needs to provide an interface that provides information to the operators of the relative position of the deployed buoys and the target vessel (inclusive of its depth). In addition it needs to be able to provide a "quick look" at the validity of the results recorded by the data acquisition system. The "quick look" analysis needs to be able to verify the veracity of the data so as to indicate to the operators that they can progress to the next serial.

Post processing software needs to provide, as a minimum, a frequency domain analysis tool and a time domain editing tool for the analysis of transient information. It is suggested that in the early phases of the program that commercial off the shelf software be employed for this purpose and that a minimum of software be written specifically for the application. Software development is an expensive and time-consuming process that is notoriously difficult to estimate and manage reliably. There are numerous examples of software development efforts that for some reason or other have either failed to deliver the required product or have failed completely. Critical to a successful software development process is a full understanding by both the client and the supplier of the requirements. This can be difficult to achieve when the client has little operational experience. It is therefore suggested that for an initial developmental period, COTS software be used to provide at least a basic capability and only interface software be developed to provide system functionality. In particular the spectraPro and spectraLab series of products from Cetacean Research in Seattle may form a useful basis for such a system.

For the post processing software, Matlab™ from Mathworks can quickly be configured to provide a series of scripts that facilitate the post processing effort. Matlab is a very high level language that, while probably not suitable for production quality software, is ideal for prototyping and providing a basic operational capability.

Once the client and operators are familiar with ranging operations and direct experience has drawn out their specific requirements, it is recommended that a dedicated software effort be initiated to provide a fully integrated system.

3.2.6 RANGING OPERATIONS

Sonobuoy based ranging operations, like all operations at sea, depend for their success on careful planning by all involved parties prior to the

exercise. Sonobuoy based ranging exercises can be particularly problematic because of potential drift by the sonobuoys and the necessity to update their position to the target vessel.

Inherent in the conduct of ranging operations, is the requirement to conduct the at-sea operations as expediently as possible. As noted earlier, vessel time is always limited. Moreover, ranging operations can be quite monotonous for the crew and are often perceived as not being a priority, particularly when the exercise may require repetitive manoeuvring of the vessel over extended periods of time. Hence to gain maximum efforts from the crew and minimise the cost of the exercise it is imperative to pre-plan the exercise as completely as possible.

As noted in Section 2 above, intrinsic to the success of any ranging exercise is a good understanding of the requirements of the exercise. In evaluating the radiated noise signature for a submarine a number of motivating requirements recur. Whilst not exclusive, they include

- Contract Acceptance
- Routine Hygiene
- Baseline Measurement
- Signature Reduction Efforts
- Vulnerability Assessment

Each of these requirements has a differing focus and will result in a different scope of operations. However whatever the scope of operations, it is considered critical to have a standardised operational and analysis report format. NATO STANAG 1136[8] specifies many of the operational instruction and subsequent reporting formats. While somewhat dated, particularly with reference to the arrangement of hydrophones that are suggested, the STANAG does provide a useful template for trials instruction and analysis reports which can be used as a basis for more documentation.

3.2.7 TARGET STRENGTH ASSESSMENT

Signature assessment of the radiated noise is only one half of the acoustic signature measurement process. An evaluation of the acoustic cross section of the vessel and its effect on the target strength of the vessel is increasingly important when considering the vulnerability of the vessel to active sonar. In particular the wide scale construction and deployment of high power and low frequency active sources by several navies has increased an awareness of the vulnerability of submarines to active sonar.

A typical target strength evaluation involves towing an acoustic projector, directed at, but at some distance from the submarine and then collecting and evaluating the echoes from the vessel as a function of azimuth.

While target strength evaluation is one step on from a radiated noise signature facility, the provision of a sonobuoy based acoustic range does provide the basic infrastructure to evaluate target strength values.

[8] "Standards for Use when Measuring and Reporting Radiated Noise Characteristics of Surface Ships, Submarines, Helicopters etc in Relation to Sonar Detection and Acquisitions Risk". NATO STANAG No 1136, 29 May 1995.

4 SUMMARY

The establishment and operation of an acoustic ranging capability by any organisation can be an expensive and time-consuming exercise. Acoustic signature assessment is based on standard physical principles but the complexity of the process and environment mean that it will always be a somewhat inexact science, relying greatly on the skills of the operators and analysts to provide robust and useful results. Those skill sets are acquired over time and only with significant amounts of experience in the field. Similarly, the specification of an acoustic range relies on an intimate knowledge of the requirements of the submarine operators.

As is true for any complex measurement system for which an acoustic range is a prime example, it is always significantly easier to base the specification of a new system on the experience and capabilities of the existing system rather than establish a completely new facility.

For this reason it is recommended that a sonobuoy-based data collection system provides an ideal entry point to acoustic signature assessment. It is relatively easy to operate; portable, so its usefulness is not restricted by the prevailing environmental and geographic conditions, and most importantly it represents a comparatively low cost entry point. The latter condition is important. Before embarking on the specification, construction and operation of a facility which could easily cost US$ 5-10 million or more, a sonobuoy-based system provides a relatively risk free method of assessing exactly what is required while still providing a basic acoustic measurement capability. A sonobuoy based system will never provide the high gain measurements that can be achieved with an appropriately mounted and operated nested array but by providing suitably quiet environmental conditions the proportion of the target vessel's operational envelope that cannot be evaluated by a single hydrophone can be minimised.

For countries that share some of the geographic problems of Australia, an acoustic ranging system based on sonobuoys provides an ideal solution. It can be readily transported between operational areas, and its relatively low cost means that, if required, the experience gained with its operation can form the basis for the specification of a fixed, high gain facility at some future date. However, and most importantly, it provides submarine forces with the capability to, at least, baseline and compare vessels of the same class as soon as possible and with a minimum of expenditure and commitment.

5 RECOMMENDATIONS

The science of acoustic noise ranging is complex. The success and viability of any noise ranging system intrinsically relies on the successful definition of the systems requirements, the environmental conditions and the parameters of the vessel to be ranged. Whether it is a fixed location array based system or a portable system based on sonobuoys, it is absolutely essential to scope the design parameters adequately. Therefore, it is suggested that the first task be to quantify the requirements.

i) Evaluate the potential geographical locations with regard to ambient noise, environmental factors (eg shipping, level of fishing activity etc) and to obtain information on the prevailing weather conditions.

ii) Estimate the signature levels and components of the target vessel that the system will need to be able to measure.

iii) Prioritise the operational profiles of the vessel that require signature measurement.

iv) Assess the manpower capabilities available and the expectations of the frequency of ranging activities.

v) Determine whether the ranging platform should be an aircraft or surface vessel. The recommendation depends on the availability of platforms to the vessel operator and the geographical distribution of the ranging operations.

vi) Compile and provide an assessment as to whether a sonobuoy based system can demonstrate the requisite figure of merit for an operational system. The recommendation should also include an assessment as to whether the requisite physical infrastructure is available and suitable.