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Stage 1 AUV-Submarine Docking Acoustic Systems

G. J. Heard
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Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2013-164
August 2013

Canada

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Abstract

This report has been generated in support of the DRDC AUV (autonomous underwater vehicle) Docking Technology Investment Fund (TIF) project. The report provides a level of detail for the conceptual rendezvous and Stage 1 docking procedures. Three acoustic systems are required to conduct Stage 1 docking: an AUV beacon signal generator, an AUV vector sensor-based homing signal receiver, and underwater modems. The role of these acoustic systems is discussed and a suggested procedure is developed. Design issues for the acoustic systems are explored and potential designs for the beacon and vector sensor systems are presented. The beacon is a new, but relatively simple device. The proposed vector sensor is a second generation version of an existing DRDC homing system. The modems are expected to be a variant of a commercially available system. The Teledyne telesonar modems are the suggested solution as they are the only modems to support a full underwater networking protocol and they have a data streaming capability that will be important for final stage docking.

Résumé

Le présent rapport a été produit pour appuyer le projet d'accostage VSA (véhicules sous-marins autonomes) du Fonds d'investissement technologique (FIT) de RDDC. Le rapport donne des détails sur les procédures d'accostage d'étape 1 et de rendez-vous de type conceptuel. Trois systèmes acoustiques sont nécessaires pour effectuer l'accostage d'étape 1 : un générateur de signal de balise de type VSA, un récepteur de signal de ralliement à capteur vectoriel de type VSA et des modems sous-marins. Le présent rapport explique le rôle de ces systèmes acoustiques et présente la procédure élaborée. Il explore les problèmes de conception des systèmes acoustiques et présente des modèles potentiels de balise et de capteur vectoriel. La balise est un dispositif nouveau, mais relativement simple. Le capteur vectoriel proposé est une version de deuxième génération d'un système de ralliement de RDDC existant. Les modems, quant à eux, devraient être une variante d'un système disponible commercialement. Les modems de type télésonar Teledyne sont la solution proposée, car ils sont les seuls modems à supporter un protocole de réseautage sous-marin complet et ils ont une capacité de diffusion de données en mode continu qui sera importante pour l'accostage de dernière étape.

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Executive summary

Stage 1 AUV-Submarine Docking Acoustic Systems

G. J. Heard, G. D. Watt, G. Schattschneider; DRDC Atlantic TM 2013-164;
Defence Research and Development Canada – Atlantic; August 2013

Background: There is a growing requirement for the deployment and recovery of autonomous underwater vehicles (AUV) by submarines as a means of extending the scope of reconnaissance and surveillance in future submarine missions. Deployment of AUVs from submarines is relatively straight-forward in technological complexity compared with the difficulty of recovering an AUV with a moving submarine under the influence of waves. DRDC has established a future-looking project under the Technology Investment Fund (TIF) to investigate options for recovery of AUVs by submarines. The TIF project is comparatively small and is therefore focused on system simulation to devise a docking strategy and building and testing system components to verify their capabilities. In other words, the project is building a means of evaluating various docking techniques while limiting expenditures. If AUV recovery by submarines becomes a necessity, then this current project will provide a significant step forward in the development of an operational solution.

Principal results: This document focuses on details of the rendezvous and early docking, or Stage 1 docking, procedures. Primarily, the document discusses the role of three acoustic systems required to facilitate Stage 1. A preliminary system design for the first of the three acoustic systems, an AUV beacon signal, is provided. The second acoustic system, the homing system, is proposed to be an enhancement of an existing device that was developed by DRDC for use in the mapping of the deep, ice-covered Arctic Ocean by an AUV. The third acoustic system, an acoustic modem link, is proposed to make use of existing commercial modems operating with an underwater acoustic networking protocol.

Significance of results: The results and information provided in this report are already being incorporated in early simulations of the AUV docking procedure. The concepts developed in this document are of general use in AUV operations and other underwater acoustic sensing and communication applications. The AUV beacon is of general value as is the enhanced homing system. The homing system enhancements will allow for simultaneous operation of other acoustic systems alongside the homing system. In particular, the acoustic modem with its relatively high source level will be able to operate while the AUV is receiving weak acoustic signals from the homing sound source. The acoustic modem operations include a mode that has not been previously exploited. Understanding the operation and limitations of this modem capability will lead to new applications in the underwater regime.

Future work: Work has already begun to prove the performance of the new vector sensor preamplifier design. Work has also begun on the investigation of linear array designs that could be attached externally to an AUV with a resulting internal space saving. In-air testing of the modem data streaming mode has also begun and we expect to move this testing to a controlled underwater environment at the DRDC Calibration Barge in a few months. Reliability, mode duration, and latency are all factors of interest and, once characterized, will be modelled in the docking simulation.

Other future work may include testing of various spread spectrum techniques for both the beacon and homing signal receiver.

Sommaire

Stage 1 AUV-Submarine Docking Acoustic Systems

G. J. Heard, G. D. Watt, G. Schattschneider ; DRDC Atlantic TM 2013-164 ;
Recherche et développement pour la défense Canada – Atlantique ; août 2013.

Introduction : Il est de plus en plus nécessaire de déployer et de récupérer les véhicules sous-marins autonomes (VSA) à l'aide de sous-marins afin d'augmenter la portée de la reconnaissance et de la surveillance des missions futures. Le déploiement des VSA à partir des sous-marins est relativement simple sur le plan technologique comparativement à la récupération d'un VSA à l'aide d'un sous-marin en mouvement soumis aux vagues. RDDC a mis sur pied un projet axé sur l'avenir par le biais du Fonds d'investissement technologique (FIT) pour étudier les options de récupération des VSA à l'aide de sous-marins. Le projet de FIT est relativement petit et il se concentre donc sur la simulation qui permettra de concevoir une stratégie d'accostage. Le projet permettra aussi de fabriquer des composantes et de les mettre à l'essai pour vérifier leurs capacités. En d'autres mots, le projet permet de concevoir un moyen d'évaluer diverses techniques d'accostage tout en limitant les dépenses. Si la récupération des VSA à l'aide de sous-marins devient une nécessité, ce projet constitue donc un grand pas en avant pour le développement d'une solution opérationnelle.

Résultats : Le présent document se concentre sur les détails des procédures de rendez-vous et d'accostage précoce ou d'accostage d'étape 1. Principalement, le document traite du rôle de trois systèmes acoustiques nécessaires pour faciliter l'étape 1. Ainsi, un modèle de système préliminaire pour le premier des trois systèmes acoustiques, un signal de balise de type VSA, est fourni. Le deuxime système acoustique (le système de ralliement) est proposé pour améliorer un dispositif existant ayant été élaboré par RDDC pour la cartographie de l'océan arctique (profond et recouvert de glace) par un VSA. Le troisième système acoustique (une liaison modem acoustique) est proposé pour utiliser les modems commerciaux actuels qui se servent d'un protocole de réseautage acoustique sous-marin.

Portée : Les résultats et les renseignements fournis dans le présent rapport sont présentement incorporés aux premières simulations de la procédure d'accostage de VSA. Les concepts élaborés dans ce document sont d'usage général dans les opérations de VSA et les autres applications de communication et de détection acoustiques sous-marines. La balise de type VSA est de valeur générale tout comme le système de ralliement amélioré. Les améliorations du système de ralliement permettront d'utiliser simultane d'autres systèmes acoustiques avec le système de ralliement. En particulier, le modem acoustique, grâce à son niveau source relativement élevé, sera en mesure de fonctionner pendant que le VSA recevra des signaux acoustiques faibles de la source sonore de ralliement. Les opérations de modem

acoustique comprennent un mode qui n'a pas été exploité dans le passé. Le fait de comprendre le fonctionnement et les limites de cette capacité (modem) mènera à de nouvelles applications dans le régime sous-marin.

Recherches futures : Les recherches ont déjà débuté pour démontrer la performance du nouveau modèle de préamplificateur de type capteur vectoriel. Les recherches ont aussi débuté sur l'étude des modèles de réseau linéaire qui pourraient être fixés à l'extérieur d'un VSA et qui permettraient d'effectuer une économie d'espace à l'intérieur. L'essai dans l'air du mode de diffusion de données en continu (modem) a aussi débuté, et nous nous attendons à déplacer cet essai vers un environnement sous-marin contrôlé à la barge d'étalonnage de RDDC dans quelques mois. La fiabilité, le mode durée et la latence sont tous des facteurs d'intérêt et, une fois caractérisés, ils seront modélisés dans la simulation d'accostage.

D'autres recherches futures pourraient inclure l'essai de diverses techniques de spectre d'étalement pour la balise et le récepteur de signal de ralliement.

Table of contents

List of figures

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1 Introduction

This document describes a proposed procedure for the initial stage of an autonomous underwater vehicle (AUV) docking to a moving, submerged submarine. Included in the report is a description of the design factors and possible implementation of the required acoustic sub-systems. The document has been prepared as support to the AUV-Submarine Docking Technology Investment Fund (TIF) project [1] that is being carried out at DRDC Atlantic by a team of scientists from DRDC Atlantic and Suffield, the University of New Brunswick, and contractor Dynamic Systems Analysis Ltd.

Information on the initial stage, or Stage 1 Docking, was originally described by Watt [2] in an informal note that was distributed to project participants. The current document builds on this description modifying the scheme slightly and adding details for the sequence of operations and the necessary and optional communications required for the Stage 1 Docking procedure.

Three acoustic systems are required for use during Stage 1. These acoustic systems are:

1. An acoustic beacon on the AUV to allow the cooperating submarine to approximately localize the loitering AUV at the end of a mission,
2. A specialized acoustic homing/communication system on the AUV that will bring the AUV into proximity with the submarine dock mechanism. Including a spread-spectrum acoustic beacon on the submarine to which the AUV homes, and
3. Acoustic modems with ranging capability and low-latency data streaming capabilities on both the AUV and submarine.

Section 2 describes the AUV-Submarine docking scenario in detail. The necessary and optional communication requirements are identified. Simple trigonometric formulae are derived to solve for the required AUV speed of advance and the time to completion of Stage 1 Docking.

Section 3 summarizes the design issues relating to spectrum usage, interference, spectral source purity, and acoustic propagation relevant to the design and operation of the acoustic systems. The physical, shallow-water, environment in which AUV docking shall occur is one of enormous variability and complexity. It is impossible to adequately describe all possible conditions and the resulting performance of the acoustic systems in such an environment. Instead, the acoustic systems will be conservative in design and operate in the simplest manner possible in order to provide a degree of robustness in operation.

Section 4 provides details of a suitable design for the acoustic beacon prototype. This beacon must be reliably detectable by the submarine at a distance of 2 km, but it must not be easily available to exploitation by opposing forces.

Section 5 discusses a potential system design for the homing system or vector sensor. The proposed homing system will track a low-level emission from the submarine and hold the AUV on a selected course with an appropriate speed of advance.

Section 6 describes the requirements of the data communications modem for Stage 1 and Stage 2 Docking. There is considerable flexibility in the modem usage during Stage 1. The proposed scheme minimizes the use of the data modem and takes the view that underwater acoustic communications are inherently unreliable and are in general vulnerable to counter-detection.

And finally, Section 7 summarizes the ideas presented in the paper.

2 The Docking Scenario

The beginning of the docking procedure, up to the point where the AUV is in close proximity ($\sim$10–30 m range) with the submarine dock, is called Stage 1 Docking (Stage 1 for brevity). The Stage 1 scenario has been briefly described by Watt [2]. As a result of numerous discussions this scenario has altered slightly from the description provided by Watt and now has some options that can be included in terms of communications between the AUV and submarine.

This section elaborates on the Stage 1 scenario, illustrating details with calculations and diagrams. The points where AUV-submarine communication and data exchange are required are described.

An AUV-Submarine mission is expected to include a general area for the rendezvous of the vehicles. Due to the influence of tides and currents, navigational system drift, timing drift, and unavoidable delays an exact location for the rendezvous may not be possible. The submarine will have to determine the AUV presence and location when it is in the general rendezvous area.

When the AUV determines that it has reached the rendezvous location it is expected to shift into a low-power loitering state. This loitering will most likely take the form of slow circuits of moderate size centred around the AUV's estimate of the rendezvous location, which has an assured accuracy due to GPS fixes taken at intervals prior to arrival. The depth of the loiter manoeuvres will have been prearranged and stored in the mission profile. The AUV is expected to be able to accurately determine its own depth by direct sensing of the hydrostatic pressure. This loiter situation is illustrated in Figure 1.

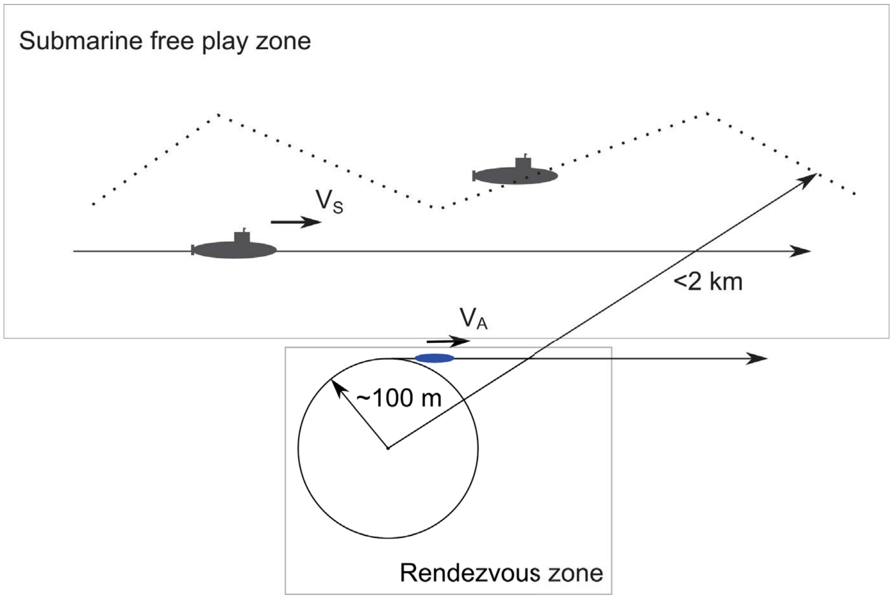

Figure 1: *Initially the AUV loiters in a lower power state somewhere within a prearranged Rendezvous Zone. The submarine localizes the AUV by operating within 2 km from the AUV.*

2.1 AUV Acoustic Beacon

At a pre-arranged time, or immediately, if the AUV is late arriving at the rendezvous, the AUV will activate the acoustic beacon signal. This signal will propagate in the water and be detected by the submarine. Using its passive listening capabilities the submarine crew will localize the source of the acoustic signals. The beacon should allow the submarine to detect the AUV's presence and determine its location at a range of up to 2 km. Figure 1 illustrates this localization procedure denoting the operational regions and the need for submarine manoeuvres in order to localize the AUV.

The acoustic beacon will likely make use of some degree of spread spectrum modulation to increase the detection and the covertness of the signals for those with and without the signal spreading code. Simple state messages can be sent from the AUV to the submarine through the use of several allowable spreading codes. For example, a normal AUV condition could be indicated to the submarine by use of a spreading code A, while a particular error or malfunction condition could be indicated by use of any of several other codes B, C, . . ., or, if the AUV has been able to acquire a depth profile and determine the optimum communication depth while waiting at the rendezvous point, this could be transmitted to the submarine. The beacon will likely run on an apparently random schedule (initially set by the submarine in the AUV mission profile) to both save energy in the AUV and make interception of the signals more difficult. Although not strictly necessary, the beacon-off times can also be used by the AUV to activate the second acoustic docking system, which is an acoustic homing and one-way (from submarine to AUV) communication device.

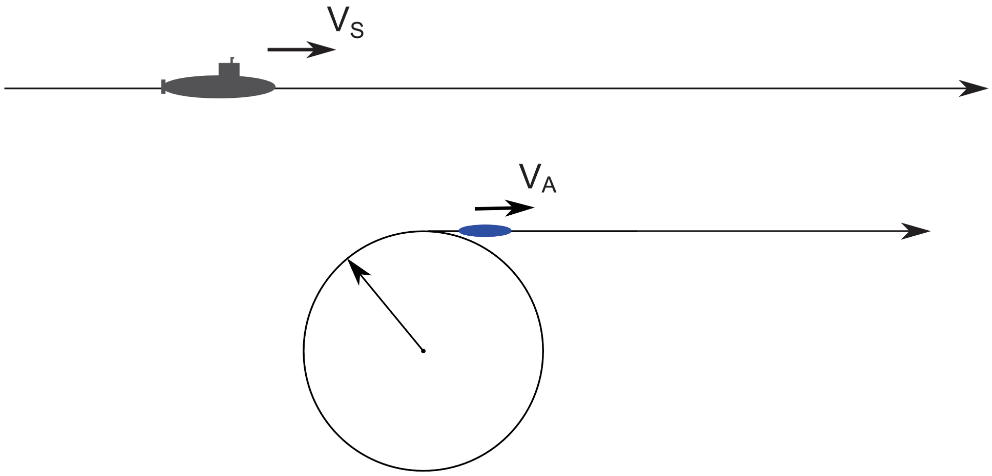

Figure 2: *The submarine transmits a single code symbol to the AUV and arranges itself on a parallel offset course at a speed larger than that of the AUV.*

This initial behaviour of the AUV is simple to implement and requires only a moderately accurate on-board timing capability. No advanced signal processing, sensing, communication, or computing demands are necessary on board the AUV. The AUV makes noise, but the submarine does not. The submarine is free to delay, proceed with docking, or depart as needs dictate. The more complex localization procedure is carried out on board the submarine where human intelligence and greater sensing and processing capabilities are already available.

2.2 AUV Homing System

Once the submarine has detected and localized the AUV beacon signal, the submarine repositions itself, adjusts course and timing, and begins a slow-speed straight run at the prearranged docking depth as shown in Figure 2. The speed of advance of the submarine will be just slightly larger than the cruise speed of the AUV. At the appropriate time, the submarine begins to transmit a low source level (SL) coded acoustic signal.

The coding serves several purposes. First, it will introduce a spread in the bandwidth of the signal (direct spreading, frequency hopping, or other scheme) allowing a lower SL to be used successfully, and second, the coding will allow the transmission of one of several possible symbols. The single symbol will be transmitted for a significant length of time and this together with the increased bandwidth of the signal will improve the odds of the AUV detecting the symbol and decoding it properly in sufficient time to begin the docking approach.

Once the AUV hears and decodes the submarine signal, it will look up various docking parameters, which will include a heading, speed, and possibly other items such as depth or even an alternative option to submarine docking. This information would all be included in the AUV's pre-programmed mission profile.

Normally, the AUV would be expected to receive a symbol denoting a docking profile which would direct the AUV on a course initially parallel to the course to be run by the submarine. The AUV would likely then discontinue use of its own beacon signal, but it may use the beacon to acknowledge receipt of a symbol prior to shutting the beacon signal off. The beacon might also be reactivated for short intervals during the docking approach to allow for independent checks of the progress by the submarine sonar operators or to restart the docking operation should something go awry. Experience with AUV operations has shown how important it is to keep the operators "in the loop", thus acknowledgements and independent means of tracking progress are extremely valuable.

Once the AUV has stabilized on the designated course and depth it will monitor the arrival angle of the acoustic signal from the submarine. In an ideal world, this would be a simple thing to measure and interpret. In the real world, this is not necessarily the situation. More details on potential difficulties with bearing estimation will be provided in later sections. For now we will assume that a reasonable bearing estimate is possible.

At this point of Stage 1 Docking, the AUV is headed on a fixed course and depth with the submarine on a parallel, offset, course at the same depth. This is illustrated in Figure 3. The submarine is behind the AUV and is closing the separation by virtue of its greater speed. As the submarine approaches the AUV, the bearing, α, of the submarine with respect to the AUV heading will be slowly reducing. When the AUV estimates the submarine to be at an angle α_0 relative to the AUV heading, the AUV alters course by an angle β toward the submarine. The AUV can then adjust its forward speed so as to keep the bearing of submarine, α_0, relative to the original AUV heading constant. This requires that the AUV increase its forward speed to keep V_A, the speed along the original direction of travel, nearly constant.

We can determine the required speed of the AUV, V_A, from a geometrical argument that the submarine and AUV meet at the point where the AUV's altered track crosses the submarines track. For a constant submarine speed and fixed AUV course, following Figure 3, we arrive at:

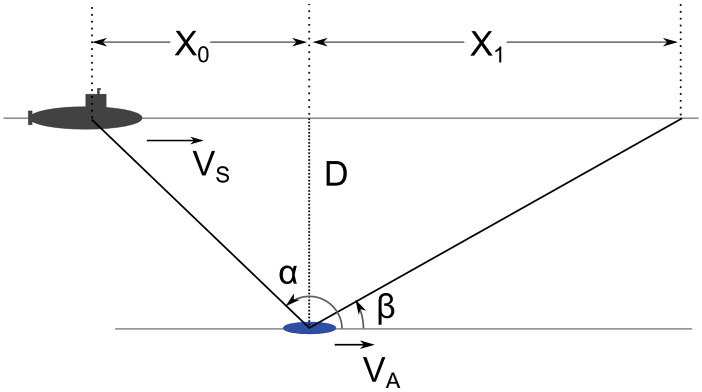

Figure 3: *Stage 1 docking. The figure defines the symbols used in the equations in the text. The AUV is shown facing the direction of travel prior to the turn toward the submarine. The initial offset distance between the tracks is D. The submarine advances along the track at speed V_S, while the AUV advances at speed V_A, which is less than the submarine's speed. The turn toward the submarine requires the AUV to increase speed to maintain the original component of speed parallel to the submarine. The AUV steers a course β with respect to the initial heading and the bearing of the submarine relative to the initial heading is α. Initially the submarine is a distance X_0 behind the AUV when the AUV changes course. The AUV and submarine meet at a distance X_1 along the track ahead of the AUV at the point where it changes course.*

$$V_A = \frac{X_1}{X_0 + X_1} \cdot \frac{V_S}{\cos\beta}. \tag{1}$$

The distances X_0 and X_1 can be expressed in terms of the bearings and track offset distance D. The expressions are:

$$X_0 = \frac{-D}{\tan\alpha_0} \tag{2}$$

and

$$X_1 = \frac{D}{\tan\beta}. \tag{3}$$

Substituting Eqs.(2) and (3) into Eq.(1) yields:

$$V_A = \frac{1}{1 - \frac{\tan\beta}{\tan\alpha_0}} \cdot \frac{V_S}{\cos\beta} = V_S \frac{\sin\alpha_0}{\sin(\alpha_0 - \beta)}. \tag{4}$$

Equation (4) describes the necessary AUV speed of advance as a function of the two bearing angles and the submarine's speed. Note that:

- by holding the angles and the submarine speed constant (required for the derivation of the formulae), the AUV speed is also constant,
- the solution for V_A is independent of the track offset D; however, the time for interception is dependent on this quantity,
- for Eq.(4) to be valid, α_0 cannot equal β,
- if $\alpha_0 - \beta \sim 90$, then $\sin(\alpha_0 - \beta) \sim 1$ and the solution for V_A is insensitive to β which greatly simplifies control,
- since the AUV has a limited forward speed Eq.(4) imposes limits on the bearing angles and/or the submarine's speed, and
- AUV speed can be used to keep α_0 constant, while the AUV rudder can be used to control β.

One particularly interesting case occurs when $\alpha_0 = 135^\circ$. In this special case, the longitudinal distance of the submarine behind the AUV, X_0, and the lateral separation of the vehicles, D, would form the legs of an isosceles triangle, which are of equal length. If β is then chosen to be 45°, the bearing of the submarine would then reduce to 90° relative to the AUV heading. This particular choice results in the interception point being a distance $2D$ ahead of the submarine (see Figure 3). Thus the submarine has to move a distance $2D$ along the track and the AUV a distance $\sqrt{2}D$, which is smaller. The ratio of the vessel speeds is thus equal to $V_{AUV}/V_S = \sqrt{2}/2 \approx 0.7$ with $V_{AUV} = V_S/2$, which favours the AUV with its expected limited speed capabilities and favours the submarine with a faster forward speed where it will be able to maintain a precise course more easily.

For example, if the AUV has a maximum speed of 4 kts, then the submarine is limited to speeds less than about 5.6 kts. The AUV will have to travel fastest during the portion of the track where it is on an intercept course with the submarine. It is reasonable to assume that a nominal speed of about 75% of maximum is acceptable. If the maximum AUV speed is 4 kts, then the forward speed would be $V_{AUV} = 3$ kts on this intercept portion of the track. This leads in the special case, to a speed $V_A = 4/2 = 2$ kts with $V_S = 4$ kts. Thus the AUV would normally operate between approximately 50% and 80% of its maximum forward speed.

If the AUV uses a linear homing array, then the relative 90° bearing would be the optimum in terms of beamwidth and computational load. Not only would the array be best able to discriminate the angle of the source, but the array would have the greatest directivity index minimizing interfering noise, and the computational load on the AUV could be potentially reduced to three simple shift-and-sum operations that would provide the central array beam, one forward-of-centre beam, and one aft-of-centre beam. A simple comparison of the signal amplitudes in these three homing array beams and an AUV heading measurement should be adequate to provide control signals that would maintain the proper AUV course and speed for interception.

2.3 Acoustic Modems

The third acoustic system used in the Stage 1 Docking is the data modem. As has already been mentioned, underwater (UW) data transmission is a problematic issue. The success of a single communication link between two spatially separated locations is subject to a great many factors that include the properties of the noise, the velocities of the source and receiver, the data rate, the communication protocol, and the environmentally sensitive properties of the communication channel. It tends to surprise people to discover that underwater is amongst the most difficult and challenging of communications media. It is far easier to communicate with a rapidly moving distant spacecraft than it is with a slowly moving underwater receiver just a few kilometres distant.

The limitations and variability of the UW communication channel are one reason for limiting the use of modems to facilitate Stage 1 Docking. The second reason is that data communications generally require higher source levels than the acoustic beacon and acoustic homing system already described. This higher source level translates into more opportunity for detection of the communication signals. In fact, detection is usually possible at ranges much larger than those at which communication is successful.

The acoustic beacon and homing system also optionally employs a form of UW communications known as ”state messaging”. The reason these systems can include this feature without incurring the problems of the data modem is that they only send a single symbol over a long period of time to indicate a particular system state. The single symbol is often sent over a time interval thousands of times longer than is available to a single symbol in a chain of symbols (or message) transmitted by a data modem. A common mistake by users of the state messaging scheme is to believe that they can successfully chain symbols together to increase the data moved between points, while this is possible it must be realized that only extremely low fractional baud rates are possible.

The modems have an obvious role to play in Stage 1 once the AUV has detected the submarine transmissions and the angle to the submarine, α, is nearing the chosen trigger point, α_0. At this time, the AUV and submarine are expected to be within 500 m of each other. If the $\alpha_0 = 135^\circ$ value is chosen and the track offset is a nominal 200 m, then we can expect the AUV and submarine to be within 300 m of each other. At such a range, at a depth well separated from the surface and bottom (say, 50 m in either direction), there is a high probability of successful data communication. Tests have shown that successful communication is possible at these ranges with a SL of just 130-140 dB//1μPa @ 1m for conservative (200 bps) data rates.

Once the AUV and submarine are in close proximity, the vehicles can share information about their course parameters and ensure that the system is indeed ready to begin the docking approach. The other key piece of information that can be easily provided by the modem is the range, R_s between the AUV and submarine. Range measurement is a standard feature in a number of modems including the Teledyne Benthos telesonar. By passing position information and range[1] or just using the range and the submarine bearing, the track offset, $D = R_s \sin\alpha$, can be calculated. Since the modems can measure time accurately, the ranges obtained in direct-path conditions are quite accurate and the uncertainty in D is primarily due to the uncertainty in α. For a 200 m track offset and $\alpha = 135°$, we can expect about 8 m of error in the calculation of D. The track offset is important because it will determine how long the Stage 1 operation will take to complete. It also allows for the termination of Stage 1 docking when the offset is too large and it is used to determine when the AUV should begin the transition to Stage 2 docking.

An estimate of the track offset can also be calculated by a series of bearing measurements and knowledge of the AUV and submarine speeds. The speeds of the vessels would be assumed constant and taken from the stored mission profile.

To estimate the track offset from a series of bearing measurements and knowledge of the vessel speeds we proceed using the notation defined in Figure 4. First note that for two measurements i and j:

$$\begin{aligned} u &= V_A(t_j - t_i), \\ v &= V_S(t_j - t_i), \\ \Delta &= v - u = (V_S - V_A)(t_j - t_i), \\ \delta &= \alpha_i - 90, \text{and} \\ \gamma &= \alpha_j - 90. \end{aligned} \tag{5}$$

By building a triangle from the pair of measurements as shown in Figure 4(b) we note that:

$$a = D\tan\gamma \tag{6}$$

$$a + \Delta = D\tan\delta. \tag{7}$$

The above equations can then be solved for D by elimination of a. The result is:

$$D = \frac{\Delta}{\tan\delta - \tan\gamma} = \frac{(V_S - V_A)(t_j - t_i)}{\cot\alpha_i - \cot\alpha_j} = (V_S - V_A)(t_j - t_i)\frac{\sin(\alpha_i)\sin(\alpha_j)}{\sin(\alpha_j - \alpha_i)}, \tag{8}$$

j indicates a measurement at a time later than that for measurement i.

Unfortunately, Eq.(8) cannot be applied with certainty to measurements that are close in time, and hence, separated by just a small angle. By ignoring the error arising from the

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[1] Range is known only to the modem requesting it. In order for both submarine and AUV to know the range either both must request the range or the range must be transmitted in a data packet.

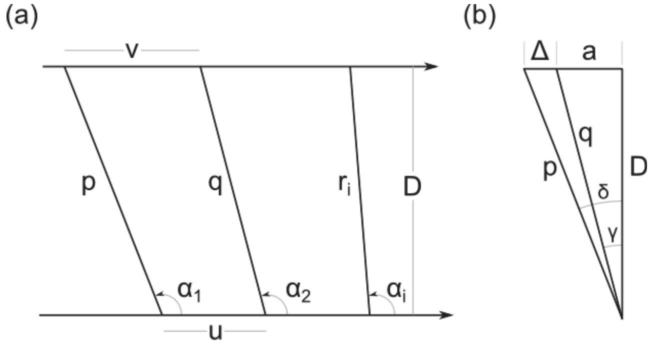

Figure 4: *The track offset can be determined from two or more observations of the submarine bearing at known times. Part (a) illustrates the bearing measurements, while part (b) shows how to construct a triangle from a pair of bearing measurements.*

integration of the speed difference between the submarine and AUV over the time interval between i and j we can determine the differential of D with respect to the angle α as:

$$\frac{\partial D}{\partial \alpha_i} = \Delta \cdot (\cot\alpha_i - \cot\alpha_j)^{-2} \cdot \csc^2\alpha_i, \tag{9}$$

$$\frac{\partial D}{\partial \alpha_i} = \Delta \cdot (\cot\alpha_i - \cot\alpha_j)^{-2} \cdot \csc^2\alpha_j, \text{and} \tag{10}$$

$$dD = \frac{\partial D}{\partial \alpha_i} \cdot d\alpha_i + \frac{\partial D}{\partial \alpha_j} \cdot d\alpha_j. \tag{11}$$

We can argue that $|d\alpha_i| = |d\alpha_j|$ with the result that:

$$\xi_D = \Delta\xi_\alpha \cdot \sqrt{\left(\frac{\csc^2\alpha_i}{(\cot\alpha_i - \cot\alpha_j)^2}\right)^2 + \left(\frac{\csc^2\alpha_j}{(\cot\alpha_i - \cot\alpha_j)^2}\right)^2} = \Delta\xi_\alpha \frac{\sqrt{\sin(\alpha_i)^4 + \sin(\alpha_j)^4}}{\sin(\alpha_j - \alpha_i)^2}, \tag{12}$$

where ξ_D is the error in D due to uncertainty in the measurement of the angles α and ξ_α is the uncertainty in α. Experience with homing systems and bearing determination has shown that for good SNR, $\xi_\alpha \approx 1.5^\circ$.

Figure 5 shows an estimate of the error in determining D from a pair of uncertain angular measurements. In this case we assume that the measurement accuracy is 1.5° and that the AUV and submarine have a track offset, $D = 200$ m. For measurement angles less than 7° apart the calculation results in an error larger than the actual track separation. At least 15° of angular separation is necessary in order to obtain a 10% error in D. This angular separation translates into a time difference of approximately 300 s for a vessel speed difference of 0.5 m/s.

The series of submarine bearing measurements allows the AUV to estimate the track offset and hence the time required for intersection of the AUV and submarine. Unfortunately, the

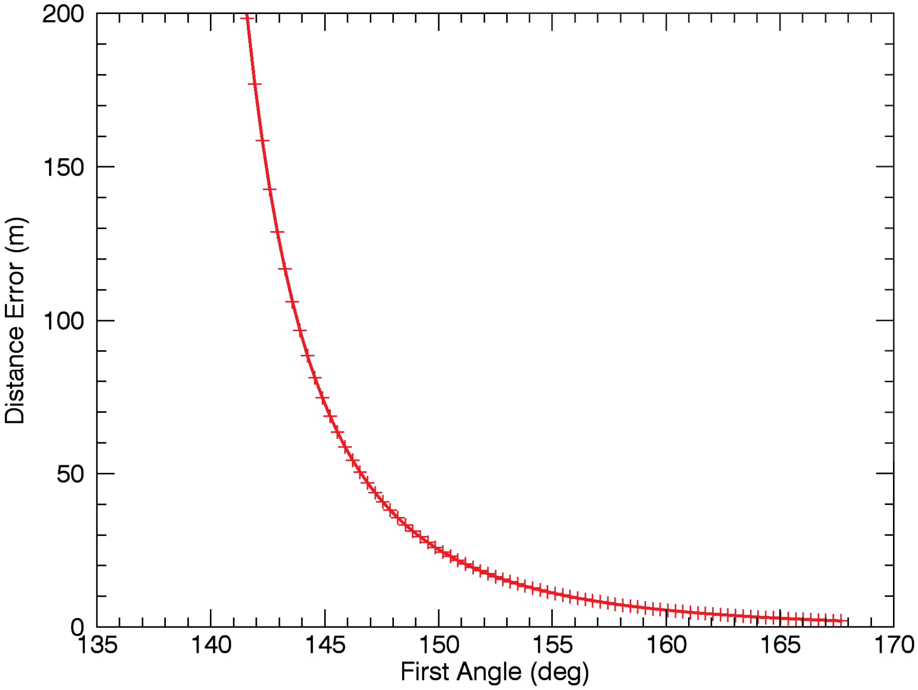

Figure 5: *An example of the error in determining* D *based on uncertainty in the angular bearing measurments. Here one bearing angle is measured at* 135° *and the other bearing angle is given by the x-axis value.*

results are uncertain for small angular separations, thus the benefit of using the modem for this measurement is clear. Once the value of D is known, the time required for intersection is

$$T = \frac{D}{V_A \sin\beta} = \frac{D}{V_S} \cdot (\cot\beta - \cot\alpha). \tag{13}$$

The intersection time (Eq.(13)) is also subject to the uncertainty in the angular measurements, thus, it is important to regularly track the approach progress using the modem range measurement capability. Despite the uncertainty in the result, the use of the bearing measurements is useful in that it allows the progress to be tracked by the AUV without the higher source level modem signals being present until they are actually required and have a high probability of success. The same angular measurement technique can be used by the submarine, provided the AUV periodically enables its acoustic beacon.

This simple derivation ignores the error arising from the integration of the speed difference between the submarine and AUV over the time interval between i and j. The errors will grow with the integrated speed difference, but in general this contribution is smaller than the error due to the uncertain angular measurements. The important point is that the modems provide the most accurate means of ensuring the Stage 1 docking success and they should be used for this purpose.

3 Acoustic System Design Issues

3.1 Spectrum Usage

The three acoustic systems required for Stage 1 docking include: the AUV acoustic beacon, the AUV vector sensor (homing system), and the acoustic modems. All three devices have to share the available spectrum with each other and with other acoustic devices that may be in use on the submarine or AUV. Since all three acoustic devices might potentially operate simultaneously, there is a need to provide substantial frequency separation in the operating bands for these devices.

To keep our discussion unclassified, we note that our mandate is to devise a generic docking concept that can work with any AUV or submarine. At this time, we discuss spectrum usage without regard for any other acoustic system present on the AUV, or for the submarine's actual receiving capability. However, a particular application should adjust spectrum usage to either exploit or avoid interference from these other systems, as required.

Based on practical experience with acoustic homing systems and with acoustic modems, the full bandwidth of the three acoustic devices is expected to run from 1000 Hz to 27 kHz. Our existing AUV homing systems [3] operate in the band from 1–2 kHz. We propose

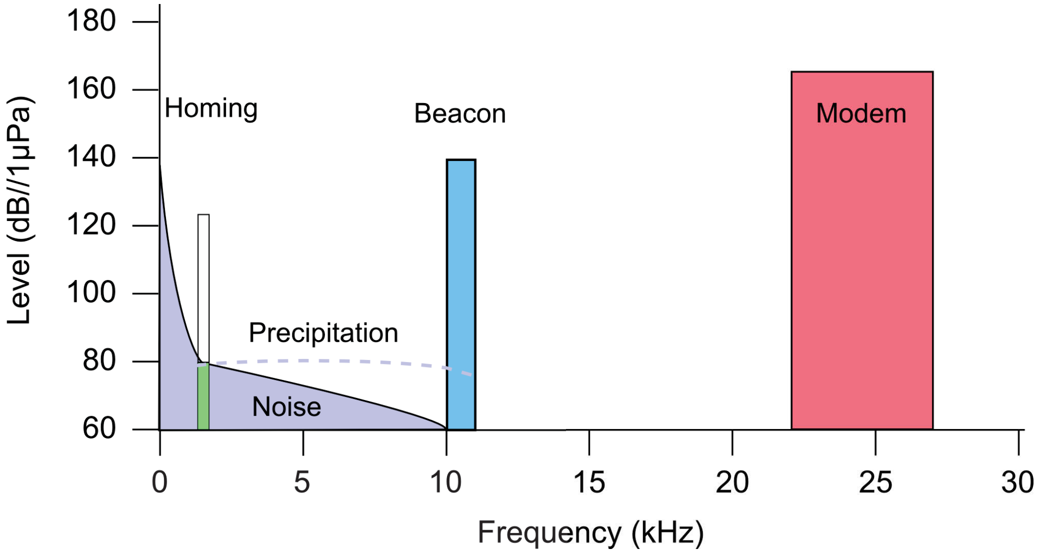

Figure 6: *The three AUV acoustic device spectral allocations and anticipated source (beacon and modem) or spectrum (vector sensor) levels. The modem source level is shown in red, the beacon in blue, the range of the received vector sensor sound pressure level (SPL) denoted by the green and unfilled box, and the typical maximum level of the ambient noise denoted by the grey region. Heavy precipation noise levels are denoted by the dashed line. Bandwidths of the devices are indicated by the widths of the boxes.*

that this same band be employed for the docking concept. Most of the modems that we have employed operate in the 9–14 kHz band where, unfortunately, modem transmissions can be very disruptive. For this reason, and to reduce transducer size for the modem, we propose that modem operation be shifted to 22–27 kHz. The acoustic beacon would then be established at an intermediate frequency, say 10 kHz. This spectrum usage is illustrated in Figure 6.

Figure 6 shows the idealized relative levels of the received homing signal, ambient noise, AUV beacon, and AUV modem. The determination of the levels will be described in later sections with the exception of the level for the ambient noise. The figure shows the typical deep water ambient noise under high wind and shipping activity conditions. This level is usually only exceeded during periods of heavy precipitation. When heavy rain does occur, the level can be approximately constant at up to 82 dB from 100 Hz to 11 kHz.

3.2 Vector Sensor Interference

Reception of the homing signal from the submarine by the vector sensor on the AUV is subject to propagation losses and is complicated by the proximity of the beacon and modem acoustic sources, which might operate simultaneously with the vector sensor receiver. These complications arise from three main sources: i) the linearity of the hydrophone transducers in the vector sensor, ii) the output dynamic range of the vector sensor receiver, and iii) the linearity and dynamic range of the input stages of the vector sensor amplifiers.

Hydrophones are capable of a wide range of linear amplitude response. Just how wide the linear amplitude response region is for any given hydrophone is difficult to determine and this is not a parameter usually supplied by the manufacturer. Fortunately, some measurements were made by Moffat and Henriquez [4] in 1980–81 for various common hydrophones of the time. These authors determined a figure of merit for nonlinear effects in their hydrophones. Typically, for a *good* hydrophone, this FOM exceeds 250 dB and implies that our 80–90 dB difference (*cf.* Fig. 6) in modem and vector sensor signals should not give rise to problems from nonlinearity of the hydrophones. Geospectrum Technologies, a local transducer company, regularly tests their hydrophones for amplitude nonlinearity and their data, even with bender-type hydrophones, indicates that nonlinearity of the transducer should not be an issue for signals with as much as 200 dB level difference [5].

The dynamic range of the digital sensor receiver is often controlled by the width of the A/D system in bits. For example, a 16-bit A/D is capable of providing 96 dB of dynamic range in the absence of any noise. Unfortunately, 1–2 bits are almost always lost due to the quantization noise and system noise. A 24-bit A/D is usually subject to even greater quantization noise and with a well designed system, the practical limit is often 20–21 bits with a resulting 120–126 dB of dynamic range. With careful level controls and filtering either a 16-bit or 24-bit A/D is appropriate for our system.

The third factor arises from the dynamic range and linearity of the input stage of the hydrophone preamplifiers. As a result of the proximity of the modem (loudest source) we can expect a SPL of about 165 dB//1μPa. Approaching the worst case, where the homing signal from the submarine falls to about 60 dB, we can expect to have to attenuate the modem band signal by as much as 105 dB in order to bring the signals to approximately the same received level. The input voltage differences arising from the two signals are large, but suitable linearity and dynamic range are achievable with care.

3.3 Spectral Purity of Source Signals

All three acoustic sources required for the AUV docking equipment will produce signals outside of the nominal bands shown in Fig. 6. The AUV beacon and the submarine homing signal transducer are relatively low SL devices. Their design and construction can be arranged to limit the spectral content outside of the desired transmission bands. For example, with no particular effort one acoustic source that has been studied generally exhibited less than 1% total harmonic distortion [6]. This level of out-of-band signal production is easily handled by a low-pass filter in the AUV vector sensor receiver.

The AUV beacon will similarly produce out-of-band signals; however, due to the low signal level and the ability to use a linear amplifier we can expect very low sub-fundamental

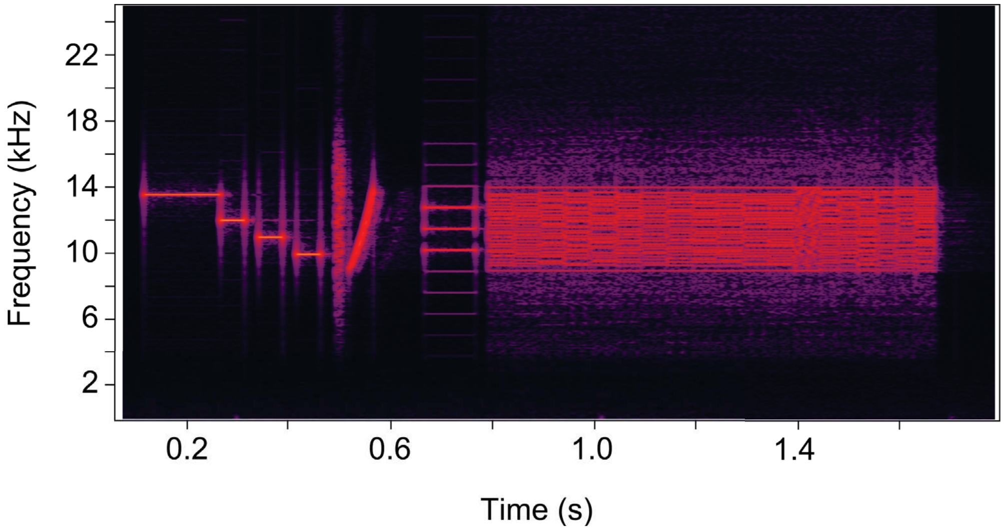

Figure 7: *A sonagram (frequency-time-level display) of a modem data burst in the 9-14 kHz band.*

signal content. Again the vector receiver filter should easily reduce unwanted signals to an acceptable level.

The largest issue with source spectral purity arises from the use of a commercial modem. The source levels of the modem are the highest to be found in our proposed equipment and modem transducers are often driven in such a way that out-of-band signals are not minimized. The degree of issue arising from the use of the modem will depend on the particular modem that is chosen. Specification of limits for the out-of-band modem signals should be included in the final AUV system design.

As an example, Figure 7 shows the Frequency-Time-Level of a commercial modem operating in the 9–14 kHz band. The data for this image were collected in Bedford Basin under the influence of a relatively high background noise level. The majority of the modem signal energy is contained within the 9-14 kHz band, but harmonics and spectral leakage produce significant levels above and below this main band of operation. The signals above the band are easily eliminated by the low-pass receiver filter, but signals below the band can cause difficulty as they are usually subject to less attenuation by the receiver's filters. In this example, the worst levels occur during the 'ladder-tone' burst just prior to the data packet. Fortunately, this particular modem seems to produce very little signal below 3 kHz providing a minimum of one-octave of bandwidth separation between the homing signal and the onset of interfering source.

Unfortunately, we do not have any data on the spectral purity of the same type of modem using the 22–27 kHz band of operation. Presumably, the extra frequency separation will allow the sub-band frequency components to be reduced to an even lower level than for the 9–14 kHz band modem.

3.4 Acoustic Propagation

Much of the preliminary AUV docking project work makes use of a worst case scenario for designing the active dock [7]. This worst case scenario involves docking an AUV with a slowly moving submarine at 15 m depth in water just 30 m deep, under the influence of sea-state 6 wave conditions. While this scenario is useful for modelling the impact of extreme relative motion between the AUV and submarine on the mechanical systems, it is an unlikely scenario that would only be forced on the operators by necessity.

This worst case scenario would also be a difficult acoustic environment due to the high ambient noise level and strong surface scattering under such conditions. In some ways it could also be beneficial. For example the strong wave action would result in a well mixed water mass that would not have a strong layered velocity structure that is well known to be difficult for acoustic modem communications.

There is in fact an enormous variation in possible underwater acoustic conditions. Our approach in this report will be to consider the propagation relative to the most likely conditions under which docking could be expected to occur. We will then try to be conservative in the system design to end up with a robust acoustic sub-system.

The most likely docking conditions for an AUV and submarine are expected to occur in water with a minimum depth of 100 m and probably less than 500 m depth. Both the submarine and the AUV would be operating somewhere in the depth region limited by the submarine's minimum safe depth and the minimum safe bottom clearance. For purposes of illustration, we will assume that the AUV and submarine operate at a depth of 60 m. The water depth will be taken to be a uniform 200 m. We will also assume that the sea is under the influence of sea state 6 conditions and that there is a heavy precipitation resulting in a high noise level across the band.

As a very rough rule-of-thumb, the propagation losses for the transducer signals in shallow water can be estimated as spherical spreading losses ($20\log r$) out to ranges of about four water depths—in our case, ranges of 800–1000 m. Beyond that range the spreading losses are better estimated by assuming cylindrical spreading ($10\log r$).

Attenuation or absorption of the signal energy can be estimated by $PL_a = \alpha(f)r$, where α is a function of frequency f and has units of dB/km. The range, r, is expressed in kilometers. The value of α can be found in various references, including Urick [8], and will generally run from approximately 0.06–6 dB/km in the band from 1.5–27 kHz.

Figure 8 shows a comparison of the simplified propagation model described above and the result obtained with a parabolic equation underwater acoustic propagation model known as PECan [9]. The PECan model was run for a 10 kHz signal in an acoustic environment typical of the Scotian Shelf. The transmission loss for the 10 kHz signal is representative of the condition when the source and receiver are at 60 m depth and the water is a constant

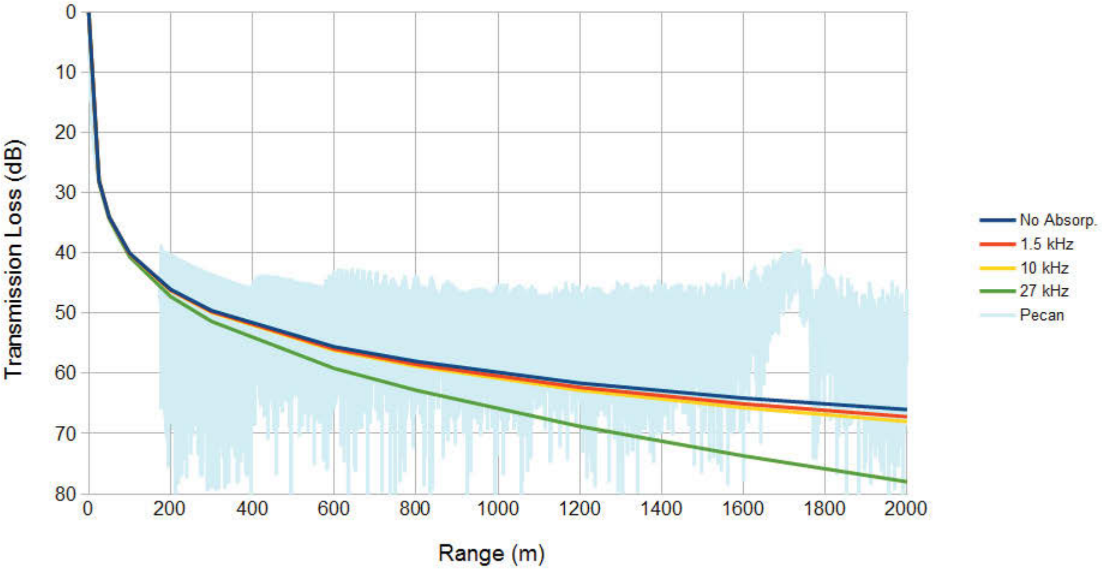

Figure 8: *Estimated propagation losses obtained using a parabolic wave equation model (PECan) and the simplified rule of thumb with absorption losses.*

200 m deep. The 200 m water depth was chosen randomly on the assumption that most operations would be in coastal regions. Rough surface losses are not included in the PECan result.

The PECan result should not be considered accurate at ranges less than 200 m as the interference of surface and bottom reflected signals are not included at these small ranges. At ranges where their effects are included, the transmission loss oscillates in accordance with constructive and destructive interference. A particularly strong constructive interference occurs near 1700 m range. Absorption is included in the PECan result, but it is not obvious. Possibly this is due to the extra energy from the reflected arrivals offsetting the absorption losses at these relatively small ranges.

The comparison of the PECan and simplified model results is generally quite good. At short ranges the simplified model agrees with the geometric mean of the PECan result; however, at longer ranges it is apparent that the simplified model is too pessimistic. The inclusion of scattering losses at the surface and sea floor will increase the loss over that predicted by the smooth surface result, but due to the small number of surface interactions, the losses are not expected to be particularly large. Therefore, it seems reasonable to use the simplified loss model as the basis of a conservative prediction. Using it will generally result in a prediction of a weaker signal at the vector receiver than what would occur in actual practice. Designing the system to work with the weaker signals will result in better performance with the real signals.

4 AUV Beacon

This section describes a concept for the implementation of an AUV acoustic beacon. The acoustic beacon is not a very difficult device to design, but the implementation of the beacon can have a major impact on the cost of the system where it relates to the receiver implementation on a submarine.

The actual beacon design would ideally need to produce a spectral content within the bandwidth of an existing submarine sonar. Further, it is possible that the existing sonar may not be alterable either in regard to the processing requirement or with regard to the accessibility of raw hydrophone signals that would be required to provide an independent processing capability. The ability to localize the beacon signal would then have to be pre-existing in the submarine equipment.

Section 2 describes the docking process and some of the requirements for the acoustic beacon. The primary requirement is that it must be detectable at a range of 2 km. It must be hard to detect for non-allied users, which implies that the source level must be limited, the signal content spread over a significant bandwidth, and the transmissions should not be continuous, but short in duration and emitted on a pseudo-random schedule.

The docking scenario also suggests that the AUV is likely to be of the mid-size category with a diameter generally in the range 8–21 inches, with an emphasis on the smaller diameter vehicles. The vehicle size is a big factor in determining the type of transducer to be used for the acoustic beacon. The smaller the vehicle, the smaller the transducer, and the higher the frequency of operation. This is dictated by both the physical size and weight of the transducer and the amount of energy required to create the signals for the beacon.

Another design requirement is the maximum operating depth of the AUV. Many transducers and AUV are depth limited. We shall assume, since typical operations are likely in shallow coastal waters that a maximum operating depth of 200 m is required.

Optionally, the acoustic beacon transducer might also be useful as an acoustic receiver to receive the submarine's broadcast of the coded signal that will initiate the Stage 1 docking. Not all acoustic sources are good acoustic receivers. The AUV will require the receive capability, but it could be provided by the AUV homing system, which is the subject of the next section.

There are many transducers that could be used to meet the beacon requirements. The Benthowave BII-7534 is an example. This particular transducer is shown in outline in Fig. 9. The 7534 is 9 cm in diameter, 4 cm high, and weighs 330 g. It is useable over a wide bandwidth and provides a transmitting voltage response (TVR) of approximately 128 dB from 8–10 kHz.

The physical size of the transducer and directionality can have a major impact on the AUV,

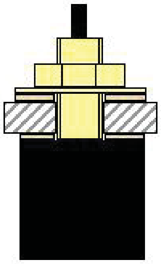

Figure 9: *An outline drawing of the Benthowave BII-7534 transducer. The Teledyne modems use a similar design for their transducers (cf. Section 6)*

especially the smaller AUV's where a large transducer could add significantly to the drag, average density, and size of the vehicle. The 7534 transducer would typically be mounted on the AUV's dorsal surface and would provide a hemispherical or better signal broadcast directionality. The transducers do not have to protrude from the hull, they can be built into acoustically transparent AUV hull secions, but this is rarely done due to the extra volume requirements and significant additional testing and development required.

Figure 10 is a block diagram of the components required for the AUV Beacon. A transducer with both send and receive capabilities is required so that broadcasts from the submarine can be received when the transducer (XDCR) is not operating as a source. A diode cross-over protection network allows switchless operation between transmit and receive modes. A signal generator and power amplifier drive the XDCR with suitable spread-spectrum waveforms in the transmit mode. A preamplifier and analogue-to-digital converter (A/D) provide a digital receive capability. The processing unit (CPU) provides the operational control as a result of commands sent from the AUV central control via the System Network. The CPU also interprets received signals and sends messages to the central control via the System Network. The timing control is a form of real-time clock and algorithm for generation of pseudo-random transmission from the beacon.

We can determine the required source level of the AUV beacon from a direct application of the well known Sonar Equation [8]

$$SE = SL - TL - NL + DI - DT + PG, \tag{14}$$

where SE is the Signal Excess, TL is the Transmission Loss, NL is the Noise Level, DI is the Directivity Index of the receiver, DT is the Detection Threshold, and PG is the Processing Gain. All of these terms are expressed in deciBels.

If the SE is greater than zero, then our sonar performs better than the requirements. When it equals zero, the sonar just meets the desired requirements. By setting $SE = 0$ and solving for SL, we can find the minimum source level required.

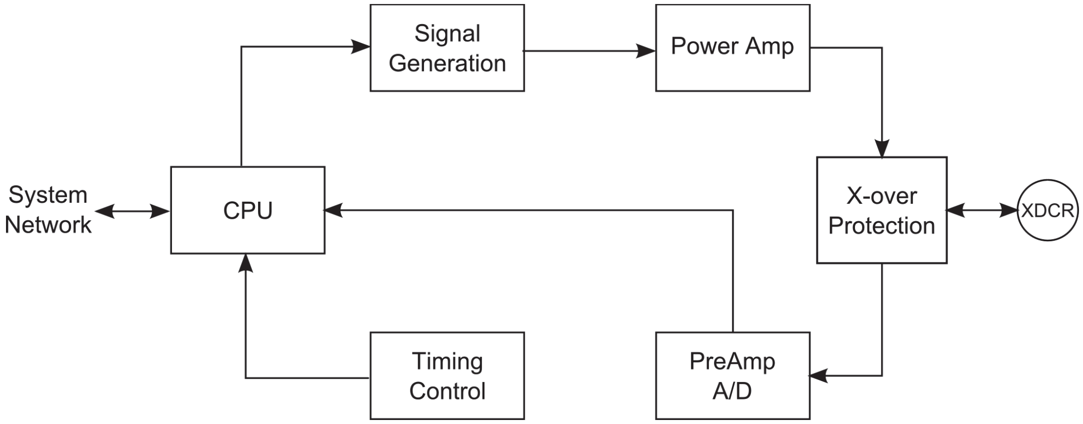

Figure 10: *A block diagram of the components necessary for the AUV Beacon. System commands and responses are communicated over the "System Network" connection. Timing control supports pseudo-random transmissions. Transducer (XDCR) operates as both a source and receiver via the cross-over (X-over) protection circuitry.*

We can find the value of TL from our simplified propagation loss model of the previous section. By choosing $TL = 68$ dB, we are using a pessimistic value representing a loss larger than we would expect in most cases.

The NL can be found from Fig. 6. If we choose $NL = 80$ dB, then we are including the expected noise conditions under heavy rain, shipping, and wind.

The receiver's directivity index is unknown, but at 10 kHz a small receiver just over a meter in length could provide 8 dB of directivity gain. This is a conservative estimate for the capability of a real receiver.

The detection threshold depends on the required probability of detection and the probability of false alarm. In our system we want to be very sure of detecting the beacon signal. A 95% detection probability is a good choice. We also don't want false detections, so a small probability of false alarm, say 10^{-6} would be a good choice.

Estimating the value of DT is complex. It is well described by Walker for narrowband signals [10]. In our case, this analysis is not strictly correct because of the spread spectrum signals that would likely be employed. We can make a first order approximation by including the PG and simply equating it to $10 \log BW$, where BW is the bandwidth in Hertz of the spread spectrum signal. While this is very approximate, it should be adequate given the nature of our approximations in determining the other terms in the sonar equation.

Following Walker, we arrive at $DT = 8.2$ for a beacon signal with a 10 kHz carrier, a sampling rate of 32768 samples/sec, a 1 Hz bin width, and a 10 second detection update rate.

Combining all these estimates we arrive at

$$SL = TL + NL - DI + DT - PG = 68 + 80 - 8 + 8.2 - 10\log BW = 148.2 - 10\log BW. \tag{15}$$

From this result we can see that any frequency spreading greater than 10 Hz will meet our conditions for a 140 dB beacon minimum SL. With the Benthowave transducer given as an example earlier, we would need to provide 12–13 V_{rms} to produce the 140 dB source level over the 10-Hz band. If we chose to spread the signal over 2000 Hz, we could reduce the *SL* by 33 dB. We would then require approximately 46 V_{rms} to drive the transducer. It may seem paradoxical that we require more voltage to produce a lower source level. The reason for this is that we have spread the signal over a wideband and must generate signals at all frequencies within that band. The result is that while the levels are lower, the energy in the signal is higher. The transducer is capable of withstanding a maximum drive of 200 V_{rms}, so we are well within the device capabilities. In fact, a 5–10 W amplifier should be sufficient.

5 AUV Homing System

DRDC has experience with acoustic underwater homing systems for large AUVs [3]. The homing system that was developed is known as the Long-Range Acoustic Bearing (LRAB) device. The LRAB device is shown in Figure 11 mounted in the nose cone of a 68.6 cm diameter AUV. This array is capable of submergence to 5000 m depth and can detect a homing signal in quiet conditions up to 100 km distant. The LRAB uses a sequence of short tone bursts in a narrow band of frequency near 1300 Hz. A processor that detects the homing signal and recognizes the particular tone sequence is housed within the AUV pressure hull and occupies a cube approximately 15 cm on a side. The processor requires approximately 300 mW to operate. The result is that the processor can determine the homing signal source bearing with an accuracy generally better than 1.5° and can act on the ‘command’ denoted by the particular tone sequence transmitted by the acoustic source.

Following the success of the LRAB, a smaller, self-contained system was built. This new homing system is known as the mini-LRAB. Figure 12 shows the mini-LRAB, which is composed of a graphite fibre structure housing a seven-element hydrophone array and a small rear-mounted processor unit in a plastic pressure canister. The mini-LRAB is less than 15 cm in diameter and is intended for small-to-medium sized AUVs. Mini-LRAB operates in a band centred on 1500 Hz and can make use of any suitable acoustic source capable of a few hundred Hertz of bandwidth around that frequency. The Benthowave BII-7534 suggested for the AUV beacon could be used as the homing signal source.

The mini-LRAB is almost the ideal solution to the requirement for the Stage 1 acoustic homing discussed in this paper. The mini-LRAB can be used as is by incorporating the integrated unit in a free-flooding section of an AUV. The array and processor can also be

Figure 11: *The Long-Range Acoustic Bearing receiver in the nose cone of a large AUV.*

Figure 12: *The mini-LRAB acoustic homing receiver. This system integrates the receiving array and processing in a water-proof package for use in small-to-medium size AUVs.*

separated, and with additional effort, a seven-element linear array could be designed for use on the exterior of the AUV. Using a linear array would require software development for the mini-LRAB processor, but there is no particular problem in doing this.

The largest problem arises if we wish to operate the mini-LRAB simultaneously with the AUV beacon and the AUV modem. The design principles for simultaneous operation have been described in the previous section. The current mini-LRAB hydrophone preamplifiers will not operate properly with these strong nearby sources in operation. A significant issue in the design of a system capable of simultaneous operations is the production of an amplifier with the required input voltage range capability while simultaneously limiting the input referenced noise level of the amplifier.

The noise level and input voltage range can be difficult to achieve when we need to deal with very weak acoustic signals. In the current application, we can ensure that the received SPL is sufficiently large that we can produce an amplifier with adequate noise performance.

Figure 13 is a schematic diagram for a low-noise, large input voltage range preamplifier. This amplifier has not yet been built, but simulation has shown that the input referenced noise level should be on the order of approximately 15–20 $nV/\sqrt{Hz}$ with proper construction. The amplifier has a 10 V_{pp} input range.

The simulated response of the amplifier circuit is shown in Fig. 14. The amplifier will pass

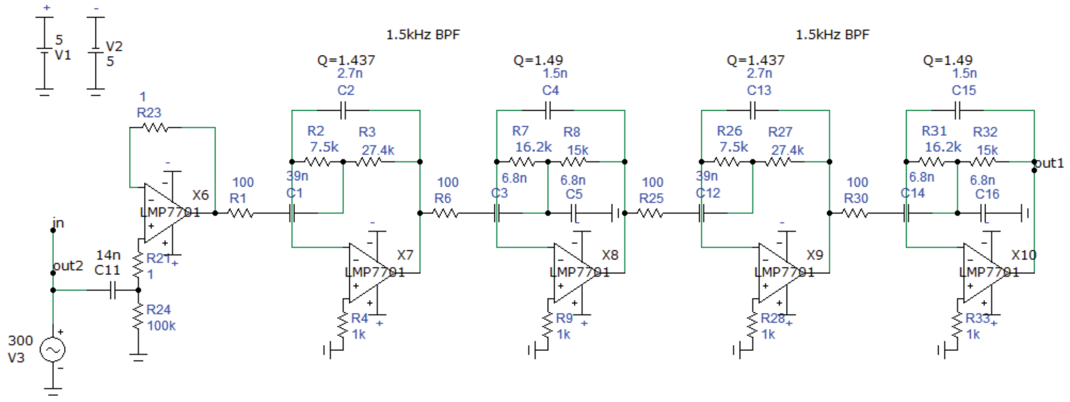

Figure 13: *Initial design of a high input voltage range preamplifier with a predicted noise floor of approximately 15–20* $nV/\sqrt{Hz}$ *allowing simultaneous reception of weak homing signals and loud interference from a nearby beacon and modem.*

frequencies from 1.1–2.0 kHz and will attenuate both higher and lower frequencies. The attenuation at the 10 kHz beacon frequency relative to the pass-band is approximately 63 dB and the attenuation for the 22–27 kHz modem frequency band is better than 90 dB. These levels of attenuation will reduce the strong source signals to levels comparable to what we expect to receive with the homing signal source. To improve matters, two additional operational amplifiers can be incorporated to increase the out-of-band attenuation so that the interfering source signals are smaller than the homing signal at the output of the pre-amplifier.

The question now arises as to what the expected input voltage range and homing signal level will be?

The receiving transducers will generate voltages corresponding to their sensitivity at each frequency. The AUV beacon, which we will take to be 1 m distant from the hydrophones, will have a SL of no more than 140 dB//1 μPa @ 1 m. A typical un-amplified hydrophone can have a sensitivity of say -195 dB//1 V/μPa. Often this sensitivity is constant across a wide band of frequency. Therefore, the output of a typical hydrophone would be about $140-195=-55$ dBV for a single tone from the beacon. Assuming a nearly white noise-like signal of 2 kHz bandwidth we would generate a signal of approximately $-55+10\log 2000=-22$ dBV or 80 mV$_{rms}$. This signal is no problem for the vector receiver. The beacon's centre frequency would be strongly attenuated by the receiver's filter and the corresponding output will be very small (-85 dBV).

The modem signal is much louder and has a wider bandwidth. Fortunately, the modem signal is not white-noise like. In fact, the signals typically employ a frequency-hopped

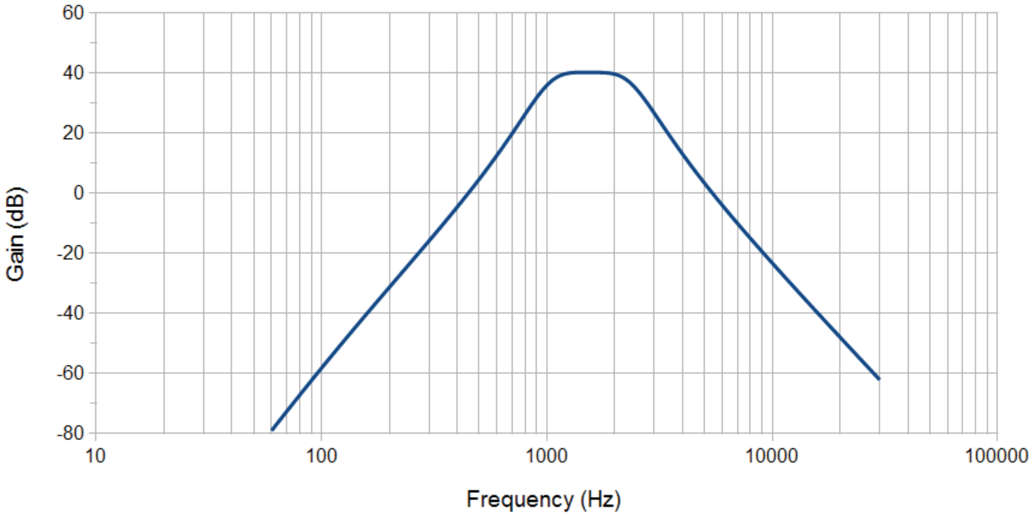

Figure 14: *The predicted filter response for the AUV vector receiver preamplifier design.*

encoding or other discrete tonal encoding so that the modem signal at any instant has a very limited bandwidth. Measurements with our Teledyne modems indicate only a 3–6 dB increase in level for a data transmission over the level for a constant tone. We can estimate the typical hydrophone voltage response to the modem, assuming a 1 m separation, as $165-195+6=-24$ dBV; similar to the beacon signal response. This is fortunate because modems are typically operated at much higher source levels. A source level of 180–186 dB//1μPa @ 1 m is not uncommon. As mentioned earlier, underwater data transmission can be difficult and it is to be expected that higher levels will be used if they are available. If we add another 20 dB to the modem level, the generated voltages start to become appreciable. In addition to these steady state conditions, it is possible for short transient signals to be generated that have high level and wide bandwidth. These transients, although short, are sufficient to cause issues in many preamplifiers. The analysis presented here has also not included the out-of-band tonals generated by the modem. The spurious tonals below the modem frequency band are not strongly attenuated and add significantly to the hydrophone response. We can expect hydrophone signals up to several volts to be generated by the modem transmissions.

Our 10 V_{pp} input voltage range is large with respect to the steady state conditions and all but the largest transients should be easily handled. Now, we turn to look at the homing signal level at the receiver and compare it with the amplifier input noise.

The homing signal is provided by a source on the submarine. As can be expected, a submarine needs to be quiet, and therefore the homing signal must be transmitted at minimal level. If we assume that a 1 km range is the maximum required, we can determine the received sound pressure level at the AUV vector sensor. Assuming that we employ the Benthowave BII-7534 transducer as the signal source, we find that the device has a TVR slightly in excess of 130 dB//1 μPa/V @1 m over most of the band 1.1–2 kHz.

We again employ the sonar equation in a slightly modified form, $SPL = SL - TL = NL - DI - DT$. The NL will once again be the worst case 80 dB. The DI depends on the form of the receiver, but generally will be less than $10 \log N$, where N is the number of hydrophones. Our LRAB devices use seven hydrophones leading to a maximum DI of about 8 dB; however, a value of 4.5 is more typical and would also be approximately correct if a short linear array is used and detection occurs in a beam that is not perpendicular to the array axis. The value of DT is more complicated to determine. In this case, not only is it a broadband signal, but we also need to determine the arrival bearing with accuracy. Practical experience has shown that good results are always obtained with a $DT = 10$ dB, so we will use that here. The result is that the SPL must exceed 85.5 dB. From our simplified loss model at 1.5 kHz we can expect 62 dB, implying a source level of 147.5 dB. This is quite a loud source. Fortunately, we can now apply a bandwidth correction that will reduce the transmission level. Our current design could make use of up to 1 kHz of signal bandwidth, which implies that we could reduce the source level by 30 dB to 117.5 dB.

A source level of 120 dB for a 1 kHz wide homing signal is quite reasonable. By adding a few additional deciBels we help to overcome flow noise at the receiver, which we have not previously included. In addition, it must be remembered that we are looking at worst case conditions. In more average conditions, a reduction of source level by up to 20 dB is possible.

With a 120 dB source and the maximum 1 km range, the SPL would be 58 dB. With hydrophones of -195 dB//1 V/μPa the output voltage would be approximately 141 nV. Thus we would be about 19.5 dB above the amplifier electronic noise floor. This means that we still have almost 20 dB of signal-to-noise ratio (for system electronic noise only, we are below the ambient noise level and rely on the processing gain to recover the signal). Thus in quieter ambient noise conditions, the homing signal source level could be reduced by the same amount (up to 20 dB) and we would still be able to recover the signal at the receiver. This means that our system is ambient noise limited for conditions above average noise. Below average ambient noise levels, the system is limited by electronic noise. With more effort, a better amplifier electronic noise floor is possible, but we would not expect to gain more than 6–7 dB. This electronic noise floor implies that in quiet ambient conditions, we would always be limited by the electronic noise unless we boost the transmission source level, increase the signal bandwidth, or build a larger more directive receiving array.

Our design is a reasonable trade-off. Electronic complexity, transmission source level, array size, and signal bandwidth are all achievable. The result is a system with good capability in most conditions.

This preliminary analysis shows that the submarine source could be built using the same equipment used to build the AUV beacon. The AUV receiver requires some build and test development, but it should be relatively easy to achieve the required performance of low noise and high input voltage ratio by starting with our supplied design. This receiver design would allow the homing system to operate simultaneously with and in the immediate proximity of both the AUV beacon and modem. The design of a linear array to replace the existing volumetric array is a bigger task. The basic layout is simple, but achieving the desired response in the flow and vibrational environment can be difficult.

6 Acoustic Modems

Unlike the AUV beacon and vector sensor, which can be developed by DRDC relatively quickly, the development of an underwater acoustic modem is a lengthy and expensive process. The AUV and submarine will almost certainly make use of an existing commercial modem.

As described earlier, modem communications should be avoided until the submarine and AUV are relatively close together. Short ranges generally yield a high link success probability and allow the use of lower source levels.

Most of our experience with modems has been with the Teledyne Benthos telesonar modems in the 9–14 kHz band of operation. As described previously, modem transmissions can interfere with sensitive acoustic receivers and because of this we have designed a new preamplifier to be more tolerant of large interference signal sources. To further improve the interference at the output of the preamplifier, we have suggested moving the modem band upward in frequency to provide greater separation between the modem and homing signals.

There are a variety of modems that could be employed for the data communications in the AUV docking application. Here we suggest the use of the Teledyne modems due to our familiarity with them, but also because they allow control of the transmitted source levels, support a continuous data streaming mode of operation, and can be run using a US military network protocol known as Seaweb [11].

Using the higher frequency band for the modems results in a lower maximum source level of 178 dB versus 185 dB for the 9–14 kHz band. This lower power level is likely due to lower noise levels and more efficient transduction at higher frequencies. The lower source level translates into a 50% saving in transmit power requirements for the modem. The modem source levels can be controlled in steps. The minimum source level is 21 dB (seven steps of -3 dB) down from the maximum, or 157 dB for the higher frequency range choice.

Normal modem operations that involve handshaking are slow. To send the request-to-send

(RTS), clear-to-send (CTS), and acknowledgment (ACK) together with channel probes can take almost 15 seconds before data begins to move from one modem to another. This high latency is tolerable for the modem ranging and data transmissions in the latter part of Stage 1 homing, but it is intolerable for the Stage 2 homing where the submarine dock is in control and sending speed and course adjustments on a continuous basis to the AUV. Such high latency would result in unstable control. A different method of communication is required for this part of the homing process.

The Teledyne modem supports a mode where after an initial synchronization between modems, data can be streamed continuously from one modem to another. If we include data structures with time stamps, speed, and course changes, using this streaming mode we should be able to realize a relatively low latency open loop control from the dock to the AUV. Closure of the control loop would come from the dock observing the AUV through electromagnetic and optical means.

To date we have only verified that this mode is operational and we do not have sufficient experience to evaluate its usefulness. This form of modem operation will need to be further studied to assess its value to the docking application.

The third feature of the Teledyne modem is the existence of the Seaweb networking code. The value of this networking capability is often over-looked, but it is essential for most practical underwater operations. This is particularly true where there maybe more than one AUV, submarine, or other source of modem signals within a given area. The networking allows addressed communications where the messages are acted upon only by the intended network nodes.

There are only a few viable underwater acoustic networking codes available. The development of such codes tends to be slow and expensive, at least where their utility has been proven in experimental and operational conditions. At present, Seaweb only runs on the Teledyne 885 and 900 series modems. It's existence has predicated our reliance on the Teledyne equipment.

Most modems are capable of a range of transmission and reception acoustic baud rates. The Teledyne modems have a series of different rates running from 140 bps to 15360 bps. Not all Teledyne modems can operate at baud rates above 2400 bps. The baud rate of the modem does not reflect directly on the actual data transfer rate. The actual data transfer rate depends on the transmission mode and the length of various guard bands. The most common mode that we have used in a variety of acoustic environments employs an acoustic transmission rate of 800 bps, a run-length encoding factor of 2, and repeats the data twice. Together this error correction and repetition with 12.5 ms guard bands results in less than 200 data bits per second actually being transmitted. In difficult environments we have used a 140 bps with run-length encoding factor 2, and four repetitions of the data, with 25 ms guard bands. This translates to approximately 17 data bps.

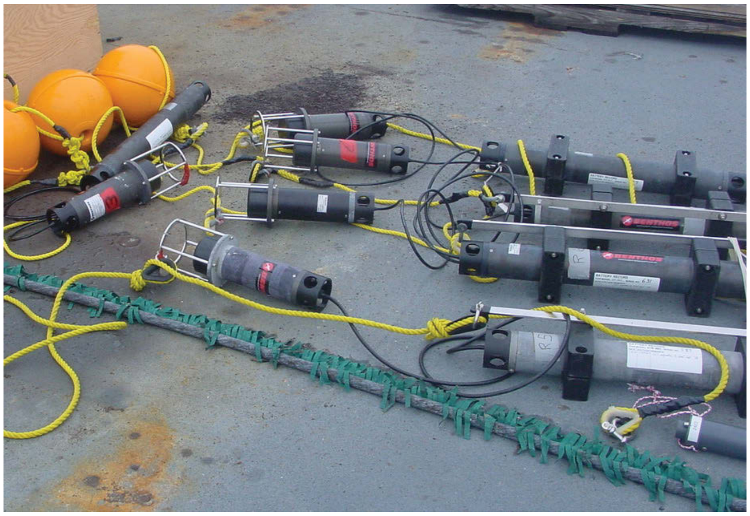

Figure 15: *Teledyne modems with separate electronics and battery canisters are ready for deployment. The transducer must be in contact with the sea water and must be located to have an acoustically transparent field of view. Generally, in AUV applications, the transducer is mounted on the dorsal or ventral surfaces.*

Due to the low data rates, acoustic modem data packets are best kept short with very terse data representation within the packet. In Stage 2 docking, with data streaming from the dock to the AUV, the update rates will not be rapid. With the 800 bps mode described above and data packets with only 4 floating numbers we cannot expect much more frequent updates to speed and course than once per second.

The Teledyne modems are relatively large devices and will require adequate space for the amplifier-processor board and the transducer. The 900 series modems require an internal space in excess of 7.6 cm x 15.2 cm x 5.1 cm for the circuit board. The transducer for the 22–27 kHz band has external dimensions of 5.2 cm diameter and 6.4 cm high. Power requirements reach 63 W peak and average 20 W in transmit mode. In receive mode the typical power drain is approximately 0.5 W. The modems also include a very low power sleep state that still allows them to recognize an incoming signal. The low-power sleep mode and the short duration of data transmissions allows the modems to have an operating life of several years under low-duty cycle applications with a standard 21 V, 18 A-h alkaline battery pack. Figure 15 shows several of the 800 series modems in one of the many physical configurations. In the configuration shown, the transducer and electronics are in the short, separated canister. The long canister is used for an extended battery pack. The same long canister is often used to house the transducer, electronics, and standard battery pack. The modems can be powered from any available power source. Generally, in AUV applications they are connected to the main propulsion battery.

7 Conclusion

This report provides a detailed description of the Stage 1 AUV docking concept. The roles of three separate acoustic systems: AUV beacon, AUV vector sensor, and modems, are described.

Design considerations for both the beacon and vector sensor are provided. The AUV beacon is a relatively simple development. The vector sensor is essentially an enhancement of existing systems that were previously developed by DRDC. The two main extensions of the existing vector sensor include an improved preamplifier design that will allow simultaneous reception of weak homing signals while both the AUV beacon and modem are operational and the possibility of developing a linear array for external mounting to the AUV. The development of the linear array is the more involved of the two.

The modem is expected to be a variant of some commercial acoustic modem. The Teledyne modems that support the US Seaweb networking code are recommended. In Stage 2 docking, the modems are expected to be used to provide guidance to the AUV. This latter stage of docking requires a low latency message passing and interpretation capability for stable control. Teledyne modems support a data streaming mode that may meet the requirements for AUV control in Stage 2. This data streaming mode has not yet been properly tested, but it appears to be quite promising.

8 Future Work

This paper has outlined the details of the Stage 1 docking process and its requirements for three acoustic systems. Concept designs for the acoustic systems have been presented. In order to further the design process additional work will be required. This section briefly lists some of the tasks required to further the docking concepts, the person effort, and the cost for steps.

Vector Receiver Preamplifiers Spectrum usage and receiver performance are key to successful operations. The vector receiver preamplifier is the single most important part of the system. The preamplifer performance for both noise level and the ability to handle strong interfering sources needs to be evaluated in actual hardware. A first look at this is expected to require 1-2 FTE (full-time equivalents) and $10–15k.

Acoustic Beacon Hardware A concept design has been developed. The next step is to test specific transducers, amplifiers, and other electronic components. Using the DRDC Calibration Barge and experiments of opportunity on various field trials, the basic beacon system could be developed with an effort of approximately 2 FTE and a cost of $10–15k.

Modems DRDC has considerable experience with 9–14 kHz modems; however, we have never used the 22–25 kHz band. Modem range and source level performance needs to be verified along with range determination accuracy and data stream mode operation in the C-band. This is expected to require approximately 1 FTE and $20–25k (a single pair of modems).

Strap-On or other homing arrays Considerable practical experience with AUV homing has been developed in past work using large AUVs operating at long ranges in moderately quiet deep-water and shallow-water environments. Smaller AUVs require the development of linear strap-on arrays or smaller volumetric arrays. This is a fairly major undertaking that would require substantial person effort and costs. However, smaller steps can be taken to investigate the flow noise, directional capability, and resistance to internal AUV noise. Investigation of several of these factors is expected to require approximately 1-2 FTE and cost $30–40k, for materials, boat rentals, and contractor assistance.

Spread Spectrum Signal Processing Basic experiments are required to verify the performance of the spread spectrum signal performance for both the beacon and homing signals. This is a 1-2 FTE effort and $10k cost.

Side-looking Array Homing Performance All of our previous homing systems have employed a forward (nose cone) mounted vector receiving array and they have always ended with the AUV circling the homing signal source. A series of experiments is required to determine the practical end-point performance of an acoustic homing system where the AUV heads toward the acoustic source and transitions to a different guidance scheme at short range. In this docking concept we look for the homing signal to be initially in the aft quarter. Due to this geometry the forward mounted receiver is not ideal. The body and structure of the AUV have a significant impact on the signal detection performance. A side-mounted linear array has been suggested as a solution; however, we do not have any practical experience with this arrangement. We need to develop an experimental system to simulate the performance of such an array and how it responds. Effort is estimated at 2–3 FTE and cost at $20–30k.

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Stage 1 AUV-Submarine Docking Acoustic Systems

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Heard, G. J.; Watt, G. D.; Schattschneider, G.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
August 2013	46	11

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

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11GH09	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
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This report has been generated in support of the DRDC AUV (autonomous underwater vehicle) Docking Technology Investment Fund (TIF) project. The report provides a level of detail for the conceptual rendezvous and Stage 1 docking procedures. Three acoustic systems are required to conduct Stage 1 docking: an AUV beacon signal generator, an AUV vector sensor-based homing signal receiver, and underwater modems. The role of these acoustic systems is discussed and a suggested procedure is developed. Design issues for the acoustic systems are explored and potential designs for the beacon and vector sensor systems are presented. The beacon is a new, but relatively simple device. The proposed vector sensor is a second generation version of an existing DRDC homing system. The modems are expected to be a variant of a commercially available system. The Teledyne telesonar modems are the suggested solution as they are the only modems to support a full underwater networking protocol and they have a data streaming capability that will be important for final stage docking.

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