A Methodology for Relative Performance Comparison of Underwater Acoustic Sensor Networks and Legacy Expendable Sonar Sensors

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Abstract

An Underwater Acoustic Sensor Network (UASN) is compared with the use of legacy expendable sonar sensors. A simple means is derived to compare these two types of systems, namely the UASN and expendable sonobuoy sensors, to determine the relative comparative use of the UASN as opposed to the legacy sensors. The comparison is utilized to demonstrate the potential advantages of using such a system over conventional sensors if the system exceeds the operational efficiency of legacy underwater expendable sonar systems by a given factor. The methodology uses a simulation of a distribution of sensors which have a performance in terms of target detection based on a Median Detection Range (MDR) and the use of a 'cookie-cutter' approach. The comparison between the dissimilar sensors is accounted for by a Relative Sensor Performance Factor (RSPF) of acoustic performance which although is based on range should also account for the sensor system performance under the same acoustic environmental conditions. Only passive acoustic underwater sensors are considered. An example deployment is used in a choke-point scenario, for the Straits of Gibraltar. Given even a nominally small RSPF between the sensors, the UASN could provide a higher operational advantage over legacy sensors.

Keywords
Sonar, modelling, relative performance

1. Introduction

1.1 Underwater Acoustic Sensor Network vs. Legacy Expendable Sonar Systems

The Defence R&D Canada Atlantic Research Centre is in the process of developing a wireless Underwater Acoustic Sensor Network (UASN). The system, as shown in Figure 1, comprises of a buoyed vertical line array which is anchored to the seabed. Multiple numbers of these sensors distributed over the sea floor provide a network of nodes that are capable of communicating with each other and to the surface for reporting of underwater contacts [1]. The problem of communication between the sensors and relays to the surface is the subject of considerable study, as discussed by Heidemann et al [2]. However, this aspect has benefited from recent developments and acoustic modem technology has progressed to a point where this is not perceived as being a technological hurdle, though it still requires astute design. Similarly, the design of the various layers, such as the physical layer, data link layer, and network layer [3] are the subject of research which is also not considered here.
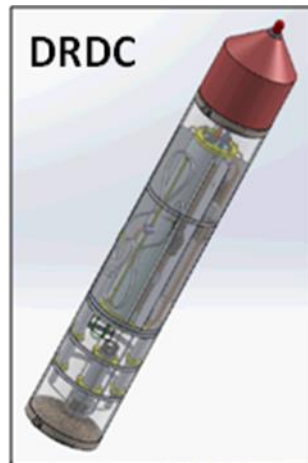
Figure 1. Underwater Acoustic Sensor Network (UASN) Single Node

Legacy sonar systems consisting of expendable sonobuoys, as shown in Figure 2, have been used for decades [4]. Sonobuoys are expendable, inexpensive sensors that have a short life endurance of several hours, and are drifting, submerged sensors that require operators to monitor the sensors in order to process the raw acoustic data into acoustic contacts.

Figure 2. Expendable Sonobuoy Underwater Sensors[1]

1.2 Aims and Objectives

The aim of the study is to derive a simple means of comparing these two types of systems, namely the UASN and expendable sonobuoy sensors, to determine the use of the UASN as opposed to the legacy sensors. At this point, only passive acoustic sensors are considered.

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[1] http://www.ultra-ms.com/products-and-capabilities/sonobuoys.aspx

2. Methodology for Geometric Analysis of Sensor Coverage using Median Detection Range (MDR)

The methodology used in this study is based on a geometric analysis of the sensor coverage using the Median Detection Range (MDR) of each type of sensor, and a "cookie cutter" approach. The methodology was largely based on and is fully described in the paper "Detection Capabilities of Randomly Deployed Underwater Sensors" [5] but some changes were made with the methodology, namely that the sensors are not randomly deployed. The methodology was applied previously in the analysis of underwater diver detection sonar [6].

In the current study, the sensors are ostensibly spaced in a line equidistant in a box appropriate for the scenario. The scenario in this case was an example for the Straits of Gibraltar as shown in Figure 3.

Figure 3. Straits of Gibraltar Straight Line Barrier Scenario

The sensors are modeled as discs or "cookie-cutters" with a sensor radius R based on the mean detection range reported by the operators. The sensor can detect the target when it enters the sensor region, which is centered at a point in the operational area formed by a rectangle of width 2U, as in [5], but with a depth 2V, given a coordinate system which is centered in the rectangle at (0,0). Figure 4 shows a rectangular box with a single sensor placed somewhere in the rectangle, and a target path entering the bottom of the rectangle and constrained to exit at the top.

The minimum number of sensors that can be deployed in the area is 1, naturally. For the purpose of the study, that sensor will be placed at the centre of the width of the region, near the middle of the area (ostensibly at a constant depth location) which represents a typical placement based on the depth of the sensor. The underwater target enters the box from the lower side at a randomly placed x position between (-U,U) and at a y position of (-V). It then follows a straight line at an angle of (0, 180 degrees). Since this could lead to an exit from the region prior to reaching the upper side of the rectangle, for statistical sampling, only those runs that can reach the top of the rectangle are used in calculating probabilities. In other words, one of the assumed constraints is that the target is trying to reach the upper side of the rectangle.
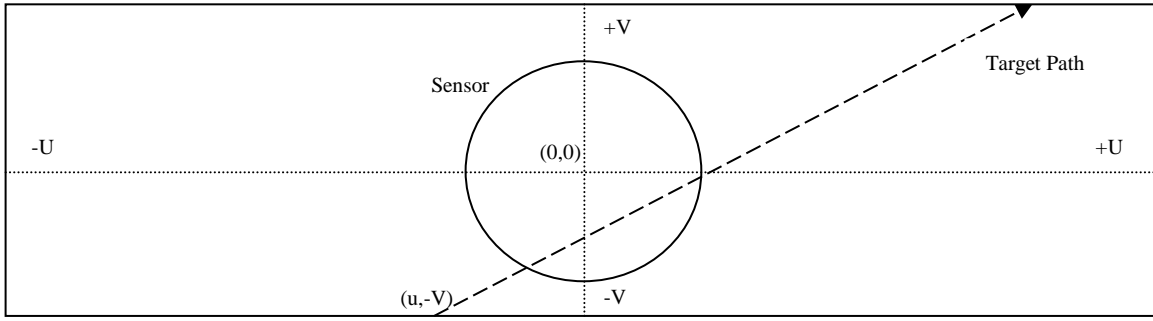
Figure 4. Rectangular Area with a Single Sensor and Target Path

When more than one sensor is used, the sensors are, for want of a better strategy, placed equidistant along the middle of the rectangle. The maximum number of sensors is calculated as the width of the rectangle 2U divided by the mean detection range. While the mean detection range was calculated for the detection probability calculations, a constant assumed MDR= 200 meters was used for the purpose of determining the maximum number of sensors. In other words, for an individual sensor at (x_c,y_c);

$$P_d(X_c,Y_c) = \begin{cases} 1, d_{min} \leq MDR \\ 1, d_{min} \leq MDR \end{cases}$$

The distance d_{min} is the minimum perpendicular distance as shown in Figure 4 between the centre of the sensor at (x_c,y_c) and the straight line of travel. Given a multiple number of sensors the probability of detection is given as in [3];

$$P_d = \iint P_d(x_c, y_c) f(x_c, y_c) dx dy$$

where $f(x_c,y_c)$ represents a given function for the area for the sensors; in this case a combination of circular areas. The straight line route from the target path is given by the line;

$$y = x \tan\theta - U - u \tan\theta$$

Hence, the d_{min} is given by;

$$d_{min} = \sqrt{\left[\frac{my_c - mb - m^2 x_c}{1+m^2}\right]^2 + \left[\frac{mx_c + b - y_c}{1+m^2}\right]^2}$$

where the slope is $m = \tan\theta$, and the y intercept is $b = -U - u \tan\theta$.

3. Simulation Parameters and MDR Results

A Matlab simulation was developed to test the various sensor probabilities of detection. The size of the rectangle based on the Gibraltar scenario is 20000 yards (or the equivalent in meters) wide and for the purpose of the barrier,

2000 yards deep. For the simulation, 5000 target iterations were used randomly starting from anywhere along the bottom of the rectangle and in any direction; those target paths that do not exit from the top of the rectangle (that is, exit from the sides of the rectangle) are not used as valid targets. The minimum number of sensors that can be deployed in the area is 1, while the maximum number could be determined by the maximum MDR. For a strict comparison between the UASN and sonobuoys, the maximum number of allowed sensors is 32 for this study, but is not necessarily fixed. Each sensor is placed equidistant along the rectangle in a straight line.

For a parametric analysis of the sensor range, the sensor MDR was divided in increments of 100 meters beginning at; 100 meters<=MDR<=800 meters. The probability of detection (PD) is determined from the number of valid target runs that enter one of the sensor's mean detection range. The results from each of the runs are shown in Figure 5.

For an MDR of 100m, a maximum PD of approximately 33% is achievable; given 32 sensors will only cover a breadth of 30% of the width of the straight. For double the MDR to 200m, a maximum PD of about 75% is possible if 32 sensors are used. A 300m MDR results in close to 95% PD as 87% of the Strait of Gibraltar width is covered. With a 400m MDR, most of the Strait is covered with close to 100% PD, and fewer sensors would be required, i.e. a maximum is achieved with about 28 sensors. Similarly close to 100% PD is achieved with and MDR of 500m-800m, with 22 sensors - 14 sensors required respectively.

While the respective PDs are given relative to the number of sensors and given MDR, it remains to compare the UASN with legacy sonobuoys. Introducing the acoustic parameter of Directivity Index (DI), each system can be characterized by its individual DI [5]. DI is measured in decibels (dB), and can be translated into range by the use of a simple formula for range, for this study, namely the use of a spherical or cylindrical spreading loss. For the Straits of Gibraltar, the use of the cylindrical 10logR, where R is range can be used. An example table for the calculation is shown in Table 1;

Table 1. Range versus decibels

Range(m)	10*Log(R)
100	20
200	23.0
300	24.8
400	26.0
500	27.0
600	27.8

The Relative Sensor Performance Factor (RSPF) between the two systems can be determined by taking the difference in dBs between the two systems and deriving a range factor between the two systems instead of a dB level. For example, assume for the purpose of demonstrating the methodology that the UASN may have a 3-7 dB difference in DI over a typical sonobuoy; in which case an RSPF of between 200/100 or 2 times the range, to 500/100 or 5 times the range can be assumed.

Referring back to the MDR results in Figure 5, if a sonobuoy has 100m MDR and the UASN is 2 times that or 200M MDR, then the PD would go from 33% to 75% using the maximum number of sensors. If a maximum relative sensors performance factor of 5 times is used; and the MDR of the sonobuoy remains at 100m, then the UASN results would correspond to the 500 m MDR and close to 100% PD would be achieved with fewer sensors, approximately 22 sensors versus 32 sonobuoys. Should the sonobuoy MDR be higher, for e.g. 400m, then a 2 times factor would give the UASN an 800m MDR. Both systems could then achieve 100% PD, but using 28 sensors for the sonobuoy versus 14 nodes for the UASN system.

The previous analysis is based on a one-dimensional geometric spreading formula. In reality, the environment is three-dimensional. More importantly, the depth-dependent sound speed profile dictates the actual acoustic propagation in the water column. This implies that the depth selection of the sensing device has a strong impact on performance. In the present one-dimensional approach, having multiple sensing devices located at different depths

translates to an increase in DI, which in turns augments the MDR. In a multiple-dimensional environment with multiple sensing devices at different depths, acoustic propagation simulations would be needed. However, in the case of an isovelocity sound speed profile, Figure 5 could still be used.
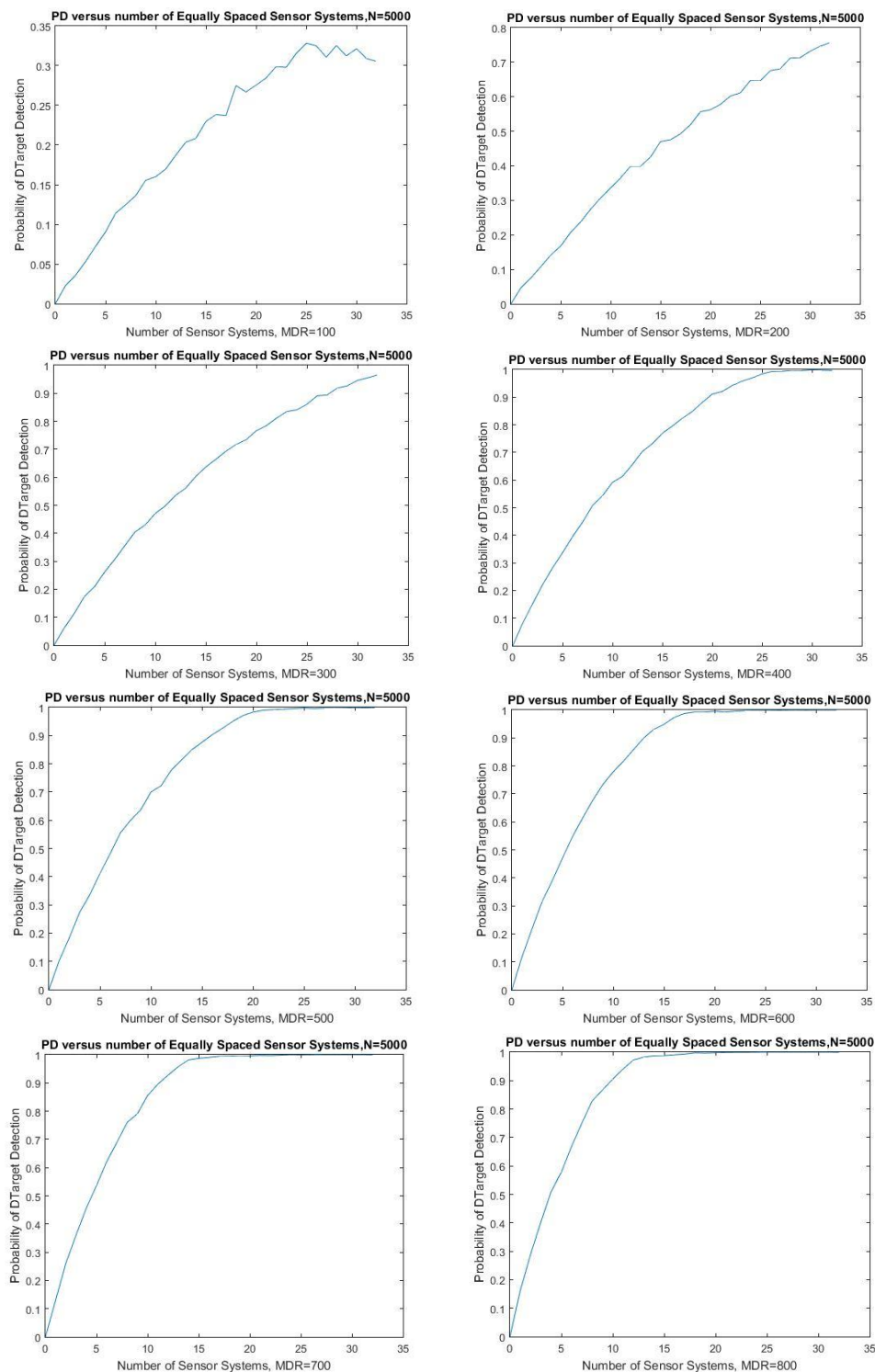

Figure 5. PD versus Number of Equally Spaced Sensors with an MDR of 100-800 meters

An example of Signal Excess (SE) for the case of 14 sensors is shown in Figure 6. The row of sensors is shown with a target having passed the barrier, where the brighter color (red) represents a higher signal excess and blue represents a lower signal excess. The approximate MDR for the sensors in the example is 800 meters. The heat map spanning the Strait of Gibraltar shows an example of sonar performance where an SE of 0 dB gives an approximate PD of 50%. This example, constructed using the Multistatic Tactical Planning Aid (MSTPA) courtesy of the NATO Center for Maritime Research and Experimentation (CMRE) [7], provides a visualization of what the potential acoustic performance of the UASN could be for a given set of environmental and system parameters. Such visualizations are thought to be useful particularly to the operational community [8].
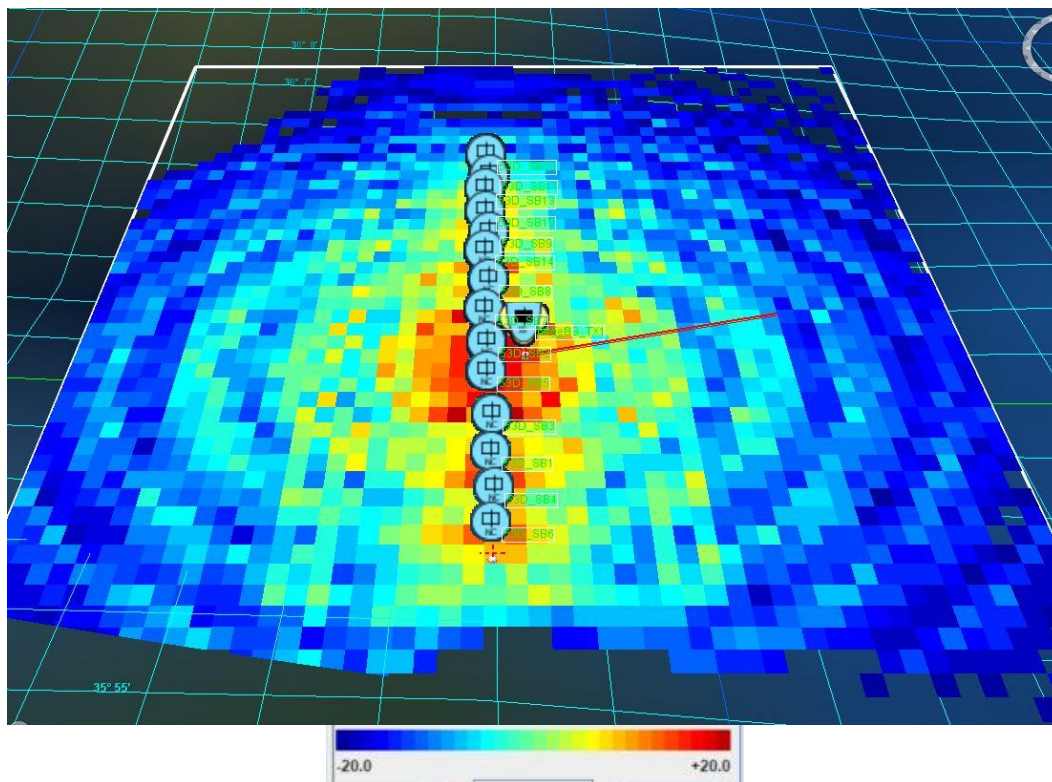

Figure 6. Signal Excess Plot Example for Sensors with an Approximate MDR of 800 meters

4. Summary and Conclusions

A methodology for comparing an Underwater Acoustic Sensor Network (UASN) to legacy sensors is used to differentiate the UASN from the use of legacy expendable sonobuoys. The methodology uses a simulation of a distribution of sensors which have a performance in terms of Probability of Detection (PD) of the target based on a Median Detection Range (MDR) for the sensor and the use of a 'cookie-cutter' approach. The scenario chosen for the example was the Straits of Gibraltar in which a straight line of equidistant sensors are placed across the Strait. The number of sensors required to achieve a PD up to a maximum 100 percent is used to give a relative performance between the systems. The difference between the systems is accounted by a straight forward difference in decibels converted to range as a Relative Sensor Performance Factor (RSPF). The number of sensors and the resulting PD can then be determined for each system, when the system parameters are known. The system parameters for the UASN should then be determined from Operational Trials and Analysis (OT&E).

Future enhancements to the methodology could examine the temporal nature of the problem, since the endurance of each sensor is also a factor in their employment. In addition, active sensors are also a possible UASN development,

as well as multiple types of underwater sensors including magnetic detection, as only passive acoustic sensors are considered in the current study.

References

1. Murad, M., et al, "A Survey on Current Underwater Acoustic Sensor Network Applications", International Journal of Computer Theory and Engineering, Vol. 7, No.1, February 2015.
2. Heidemann, J., et al, "Underwater Sensor Networks: Applications, Advances and Challenges", Philosophical Transactions of the Royal Society A, 2012, 370, pg. 158-175.
3. Kiranmayi, M. and Ayyaswamy, K., "Underwater Wireless Sensor Networks: Applications, Challenges and Design Issues of the Network Layer - A Review", International Jounral on Emerging Trends in Engineering Research (IJETER), Vol. 3, No. 1, Pg 05-11, Special issue of ICEEMC 2015, January 27th, 2015.
4. Holler, R., et al, "The Ears of Air ASW: A History of U.S. Navy Sonobuoys", Navmar Applied Sciences Corporation, 2008.
5. Nelson, J, Rowe, E., Clifford Carter, G., "Detection Capabilities of Randomly Deployed Underwater Sensors", Paper Presented at the ICASSP 2008 Conference, October 2008.
6. Gammon, M.A. "Extrapolating the Performance of Underwater Sensors: Diver Detection Performance", Underwater Acoustics Conference, 2-24 June 2011, Kos, Greece.
7. Waite, A. D., "Sonar for Practicing Engineers, (3rd. ed.)", John Wiley and Sons Ltd., 2002.
8. Strode, C., and Oddone, M., "The Multistatic Tactical Planning Aid (MSTPA) - User Guide", NURC Special Report NURC-SP-2011-002, August 2011.
9. Gammon, M and Strode, C., "Multistatic Sonar Operator Visualization Development Requirements", Journal of the Canadian Acoustical Association, Vol. 43, No. 3, 2015.

Biographies

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