Passive acoustic threat detection in estuarine environments

Brian Borowski*, Alexander Sutin, Heui-Seol Roh, Barry Bunin

Maritime Security Laboratory
Stevens Institute of Technology, 711 Hudson St., Hoboken, NJ 07030

ABSTRACT

The Maritime Security Laboratory (MSL) at Stevens Institute of Technology supports research in a range of areas relevant to harbor security, including passive acoustic detection of underwater threats. The difficulties in using passive detection in an urban estuarine environment include intensive and highly irregular ambient noise and the complexity of sound propagation in shallow water. MSL conducted a set of tests in the Hudson River near Manhattan in order to measure the main parameters defining the detection distance of a threat: source level of a scuba diver, transmission loss of acoustic signals, and ambient noise. The source level of the diver was measured by comparing the diver's sound with a reference signal from a calibrated emitter placed on his path. Transmission loss was measured by comparing noise levels of passing ships at various points along their routes, where their distance from the hydrophone was calculated with the help of cameras and custom software. The ambient noise in the Hudson River was recorded under varying environmental conditions and amounts of water traffic. The passive sonar equation was then applied to estimate the range of detection. Estimations were done for a subset of the recorded noise levels, and we demonstrated how variations in the noise level, attenuation, and the diver's source level influence the effective range of detection. Finally, we provided analytic estimates of how an array improves upon the detection distance calculated by a single hydrophone.

Keywords: Underwater, passive, sonar, scuba, diver, detection, port, security

1. INTRODUCTION

Since the bombing of the USS Cole in October 2000 and the attacks of 9/11, border and transportation security have become a priority for the Navy and Department of Homeland Security, especially for the U.S. Coast Guard division, which is "responsible for the safety and security of America's inland waterways, ports, and harbors[1]." The U.S. maritime border includes 361 ports, 95,000 miles of shoreline, and a 3.4 million square mile exclusive economic zone. As if the sheer size of the territory didn't make the task intimidating enough, reports emanated from the Philippines in 2005 noting that two terrorist organizations linked to Al Qaeda were preparing for naval attacks by training militants in scuba diving[2]. Consequently, the U.S. government has increased funding to secure critical infrastructure. In January 2007, the Department of Homeland Security granted $445 million, $46 million more than in 2006, to five programs comprising the Infrastructure Protection Program (IPP). The largest of these programs was the "Port Security Grant Program", which was allocated $201.2 million of the total funds[3].

One of the most challenging aspects of port security is to provide protection against surface and underwater threats. In particular, it is felt that a significant terrorist threat might be posed to domestic harbors in the form of an explosive device delivered underwater by a scuba diver. In general, surface threats can be detected by radar and infrared/optic surveillance systems, leaving the detection of underwater targets to the application of acoustic systems.

There are numerous commercial diver detection sonar systems in production. Among the most prevalent is the multibeam diver detection sonar (DDS series) made by KONGSBERG MESOTECH LTD. Its active sonar is one of the major components of the Integrated Anti-Swimmer System (IAS) used by the U.S. Coast Guard. The DDS series configurations provide 3,300 feet of shoreline coverage but sell for approximately $300,000[4]. The land-based sonar of the IAS deployed in San Pedro, California, has a source level of 206 dB re 1 μPa at 1 meter at 90 kHz[5]. Sonardyne produces the Sentinel IDS (Intruder Detection System), which provides 360° coverage for a radius of 900 meters. The active sonar operates at 70 kHz with a source level of 206 dB re 1 μPa at 1 meter[6]. QinetiQ's Cerberus swimmer protection system provides from 30 – 360° coverage for a radius of up to 800 meters[7].

bborowsk@stevens.edu

Optics and Photonics in Global Homeland Security IV, edited by Craig S. Halvorson, Daniel Lehrfeld, Theodore T. Saito
Proc. of SPIE Vol. 6945, 694513, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.779177

In addition to high cost, there are several major disadvantages to active sonar systems. First, there is a high rate of false alarms. Objects with an acoustic target strength similar to that of a diver, including fish, can inaccurately be detected by active sonar systems. Moreover, the problem is exacerbated in shallow water by multiple reflections from both the floor and surface. Secondly, it is possible for an enemy to detect if an active sonar system is in use before dispatching a diver. Finally, loud active sonar systems are dangerous to marine life. Middle-frequency sonar, which is often used in submarine detection, can cause tissue damage in sea animals at amplitudes near 180 dB[8]. The U.S. Navy accepted blame for the beaching of 16 whales and a spotted dolphin on Bahamian shores over 36 hours starting on March 15, 2000[8]. A naval exercise close to the site of the strandings used sonar in the 3 – 7 kHz band that generated a sound pressure level of 230 dB re 1 μPa at 1 meter. Diver detection sonar works in a much higher frequency band but still falls within the hearing range of marine mammals. The hearing sensitivity of marine mammals varies among species, but as a group ranges from 0.01 to 200 kHz[5]. The hearing sensitivity of fish, including sharks and rays, ranges from 0.5 to 200 kHz[5]. Studies have shown that stunted growth and reproduction in marine organisms is related to increases in noise, and disrupting species at any level of the food chain can adversely affect the whole ecosystem[9]. Today, the usage of powerful sonar is prohibited in many domestic harbors in order to prevent any further disturbance to marine life. For instance, while the Integrated Anti-Swimmer System is deployed and marine mammals approach or enter the 160 dB isopleth (200 meter safety zone), the operational commander, who is always present during times of deployment, will take "prudent measures" to avoid impacting the wildlife which, situation permitting, may include shutting down the system[5].

The limitations of active sonar systems have stimulated work in the development of passive diver detection methods. The first published experiments on this matter were conducted by the Naval Research Laboratory (NRL), where it was shown that a diver radiates a periodic, wideband signal that corresponds to his or her rate of breathing[10]. Acoustic signals, including those produced by a diver, can be detected by a fiber-optic hydrophone array that was developed in the United Kingdom for acoustic surveillance of the littoral[11]. Stevens Institute of Technology conducted research on various physical phenomena in the complex conditions of an actual urban estuarine environment, introducing new methods of securing ports[12-15].

This paper presents the result of recent research in this area. It provides explanations of the main acoustic parameters involved in diver detection and shows how variations in environmental conditions affect the diver detection distance. The structure of the paper is as follows:

1. It starts with a review of the parameters of the passive sonar equation necessary for estimating the range of detection.
2. Next, the procedures used to obtain the values of the parameters are described, and the results of the measurements are presented.
3. Then it addresses how, when using a single omnidirectional hydrophone, varying conditions affect the range of detection. The impact of different regulators, the difference between a moving and stationary diver, and the presence and absence of water traffic are analyzed.
4. Finally, it provides estimations of how an array improves upon the detection distance obtained with a single hydrophone.

2. ACOUSTIC PARAMETERS

In this paper we apply the passive acoustic method to the problem of threat detection, where the acoustic signal radiated by a threat is recorded by a hydrophone or acoustic array. Underwater threats include divers, diver propulsion vehicles, swimmer delivery vehicles, mini-submarines, and AUVs. The presented approach can be used for estimating the detection distance of free swimmers as well as small crafts; however, we will focus on detecting divers throughout the paper. While the application of passive sonar for submarine detection started during World War I, the main acoustic parameters of the sonar equation still apply today. The simplified form of the passive sonar equation[16],

$$SL - TL = NL, \tag{1}$$

links three acoustic parameters.

The source level, *SL*, is the acoustic spectral density produced by an acoustic source recalculated to a distance of 1 meter. Transmission loss, *TL*, is a decrease in the sound level radiated by a target over a distance. Noise level, *NL*, is the level of ambient noise. In our tests in the Hudson River, this noise was produced mainly by water traffic, though it can be influenced by water surface conditions and impacted by activity on land, such as the use of a pile driver in a nearby construction site. The way these three parameters interact dictates the range at which a diver can be detected. In other words, because of spreading and absorption, the amplitude of the sound from the diver's gear decreases with distance. At some distance the sound produced by the diver will no longer exceed the noise level, thus marking the effective range of detection without the use of advanced signal processing techniques. The use of a hydrophone array improves upon the range of detection of a single hydrophone because it is more sensitive, discriminates between sounds arriving from different directions, and affords a better S/N ratio by favoring a signal arriving in the direction the array is pointing over isotropic and quasi-isotropic noise[16]. With the directivity index, *DI*, taken into account, the passive sonar equation becomes

$$SL - TL + DI = NL \, . \tag{2}$$

2.1 Diver acoustic signature and source level

The Maritime Security Laboratory (MSL) conducted a series of experiments to measure the acoustic signals radiated by a diver in the Hudson River and in the Stevens towing tank. Here we present the results of one of the Hudson River experiments. The test area and Stevens vessels are the same as those used in previous experiments[12-14]. The depth of the test area was approximately 3 meters. An ITC-6050C hydrophone[17] was used to receive the acoustic signals. It was placed on a stand 0.6 meters off the floor of the Hudson. A calibrated emitter, the Reson TC4034[18], was positioned along the path in which the diver was about to swim. It was placed 1.5 meters from the surface of the water at a point 30 meters from the hydrophone recording the signal. This signal was used in the calculations to estimate the diver source level, which are described in detail later in this section.

A GPS device was attached to a float which was tethered to the diver, tracking his movement during the test. Figure 1 shows the recorded path of the diver. The diver swam south, that is, from the top to the bottom of the area in the picture. Red triangles indicate the positions where GPS coordinates were recorded. The white dotted line shows the smoothed diver path. The white circle toward the left marks the place where the receiving hydrophone was anchored. Figure 2 shows the spectrogram of the recorded signal of the scuba diver. Red indicates the presence of strong signal, while blue signifies weaker intensity. The periodic bursts correspond to the diver's inhalations. The entire file spans 1 minute, 42 seconds, in which the diver swam a total of 23 meters.

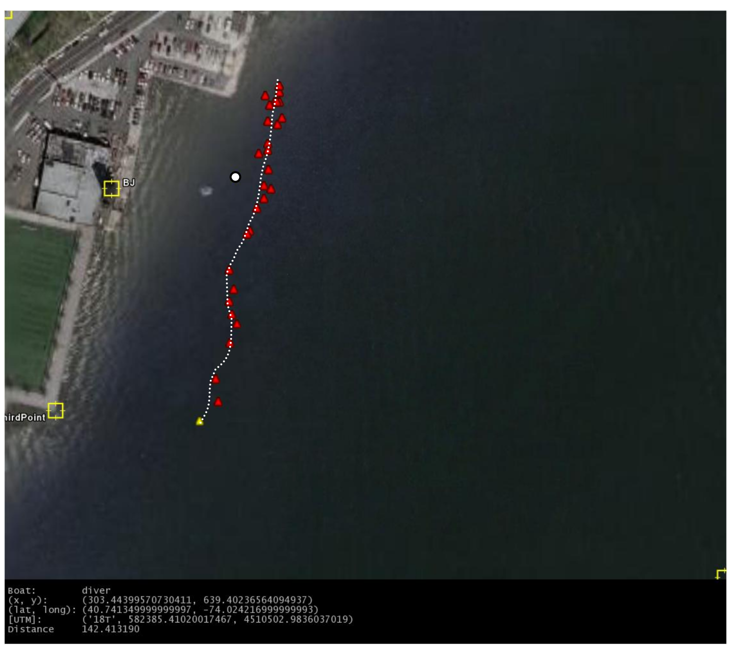


Figure 1. Map of the Hudson River test site showing the path of the scuba diver as recorded by GPS.

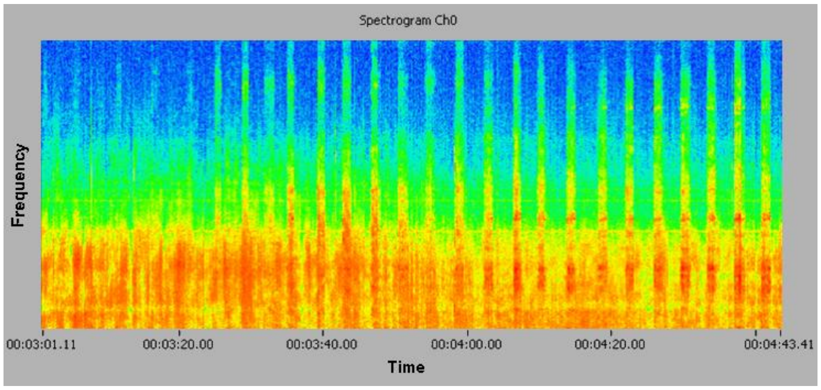


Figure 2. Spectrogram of diver signal.

A shorter test was also conducted to measure the source level of a stationary diver. In this test, the diver remained still at a point 30 meters from the hydrophone. The recorded signal of this diver was weaker than the signal from the moving diver measured at the same distance. Since propelling oneself through water requires more energy than remaining still, the diver took deeper breaths while swimming. These deeper breaths constitute an increase in the *SL* of the moving versus the stationary diver, as seen later in Figure 5, where we estimate the variation in the detection distance between the two.

The estimation of the source level, SL_{DIV}, was attained by comparing the diver signal with the signal radiated by the calibrated emitter. A reference emitter with a known transmitting sensitivity was used to obtain the values of some of the terms in the sonar equations. It radiates sound with a known source level, SL_{CAL}. M_{CAL} is the measured power spectral density level in dB re $1\text{V}/\sqrt{Hz}$ of the recorded electric signal of the emitter's output that was received by the hydrophone. The power spectral density is related to the acoustic spectral density through the hydrophone sensitivity, *T,* which is usually expressed in dB re 1 μPa/V. The difference between the radiated and recorded signals is the transmission loss, *TL*, which occurs between the source and the place where the receiving hydrophone is situated. We can now model this scenario by the equation

$$SL_{CAL} - TL = T + M_{CAL} \,. \tag{3}$$

Similarly, for the diver we have

$$SL_{DIV} - TL = T + M_{DIV} \,, \tag{4}$$

where we know the value of M_{DIV}, the measured power spectral density level in dB re $1\text{V}/\sqrt{Hz}$ of the recorded electric signal of the sound produced by the diver that was received by the hydrophone. It is now straightforward to solve the system of equations. Finally, we obtain the value for the source level of the diver,

$$SL_{DIV} = SL_{CAL} - M_{CAL} + M_{DIV} \,. \tag{5}$$

The comparison of the spectra of the radiated and recorded signals reveals the source level of the diver in narrow frequency bands.

The source level varies greatly with different scuba gear. More information about acoustic emissions from scuba gear can be found in another paper published in this volume[15].

2.2 Noise level

Ship noise constitutes most of the noise level in a harbor with heavy traffic, such as the Hudson River. It masks the acoustic signals produced by the target, thus reducing the detection distance. The MSL team recorded and measured acoustic noise produced by water traffic while recording a video of the passing vessels in the river. Estimations of each ship's location and distance from the hydrophone were obtained from the software component of MSL's Surface Traffic Tracking System[14].

Traffic passes through the part of the river that is approximately 15 meters deep; recordings were produced in an area that is about 10 meters deep. Hence, there is a small gradient along the path of the acoustic wave propagation. The wind speed at the time of the measurements was 11.3 knots, which produced waves with amplitudes of about 0.5 meters.

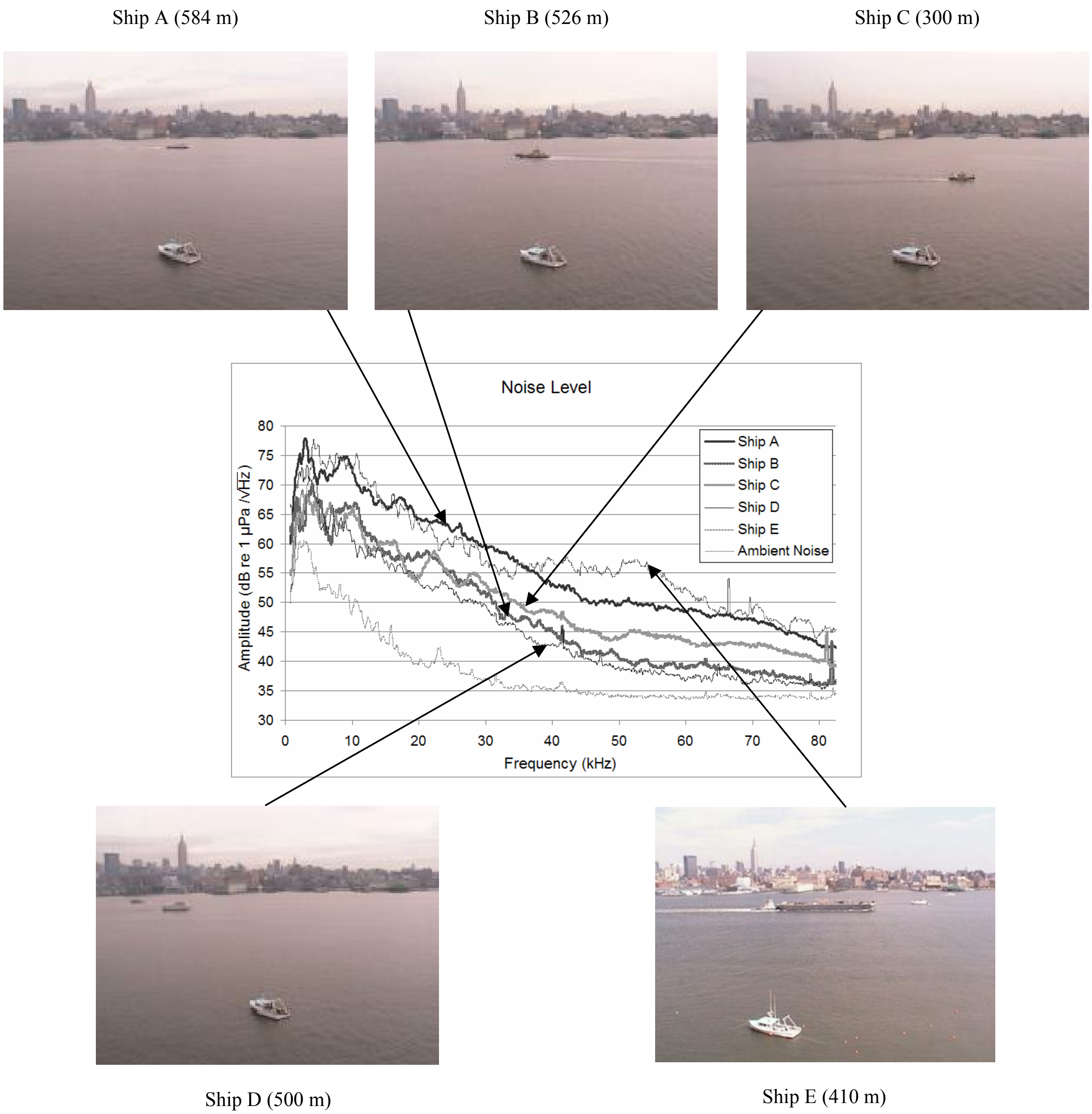


Figure 3. Noise level in the Hudson River produced by different passing ships.

The noise levels of passing ships were recorded by a Reson TC4014 hydrophone[19] placed on a stand 0.6 meters off the river's floor. The signal from the hydrophone was amplified, filtered in the 5 – 90 kHz frequency band, transformed into a digital signal, and stored in a special purpose computer on board the Stevens Research Vessel *Savitsky*. During post-processing, the spectrum of each recorded signal was recalculated in dB re 1 µPa/$\sqrt{Hz}$, accounting for the hydrophone sensitivity, preamplifier gain, and transfer function of the filters. Figure 3 presents the acoustic spectra of five ships at their respective distances from the hydrophone and the spectrum of the river itself when no traffic was present.

2.3 Transmission loss

An important parameter in the sonar equation is the attenuation of sound. Conventional methods to measure attenuation involve using a transmitter and a receiver. These tests require two research vessels and cannot be conducted safely near navigation channels where the vessels could interfere with routine water traffic. MSL took measurements of sound attenuation using the noise produced by passing ships. As in Section 2.1, each ship's location and distance from the hydrophone were obtained from tracking software[14]. The transmission loss in shallow water can be described by the equation,

$$TL = K + 10\log_{10}(r) + \alpha r\,, \tag{6}$$

where r is the distance between a sound source and the hydrophone, K is the parameter characterizing the transition between spherical spreading near a source and cylindrical spreading at greater distances, and α is the attenuation coefficient.

The average value of the attenuation coefficient α measured in one MSL test[14] was 0.058 dB/m, with a standard deviation of 0.013 dB/m. This value is relatively high, indicating a strong correlation between the observed attenuation and positive reflection of acoustic rays that hit the rough water surface. We will use this and other attenuation coefficient values in the next section to estimate the variation in diver detection distances.

3. ESTIMATING THE DETECTION DISTANCE

The previous section described how the main acoustic parameters can be measured and used for estimating the detection distance. The values of these parameters exhibit huge variations, resulting in a level of accuracy that is far from desirable. Since estimations based directly on these measurements will not be accurate, we approach the problem from a different perspective. Instead of calculating the absolute detection distance, we consider the relative variation of the distance due to changes in the acoustic parameters. In a fluctuating environment, these relative variations are much more realistic than precise distances.

Let us assume that the passive detection system based on a single hydrophone can detect a diver at some distance r_0 in, more or less, good conditions. We suppose that transmission loss is the only parameter in the passive sonar equation that is dependent on r_0. Noise is present but is not modeled to depend on distance. Therefore, we can write the passive sonar equation for this case as follows:

$$SL - TL_{r0} - NL + DI = 0\,. \tag{7}$$

By substituting (6) into (7), we obtain the following sonar equation:

$$SL - (K + 10\log_{10}(r) + \alpha r) - NL + DI = 0\,. \tag{8}$$

We now define gain to be an increase in the range of detection r based on an increase in the source level, increase in the S/N ratio with the inclusion of the directivity index, decrease in the ambient noise level, or any combination of the three parameters. Therefore, let us express gain G as follows:

$$G = \Delta SL + DI - \Delta NL\,. \tag{9}$$

To determine how changes to these parameters affect the detection distance r, we subtract the equation for the reference distance r_0 from the equation for the unknown distance r. This results in the following sonar equation, which defines the variation in distance:

$$[SL_r - (K + 10\log_{10}(r) + \alpha r) - NL_r + DI_r] - [SL_{r0} - (K + 10\log_{10}(r_0) + \alpha r_0) - NL_{r0} + DI_{r0}] = 0\,, \tag{10}$$

which by (9), implies

$$10\log_{10}(r/r_0)+\alpha(r-r_0)=G\,. \qquad (11)$$

We will now use (11) to estimate how various parameters affect the range of detection. In each of the following figures, we assume that we have a positive detection at 200 meters, a number well within the range of commercial systems[4-7], with a moving diver in low levels of ambient noise.

3.1 Effect of variation in source level on detection distance

Tests have shown that sounds produced by different regulators vary greatly[15]. Here we consider how a significant difference in *SL* affects the detection distance. In Figure 4, the source level of two regulators varies by as much as 25 dB, with *Regulator 2* being louder than *Regulator 1*. On the right is a graph that plots the percent of increase/decrease of the reference distance versus the gain in decibels. The reference point, marked with a circle, signifies the baseline detection of a diver using *Regulator 1*. If the diver were using *Regulator 2* instead, the *SL* parameter would increase by 25 dB, the difference in amplitude between the two signals. Keeping all other parameters constant, changing the value of this single term corresponds to a detection distance 177% greater than that obtained when the diver uses *Regulator 1*.

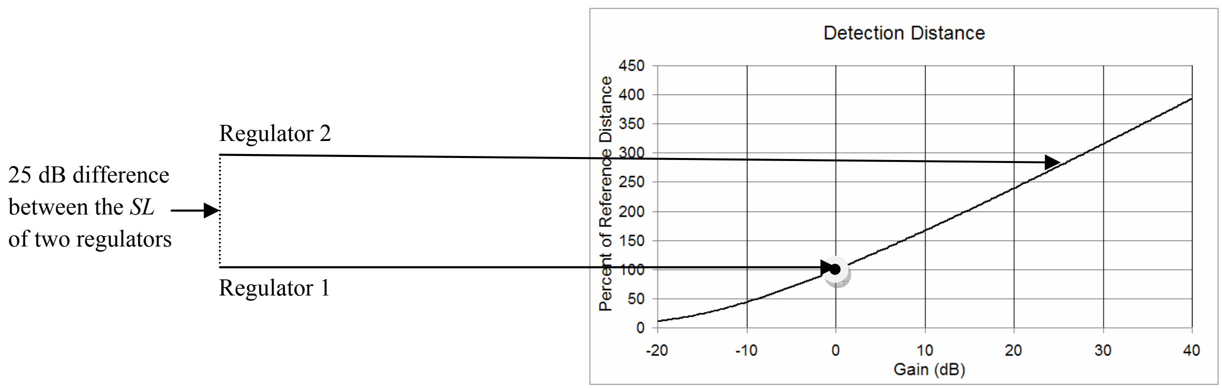


Figure 4. Percent of increase in detection distance when using a noisy regulator.

Figure 5 illustrates the difference in the range of detection between a moving and a stationary diver. The change in source level between moving and stationary is not as drastic as the difference between the two regulators described above, varying up to 15 dB[15]. Using the distance obtained with the moving diver as the reference, this difference in *SL* results in a 76% decrease in the detection distance.

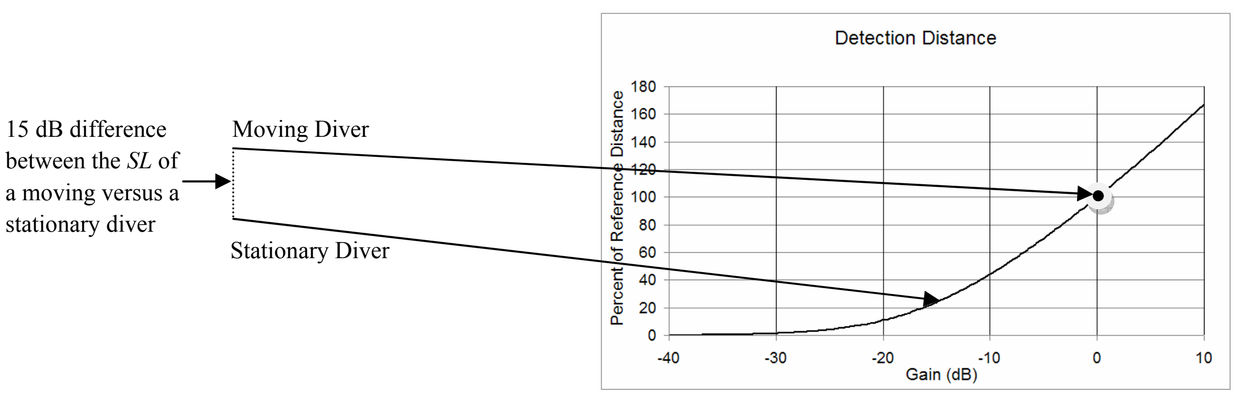


Figure 5. Percent of decrease in detection distance when diver is stationary.

3.2 Effect of noise produced by water traffic on detection distance

Figure 6 shows how noise impacts the detection distance. Using ambient noise as the reference level, we observe that in the presence of high levels of noise produced by water traffic, such as the tug and barge depicted in image E of Figure 3, the range of detection is significantly reduced. As seen below, the barge passing at a distance of about 410 meters increases the noise level by approximately 20 dB, thus decreasing the range to just slightly more than 10% of that without water traffic. It is clear that noise produced by water traffic can significantly reduce a passive system's ability to detect targets, and MSL is working on ways to mitigate this problem.

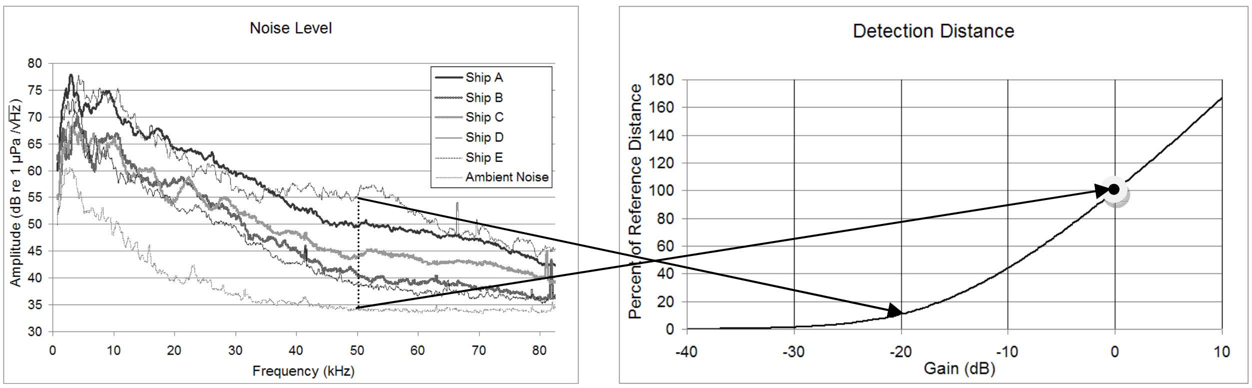
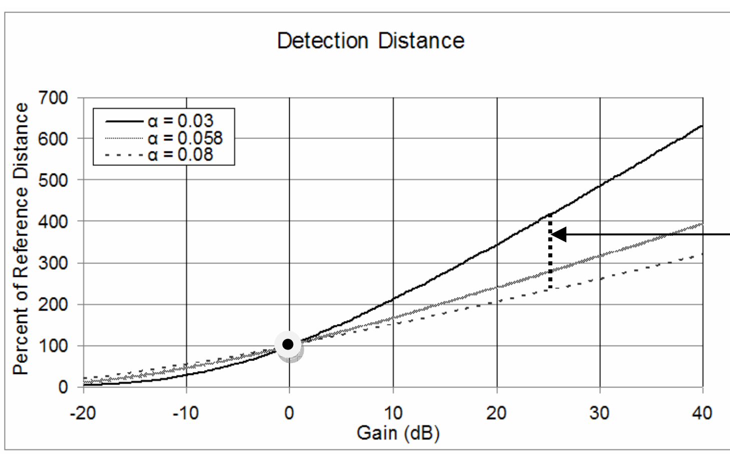


Figure 6. Percent of decrease in detection distance in the presence of water traffic.

3.3 Attenuation fluctuation and its influence on detection distance

Figure 7 shows how fluctuations in the degree of attenuation affect the detection distance. Recall that in figure 4 the difference in the source level of the two regulators was 25 dB. Using the attenuation coefficient measured by MSL in the Hudson River, α = 0.058 dB/m, resulted in one detection distance being 177% greater than the other. However, as α can potentially vary between 0.08 and 0.03, the percent of improvement over the reference distance can vary respectively from 133% to 314%.



The distance can vary by up to 181% when the gain is 25 dB.

Figure 7. Effect of varying attenuation coefficient on detection distance.

3.4 Increase in detection distance when using an array

It is well known that the application of a directional array can suppress ambient noise and increase detection distances. Since all active sonar systems take advantage of these properties, any respectable passive system should also utilize an array. The measurements taken with a single hydrophone provide the basis for the estimation of detection distances obtained with an array.

Figure 8 represents the hypothetical gain obtained in the detection distance when using a line array of hydrophones. Using the well-established formula for the directivity index[16],

$$DI = 10\log\left(\frac{n}{1+\frac{2}{n}\sum_{\rho=1}^{n-1}\frac{(n-\rho)\sin(2\rho\pi d/\lambda)}{2\rho\pi d/\lambda}}\right) \tag{12}$$

where n is the number of elements in the array, d is the space in meters between the centers of elements, and λ is the speed of sound in water divided by the frequency in Hz for which the directivity index is being computed, we calculate an average gain of approximately 8 dB for 6 hydrophones and 13.3 dB for 20 hydrophones across the 20 – 82.5 kHz band. These gains respectively correspond to a 53% and 91% increase in the range of detection.

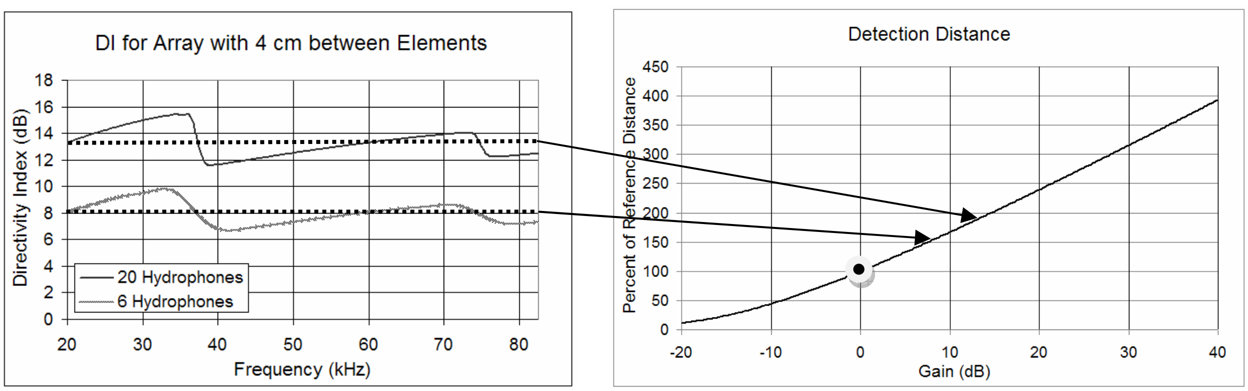


Figure 8. Percent of increase in detection distance when using a hydrophone line array.

Figure 9 again shows the hypothetical gain associated with directivity index. However, this time the gain is characteristic of a piston transducer, which is typically used in active diver detection sonar systems, with a 1 meter diameter. In this case the directivity index is defined by the formula

$$DI = 10\log\left(\frac{\pi D}{\lambda}\right)^2, \tag{13}$$

where D is the diameter of the piston in meters, and λ is the speed of sound in water divided by the frequency in Hz for which the directivity index is being computed[16]. At about 48 kHz, the gain is 40 dB, which is also the average gain across the entire 20 – 82.5 kHz band. This gain corresponds to a distance 293% greater than the reference distance.

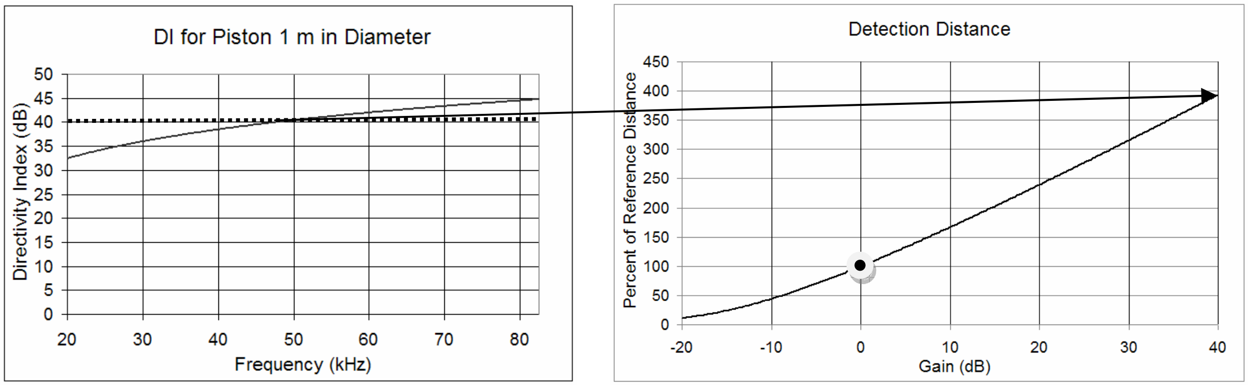


Figure 9. Percent of increase in detection distance when using a piston 1 meter in diameter.

The increase in the detection distance with the use of an array was considered for omnidirectional noise. In the case where noise is produced by water traffic, knowledge of the ship's position as determined by an optic or radar surveillance system can be applied to orient the array for maximal noise suppression, increasing the detection distance even further.

4. CONCLUSIONS AND FUTURE WORK

The paper discusses the principles of measurements and provides information on the parameters required for the development of passive acoustic diver detection methods and estimations of their efficacy. The acoustic complexities associated with an urban estuary such as the Hudson River can produce significant variations in the observed values of transmission loss and noise level. The presented estimations are based on a limited number of experiments and provide an approximate, rather than precise, view of the fluctuations in the range of detection. In addition, the estimations show how detection can be improved by using a directional hydrophone array. However, many more measurements must be taken in order to provide a statistical analysis of the variation of these acoustical parameters under different environmental conditions. In addition, we endeavor to use a hydrophone array to compare the hypothetical gain of the directivity index component to that which is actually obtained in a field test.

Improvements in the signal processing algorithms are expected to drastically increase the range of detection. Several signal processing methods have been previously proposed by researchers at Stevens Institute of Technology[20, 21], and these as well as other techniques are being investigated further. We plan to compare the range estimates obtained by each of these algorithms in the near future.

5. ACKNOWLEDGMENTS

This work was supported by ONR project #N00014-05-1-0632: Navy Force Protection Technology Assessment Project.

REFERENCES

[1] The White House: *The Department of Homeland Security – Border and Transportation Security*. http://www.whitehouse.gov/deptofhomeland/sect3.html.

[2] Clarke, P. E., "Swimmer Detection", *Special Operations Technology Online Edition*, 2005. http://www.special-operations-technology.com/article.cfm?DocID=1133.

[3] Department of Homeland Security: *DHS Announces $445 Million to Secure Critical Infrastructure*. http://www.dhs.gov/xnews/releases/pr_1168366069190.shtm.

[4] *KONGSBERG Introduces New Diver Detection Sonars*. http://www.km.kongsberg.com/KS/WEB/NOKBG0238.nsf/AllWeb/93C0AC8C90960823C12572F10053BBF8?OpenDocument.

[5] United States Coast Guard, "Environment Assessment of the Installation and Operation of an Integrated Anti-Swimmer System, San Pedro, California", 2005. http://www.uscg.mil/systems/gse/Final%20IAS-San%20Pedro_5-17-06.pdf.

[6] *Sonardyne Sentinel IDS Brochure*. http://www.sonardyne.com/Support/Brochures/sentinel_brochure.pdf.

[7] *Cerberus Swimmer Detection Sonar – System Description* http://www.qinetiq.com/home/products/cerberus.SupportingPar.21560.File.pdf.

[8] Weiss, R., "Whales' Deaths Linked to Navy's Sonar Tests". *Washington Post*, December 31, 2001. Reprinted online at http://www.commondreams.org/headlines01/1231-02.htm.

[9] McCarthy, E., *International Regulation of Underwater Sound: Establishing Rules and Standards to Address Ocean Noise Pollution*, Kluwer Academic Publishers, Boston, 14-15, 18 (2004).

[10] Stanic, S., Kirkendall, C. K., Tveten, A. B., and Barock, T., "Passive Swimmer Detection," *NRL Review,* 2004. http://www.nrl.navy.mil/content.php?P=04REVIEW97.

[11] Hill, D. and Nash, P., "Fibre-optic hydrophone array for acoustic surveillance in the littoral," Proc. SPIE 5780, 1-10 (2005).

[12] Bunin, B., Sutin, A., and Bruno, M.., "Maritime Security Laboratory for Maritime Security Research," Proc. SPIE 6540, 65400S1-65400S8 (2007).

[13] Stolkin, R., Sutin A., Radhakrishnan, S., Bruno, M., Fullerton B., Ekimov, A., and Raftery, M., "Feature based passive acoustic detection of underwater threats," Proc. SPIE 6204, 40-49 (2006).

[14] Bunin, B., Sutin, A., Kamberov, G., and Roh, H. S., "Combination of acoustic measurements with video surveillance for estuarine threat detection," Proc. SPIE 6945, (2008).

[15] Donskoy, D. M., Sedunov, N., Sedunov, A., and Tsionskiy, M., "Variability of SCUBA diver acoustic emission," Proc. SPIE 6945, (2008).

[16] Urick, R. J., *Principles of Underwater Sound*, Peninsula Publishing, 31-44 (1996).

[17] *International Transducer Corporation – Model ITC-6050C Hydrophone Specifications*. http://www.itc-transducers.com/_storefiles/129.pdf.

[18] *RESON – Model TC4034 Hydrophone Specifications*. http://www.reson.com/%5Cgraphics%5Cdesign%5CSpec%20sheets%5CHydrophones%20-%204000%20series/TC4034%20-%20US.pdf.

[19] *RESON – Model TC4014 Hydrophone Specifications*. http://www.reson.com/%5Cgraphics%5Cdesign%5CSpec%20sheets%5CHydrophones%20-%204000%20series/TC4014%20-%20US.pdf.

[20] Chen, X. and Tureli, U., "Passive Acoustic Detection of Divers Using Single Hydrophone," Proc. 40th Asilomar Conference on Signals, Systems, and Computers, 554-558 (2006).

[21] Chung, K. W., Li, H., and Sutin, A., "A frequency-domain multi-band matched-filter approach to passive diver detection," Proc. 41st Asilomar Conference on Signals, Systems, and Computers, in press (2007).