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Acoustic Littoral Engagement Response to Threats – ALERT
A System to Provide Advanced Warning of an Anti-Ship Missile Attack

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ABSTRACT

Naval warfare is shifting from an almost exclusive deep water, open ocean engagement to a littoral environment where high-value surface ships are forced to operate in close proximity to land, exposing those ships to a new, significant threat - the high speed, sea skimming missile launched from coastal defenses, mobile land launchers, and patrol craft and maritime aircraft operating close to shore. This is a formidable threat. The anti-ship missile is a low radar signature target, making it difficult to detect in any environment. As a sea-skimmer, the missile trajectory is low on the radar's scan area, and in a high clutter region, adding to the detection difficulty. However, in this case, the clutter is magnified by the land background. With missile speeds in excess of ¾ Mach, there is precious little time between detection and missile impact in which to engage this threat. The Georgia Tech Research Institute (GTRI) at the Georgia Institute of Technology has investigated a concept to provide early detection of these sea-skimming missiles and add additional response time for the surface ship. The ***A****coustic* ***L****ittoral* ***E****ngagement* ***R****esponse to* ***T****hreats (ALERT) system employs an underwater vertical transducer array to detect airborne acoustic noise from the missile that penetrates the air-water boundary. The system capitalizes on the 6 dB signal enhancement due to the pressure-doubling effect at the air-water boundary to improve detectability of the signal, plus the factor of five increase in sound speed in water versus air to reduce detection time. This paper describes the operational ALERT concept, system description, and analytical assessment of system performance. Signal processing of the information provided by the ALERT sensor can also provide a bearing to the missile and an indication of missile speed, enhancing the deployment of defensive systems. To evaluate the feasibility of the ALERT concept, GTRI conducted an internal R&D acoustic measurement program in a lake close to Georgia Tech to measure the detectability of airborne acoustic signals with an underwater transducer array. Results of these tests are presented. The paper also presents potential problems and issues associated with the operational implementation of the concept.*

1.0 INTRODUCTION

For more than a decade, naval forces throughout the world have experienced significant increased importance of missions in the littoral environment, which has resulted in major cultural, tactical. operational, and systems changes for both naval powers such as the US, who were primarily oriented towards blue-water operations and for those navies whose primary missions were homeland security and defense. The littoral is a harsh, high-threat environment. Shallow water depths limit the speed and maneuverability of large ships; reduce the effectiveness of acoustic, RF, optical, and infrared sensors for detection and navigation; and restrict the accessibility of key operating regions. And, the threat of mines in these operating areas is ever-present.

Add to this already harsh environment the increased threat from high speed, sea skimming, anti-ship missiles, launched from coastal defenses, mobile land launchers, high-speed surface patrol craft, maritime aircraft (both fixed-wing and rotary-wing), shoulder-fired manpads, or disguised civilian and

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commercial ships and pleasure craft operating close to shore. This is a formidable threat to the high-value surface combatants that must operate in the littoral to accomplish their missions. The anti-ship missile is a low radar signature target, making it difficult to detect in any environment. As a sea-skimmer, the missile trajectory is low on the radar's scan area, and in a high clutter region, adding to the detection difficulty. However, in this case, the clutter is magnified by the land background. With speeds of Mach 0.9 to Mach 2+, there is precious little time between detection of an attacking missile and missile impact in which to engage this threat.

This paper presents a concept to provide early detection of a missile attack, alerting the surface ship of the impending attack. The concept can add from 15 to 90 seconds to the surface ship's available response time. This system has been given the acronym ALERT, for Acoustic Littoral Engagement Response to Threats. Signal processing of the information provided by the ALERT sensor can also provide a bearing to the missile and an indication of missile speed, enhancing the deployment of defensive systems. The paper presents the system design concept, a discussion of design and operational considerations, and the results of a concept feasibility test conducted by Georgia Tech.

2.0 DESCRIPTION OF THE THREAT

Operations in close proximity to shore place the surface ship within the operational envelope of high speed, anti-ship missiles fired from coastal defenses, including mobile launchers on land, at-sea patrol boats, or aircraft operating close to shore. Additionally, the surface ship will most likely be denied advanced warning of a potential attack until it detects and classifies the in-coming missile. In an open ocean environment, a significant alertment factor is the detection of ships or aircrafts capable of launching an attack. In the littoral environment close to shore, the existence and location of mobile land, sea and air launchers will generally not be known until after the strike begins. Even then, missiles will be hidden from primary detection systems due to increased clutter and reduced line-of-sight (LOS) visibility.

Prosecution of a littoral engagement will fall on advanced surface combatants such as the *Aegis* and *Arleigh Burke* cruisers. These are expensive assets, valued at many hundred-million dollars, that are placed at substantial risk from comparatively cheap anti-ship missiles. The 1987 attack on the *USS Stark (FFG-31)* by two Iraqi Exocet missiles resulted in a repair bill of $42 million, the loss of over 30 lives, and the loss of the operational platform for many months. [2]

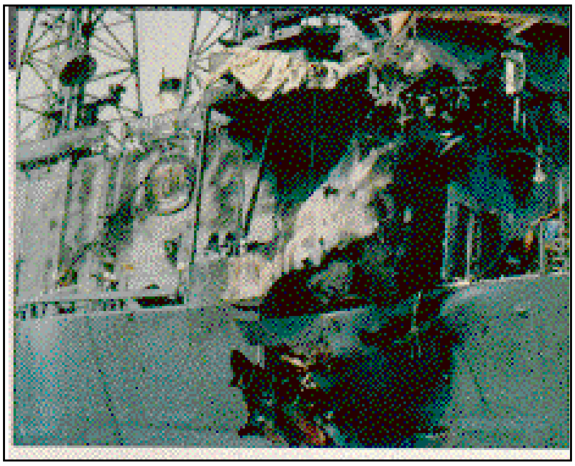

Figure 1: Damage to the *USS Stark* from Exocet Missile Attack [2]

Anti-ship missiles have been in numerous countries' arsenals for over 30 years. Open literature from the mid-1990s listed 40 anti-ship missile types. In addition, there are air-to-surface (AS), anti-radiation (ARM), and surface-to-surface (SS) missiles designed for an offensive land capability that could be employed against surface ships in littoral environments. Data also show that significant proliferation of these missiles has occurred to many countries in large quantities. [1,4]

Factors making the anti-ship missile a difficult target to defend against include:

- Low radar cross section (RCS). Based on physical dimensions and material composition, the standard anti-ship missile's nose-on RCS is nominally 0 to -10 dB/square meter (dBsm). More advanced missiles present even smaller target sizes.

- High background clutter, made worse by clutter from the land mass background. For conventional radars operated in close proximity to land with an increasing land altitude, the minimum detectable RCS can be as high as -15 to 0 dBsm
- High volume search and multifunction search and track requirements for current shipboard radars. The search interval time depends on the radar design (conventional-phased array, stationary-rotating, single/multi-beam), PRF, beamwidth, number of simultaneous beams used, etc. The search and classify time can range, nominally, from 1 to 15 seconds, depending on mission requirements. An examination of current phased array radars, configured for a mid-range search over the entire quadrant, can nominally require about eight seconds.
- Weapon engagement time. A few seconds is required to direct the weapon towards the target and fire/activate the weapon. During peacetime or low-level conflict engagements, additional time may be required due to the Rules of Engagement.
- Multiple missile attacks fired nearly simultaneously from varying aspect angles. For a multiple missile attack, the available response time must be distributed over each of the attacking missiles.

Combining each of these factors highlights the significance of the problem. For a low RCS cruise missile traveling at Mach 0.9 in a high land/sea clutter environment, and with a 10 km detection range, the response time is 25-30 seconds to localize the target and respond to the attack or attacks. If the missile is traveling at Mach 2 rather than Mach 0.9, the available response time drops to a dangerously low 7-12 seconds to defend against all incoming threats.

3.0 CONCEPT OF OPERATIONS

The basic premise of the ALERT concept is that acoustic noise generated by the missile is detected by an off-board, expendable sensor to provide advanced warning of an imminent attack. The ALERT sensor utilizes both an air and underwater noise detector for detection and to discriminate against false alarms.

Several types of noise are generated by a missile during its flight. Studies have shown that the noise from the engine has a relatively high level and is fairly flat in the 100 - 3000 Hz frequency band. Due to the low missile altitudes, these noise levels experience little atmospheric attenuation and spreading loss along the short path from the missile to the air-water boundary. As the noise penetrates this boundary, there is a pressure doubling that occurs which further increases the acoustic level. Once in the water, the noise will propagate at approximately 4.4 times the propagation speed in air, equivalent to Mach 4.4 in air, due to the higher speed of sound in water (1500 m/s in water; 343 m/s in air).

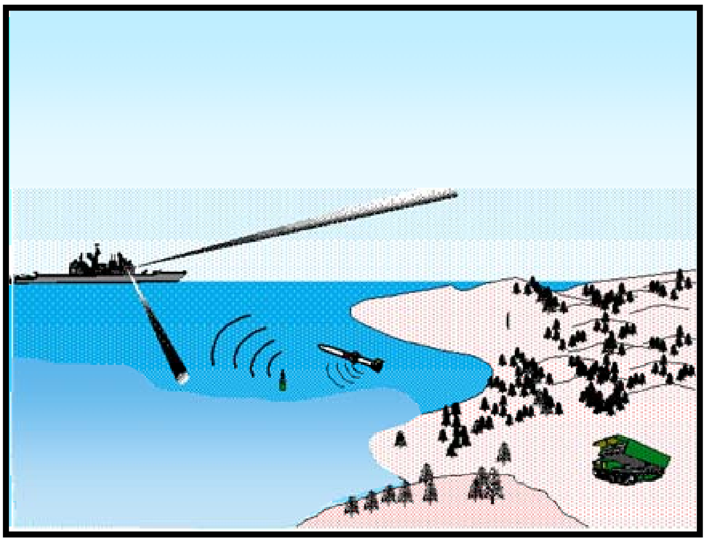

Figure 3: Concept of Operations

An underwater acoustic sensor can detect the missile-generated noise, often before the missile ever reaches the sensor, and trigger a radio signal to the surface ship to alert the ship to the impending attack. This concept is illustrated in the cartoon in Figure 3.

A line of ALERT sensors would be deployed parallel to the coast. The range for the line of sensors and the separation between sensors would be determined from the tactical situation. For example, if the closest surface ship to land was on a course 35 km from shore, then the line of sensors would be approximately 9 km from shore. The noise from an approaching missile would activate one or more of the sensors. The acoustic signal received by a sensor would be converted to an RF signal and transmitted to the surface ship where the signal, along with other information from the sensor, would be processed to:

- Verify that the noise source was a missile threat and not a false alarm,
- Determine the direction of the incoming missile, based either on sensor identification data or processed signature data,
- Estimate missile speed.

Additional sensor features can provide other useful information, such as range and bearing to the target. However, these sensors need to be expendable; therefore, there is a strong incentive to make them as inexpensive as possible. The complexity of the sensor and features desired must be balanced with the overall cost of the sensors.

3.1 System Description

The ALERT sensor is composed of a surface float, an underwater acoustic transducer or transducer line array, an in-air microphone, an electronics package, and an RF transmitter and antenna (Figure 4). The microphone, electronics package, RF transmitter, and antenna are all housed in the surface float, which could be deployed just below the surface for added security. An underwater acoustic transducer or transducer line array is suspended below the surface float. The entire sensor would be packaged in a canister the size of a standard sonobuoy and could be deployed in the same manner as a sonobuoy.

Noise from the missile is detected by both the underwater transducer and the in-air microphone. Once a detection occurs from either of these sensors that exceeds a threshold setting, output from both sensors are sent back to the surface ship over the RF link. The transmitted signal would include a sensor identification code to identify the sensor responding and GPS data to indicate the sensor's position.

A receiver and signature data processor on the surface ship receive the RF data, separate the underwater and in-air sensor signals, and conduct the processing to determine if the signal is a valid ALERT warning or a false alarm. Depending on the availability of existing surface ship RF receiving systems, the RF signals may be received and decoded by an existing, on-board system, or a dedicated receiver and decoder may be provided. A basic PC-computer with a data acquisition board is adequate for the required signal processing.

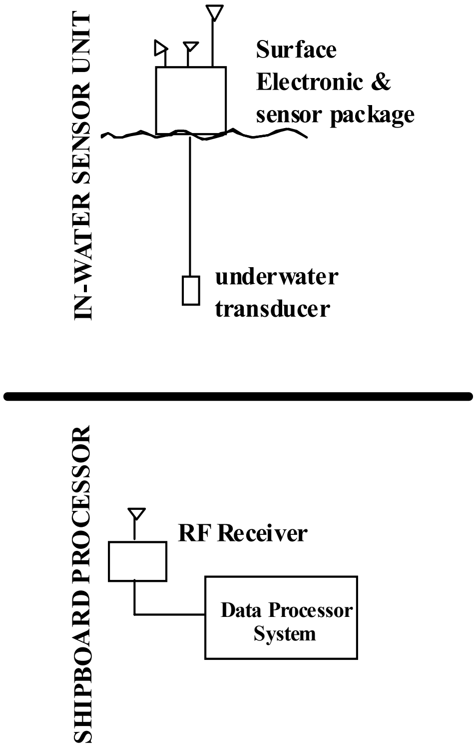

Figure 4: The ALERT System

3.2 Evaluation of the Proposed Concept

Several key issues needed to be examined, including:

- Was there adequate signal level from the missile engine to achieve a reasonable detection range (function of angle, altitude, source strength, and signal bandwidth)
- Could the system discriminate against false alarms
- Could the system provide a bearing to the missile or a direction for the attack
- Did the system provide significant advanced warning of an attack, and
- Were there other features of the system that could be beneficial?

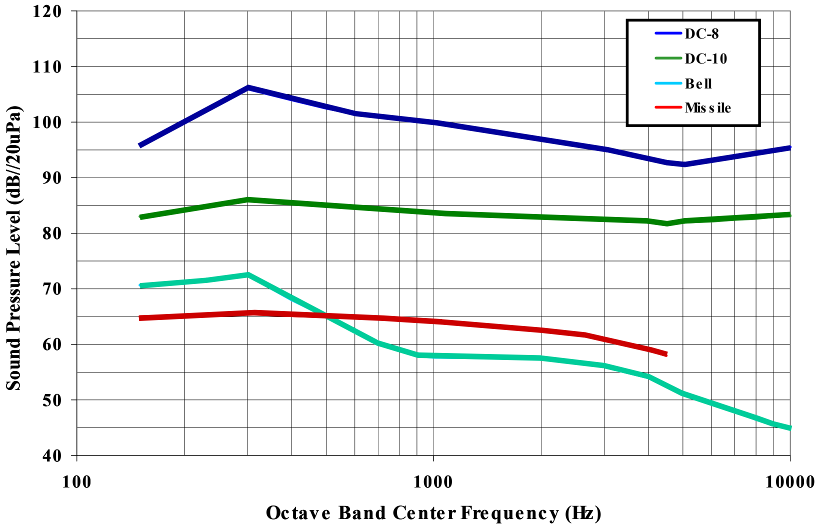

Figure 5: In-Air Acoustic Noise from Various Aircraft[7]

Representative acoustic noise spectra for several aircraft are shown in Figure 5. These spectra are referenced to 20 µPa, the audible hearing standard reference. Converting from this standard to an underwater reference (1 µPa @ 1 m) and correcting for atmospheric spreading (data in the curve are at 1000 m) gave a source level of 150dB//1 µPa @ 1m for the octave band centered at 1 kHz. For a missile traveling at 6.1m (20 ft) above mean sea level (MSL), the sound pressure level (SPL) at the air-water boundary would be 134 dB (16 dB spreading loss) and the pressure doubling that occurs as the sound enters the water raises the signal level to 140 dB.[5] Selecting a signal-to-noise ratio (SNR) of 10 dB as a reasonable threshold level that would not require sophisticated signal processing electronics in the in-water sensor unit, and choosing a background level equal to the ambient noise at a sea state 3 condition (63 dB//1 µPa at 1 m at 1 kHz[6]), the one way propagation loss that can be accommodated, based on the standard sonar equation, is 67 dB. Assuming a 20LogR spherical spreading loss and minimal absorption, this results in a detection range of approximately 2000 m. (At these ranges, the spreading loss may actually be cylindrical, in which case the loss experienced would be less and the detection range greater.) This implies that the spacing between sensors could be from 2000-4000 m, depending on the amount of overlap desired in adjacent sensor detection areas. Therefore, there appears to be adequate noise level generated by the missile engine to excite the underwater detection sensor at ranges out to 2000 m. in sea states of 3 or less.

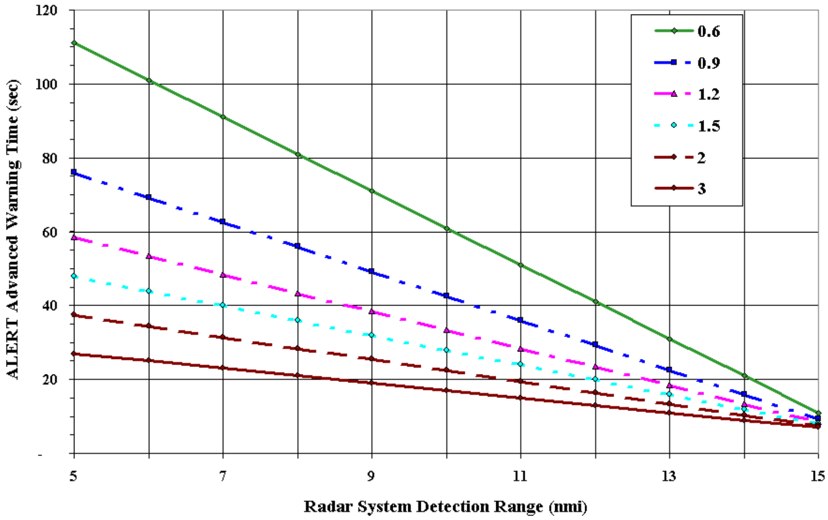

Figure 6: Advanced Warning Provided by ALERT

With a scenario where the sensors are deployed 9 km from shore and the surface ship track is approximately 35 km from shore, a Mach 0.9 missile will be detected approximately 90 seconds prior to impacting the surface ship, an improvement of 65 seconds over the standard radar detection case. For a Mach 2 missile, the alert time is approximately 40 seconds as compared to 5-7 seconds for radar detection. Figure 6 shows the ALERT system advanced warning times as a function of the shipboard radar detection range for various missile speeds. Figure 6 illustrates that the ALERT concept makes a significant improvement in the available shipboard self-defense response times.

By maintaining a geographical situation plot on-board the surface ship, showing the location of the various sensors, the shore line, and the tracks of the surface ship(s) in the area, the sensor identification code included in the transmitted sensor signal provides an approximate direction to the suspected target. Using the GPS data, the actual location of the sensor can be pinpointed. If the GPS data are not included in the ALERT sensor system, an accurate bearing to the sensor can still be obtained from the shipboard radar by direction finding (DF) on the RF signal from the sensor or from the situational display. Assuming a 2000 m detection range for the sensor and a range of 35 km between the ship and the sensor, the location of the target missile will lie within a sector ±3.3° from the bearing to the sensor, which reduces the area to be searched for the missile and further improves response time.

The remaining issue to be evaluated was the ability of the system to discriminate against false alarms. This function is the primary reason for sending the signals received by both the underwater transducer and the in-air microphone back to the surface ship over the RF link. False alarms will be caused by acoustic noise occurring in the signature band. For the underwater transducer, this can come from boating or shipping noise in the vicinity of the sensor, active sonar, fish noise, or noise from in-air sources (such as missiles or aircraft) coupled into the water. False alarms on the microphones will result from in-air noises from aircraft or ships/boats in the area as well as wind and wave noise. The shipboard signal processor (SSP) analyzes the signals from the transducer and microphone to determine if the source is a real missile threat or a false target. Signature analyses of the data from both sensors include:

- Doppler analysis that will provide an indication of the contact's speed. Doppler indicating a contact's speed in excess of Mach 0.5 will eliminate many false contacts and will signal either a missile or a high-speed aircraft. Either of these contacts qualify as worth identification by the ALERT system.
- Signature analysis will test for characteristic helicopter signatures that exhibit the fundamental and harmonic lines of the main and tail rotors.
- The sensor can also periodically monitor and report general ambient background noise that can be stored in the signal processor for reference.
- It may be feasible to evaluate the relative intensities of the received signals which would allow estimating an approximate time when the closest-point-of-approach (CPA) occurs. If the signal is being received by more than one ALERT underwater sensor, the time difference between CPAs to each sensor can provide an estimate of possible missile locations relative to each sensor, further refining the localization process.
- Correlation of the underwater transducer signal with the microphone signal provides a measure of the time delay between the two signals. Knowing the speed of sound in air and in water in the vicinity of the sensor allows the estimation of possible missile locations relative to the sensor.
- Where signature analysis shows a signal was received on the underwater transducer, but not on the in-air microphone, this indicates that the source of the noise source was generated underwater. Analysis can identify sonar signals and submarine noises as well as false alarm noises, which is an added feature of the ALERT system.
- There may also be cases where signals are detected on two or more ALERT sensors nearly simultaneously. This case would be caused by an aircraft or missile at a relatively high altitude such that the difference in path length to multiple sensors is minimal. This condition would be identified by the system and a message provided to the operator to correlate the ALERT system findings with radar since a target at the higher altitude should be readily visible on radar. This case cannot be immediately dismissed as a false alarm since there are some anti-ship missiles that approach their targets at a high altitude and then drop to sea skimming altitude in or near the terminal phase.
- Signature analysis will also examine the microphone signature for the characteristic N-wave of a supersonic contact. Reliance on the N-wave detection is not recommended since wind conditions in the vicinity can significantly affect detection. However, identifying the presence of an N-wave is an excellent classifier.

4.0 ACOUSTIC FEASIBILITY TESTING

Comments on the ALERT concept received from several US Navy organizations focused on two primary concerns. One was that the idea had been attempted previously and found to be quite expensive. In the previous case, the application was in deep-water, open ocean scenarios where the threat of attack was from 360°, significantly increasing the number of sensors required. The sensors were deployed around the entire Battle Group operating area, further increasing the number of sensors required. Additionally, the cost of fabrication of these earlier sensors was significantly higher than today's cost. In the littoral environment, coverage can be reduced to 180° or less since only the area between the surface ships and the coastal areas need be covered (radar adequately handles the open ocean side) and once the area has been populated, replacements are required only for those sensors that exceed their maximum life or ones that fail or are compromised. Additionally, advances in transducer and electronics technology will now enable the ALERT system to be fabricated at a low cost, in quantity, in a package the size of a sonobuoy, making deployment much more effective.

Another question raised by the Navy reviews was whether the signal from the missile that penetrates the air-water boundary could be detected at sufficient range to make the ALERT concept feasible. To answer this question, Georgia Tech Research Institute (GTRI) funded an internal research and development project to conduct representative acoustic measurements to assess this feasibility.

GTRI personnel fabricated an underwater receiver array composed of twelve F-42 spherical transducers, having relatively flat receive sensitivity over the frequency band from 500 Hz to 5 kHz. The transducers were spaced approximately 1.5 meters apart, vertically. Each receiver was connected to an input channel of a high-speed analog-to-digital (A/D) converter, which converted the acoustic signal to digital format. These digital data were input to an IBM PC computer. LABVIEW software was used to sample the input signal lines and save the data in computer memory. Measured data were recorded on a Bernoulli disk for subsequent analysis.

4.1 Test Setup

The measurements were made at a local lake (Lake Lanier) close to GTRI. Nominal water depth was 30-35m. Two acoustic sources were mounted on the GTRI acoustic barge at Lake Lanier. A J-11 transducer, suspended below the barge at depths ranging from 1.5 to 7.5 meters, was used to generate underwater acoustic signals. A Sound Tech H15X speaker, rated at 150 watts RMS, was mounted in the air, at approximately 2 meters above the water using an A-frame to position the speaker away from the barge and over water. The acoustic transmit signal was generated by a signal generator, fed to a power amplifier, and then to the J-11 transducer or speaker. For these tests, pure tone, continuous signals were used. Measurements were made at three frequencies - 500 Hz, 600 Hz, and 1000 Hz. The vertical, underwater receive transducer array and data collection system were installed on a second boat. The receive array was suspended below this boat. An illustration of the Lake Lanier test setup and equipment configuration is shown in Figure 7.

Because Lake Lanier is a local resort lake, it was necessary to conduct the measurements during the night, from 2200 to 0700, in order to reduce noise and interference from local boaters. Prior to beginning a data run, the two boats were brought together and a test run made with a minimum range separation between the acoustic source and the receiver array in order to check all system components and conduct a calibration. Once the equipment was operational, the receive boat would open range to approximately 3-5 km. The J-11 would be activated and the range would be closed until the J-11 signal was detected on the receive array. At that point, recording of the collected data would begin. The range between the source and receiver boats was then closed by a couple hundred meters and another set of measurements made. This process was repeated until the range between the two boats had closed to approximately 50 m. The first set of runs were made with the J-11 generating underwater signals to serve as a propagation reference. These measurements were then followed by runs where both the J-11 transducer and the speaker transmitted the acoustic signals.

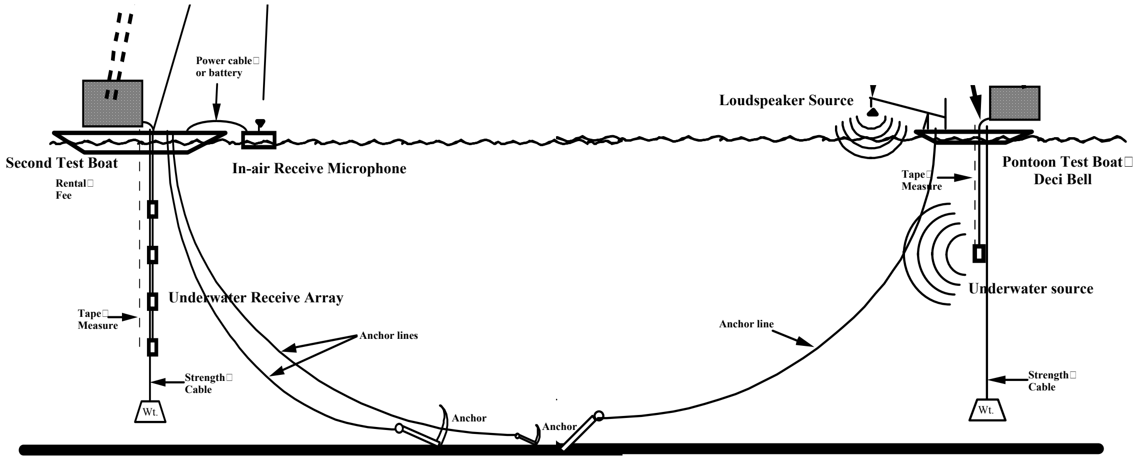

Figure 7: Lake Lanier ALERT Feasibility Test Setup

At each data collection range, the acoustic source, either the J-11 or the speaker, would be activated in continuous transmit mode at the selected transmit frequency. The transmitter would be operated for approximately 3-4 seconds to allow the transmit level to stabilize, and then approximately $^3/_4$ seconds of data would be collected. 16,384 data samples were recorded for each receive channel, using a 20 kHz sampling rate.

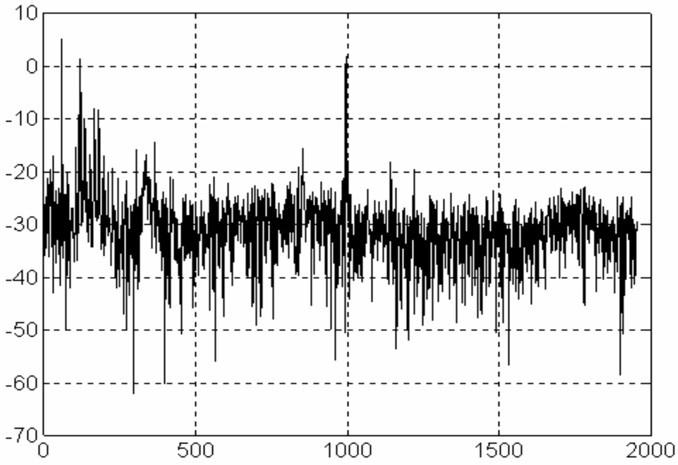

Figure 8. 16,384 Point FFT of Run 27 Channel 4 Time Series Data

4.2 Test Results

Figure 8 shows the 0-2 kHz portion of a representative 16,384 point FFT of the received signal data – 1 kHz, range 200m, receiver channel 4, depth 6m). Because of the concern about noise, the data were also filtered, using a digital Butterworth bandpass filter, to remove all but the desired frequency band containing the signal. The 1 kHz bandpass filter response is shown in Figure 9.

F igure 10 shows the expanded views of a 16,384-point FFT with and without the use of the filter. The 16,384 point FFT results in an FFT resolution of 1.22 Hz.

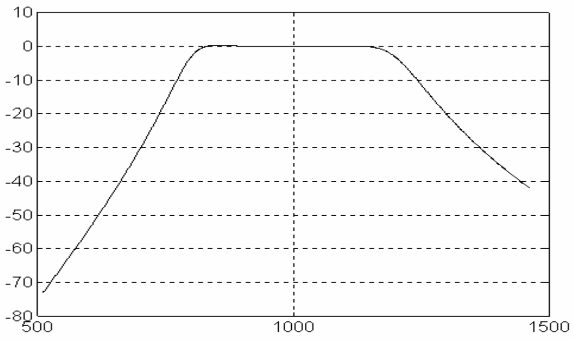

Figure 9. Frequency Response of the Butterworth Digital Bandpass Filter

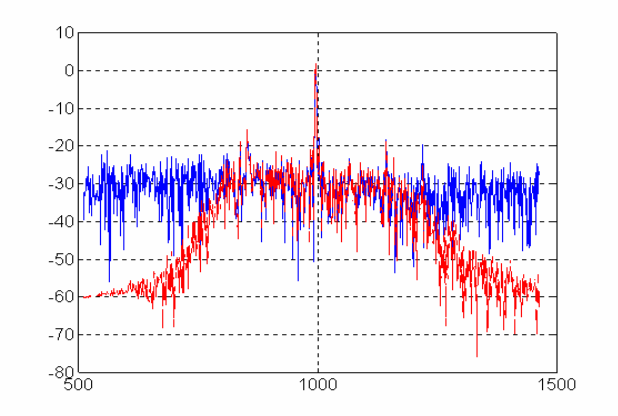

Figure 10: Filtered (red) and Unfiltered (blue) 16,384 Point FFT Data

The power spectral density (PSD) of the data was also examined and a representative trace is shown in Figure 11. The PSD was computed using a 1024 point FFT. Figure 12 shows an expanded view of the PSD for the frequency range of 0 - 2 kHz, and also shows the results from filtering the data with the Butterworth bandpass filter.

A 16,384 point FFT spectra and a 1024 point FFT PSD were computed for each channel at each range for which measurements were made. Composite plots of the FFT and PSD analyses are shown in Figures 13 and 14, respectively. The data are plotted as signal level versus range, where the noise floor was determined to be -35 dB for the 16,384 point FFT and -38 dB for the PSD data. Curves in Figures 13 and 14 connect data from the same receiver channel. Both figures exhibit a 10logR slope and show approximately 20 dB SNR at 400 yd. For a 10 dB SNR, this indicates that a reasonable detection range for these tests is approximately 2750 m.

As part of the test data collection procedure, reception of the J-11 underwater source signal was used to determine when the receiver boat was within range to detect the in-air source. However, post-run analysis of the ray path conditions, illustrated in Figure 15, showed that propagation of the J-11 signal (nominal depth = 6m) was severely restricted in range due to the sound velocity profile (SVP), which is shown in Figure 16. Ray path predictions for the in-air source (Figure 17) show that these propagation paths would have supported a much longer measurement range for that source. Unfortunately, this condition was not known at the time of the tests and as a result, data at these longer ranges were not collected.

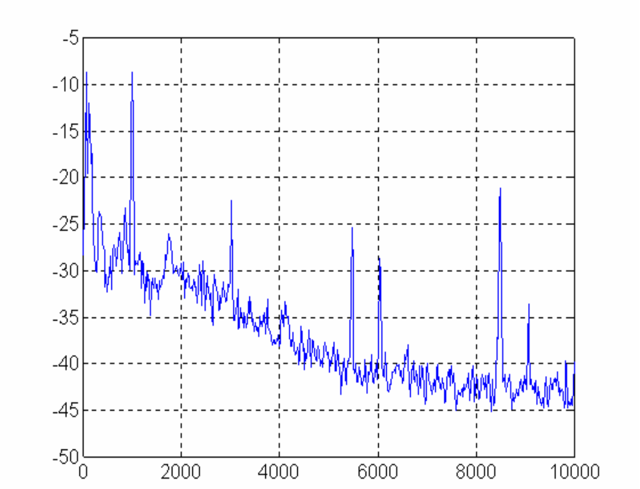

Figure 11. Power Spectral Density Plot of Run 27, Channel 4 Time Series Data

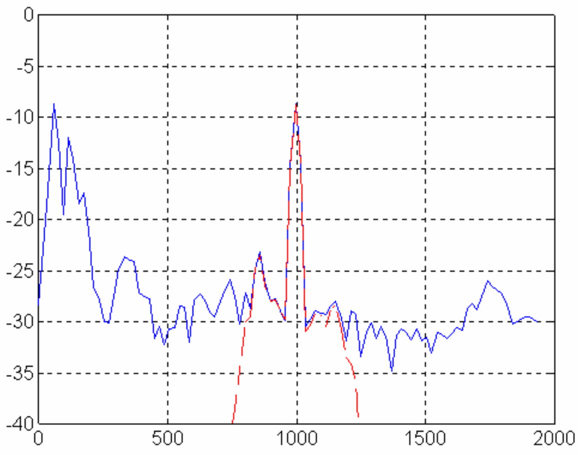

Figure 12. Power Spectral Density Expanded View Showing Both Filtered (red) and Unfiltered (blue) Profiles

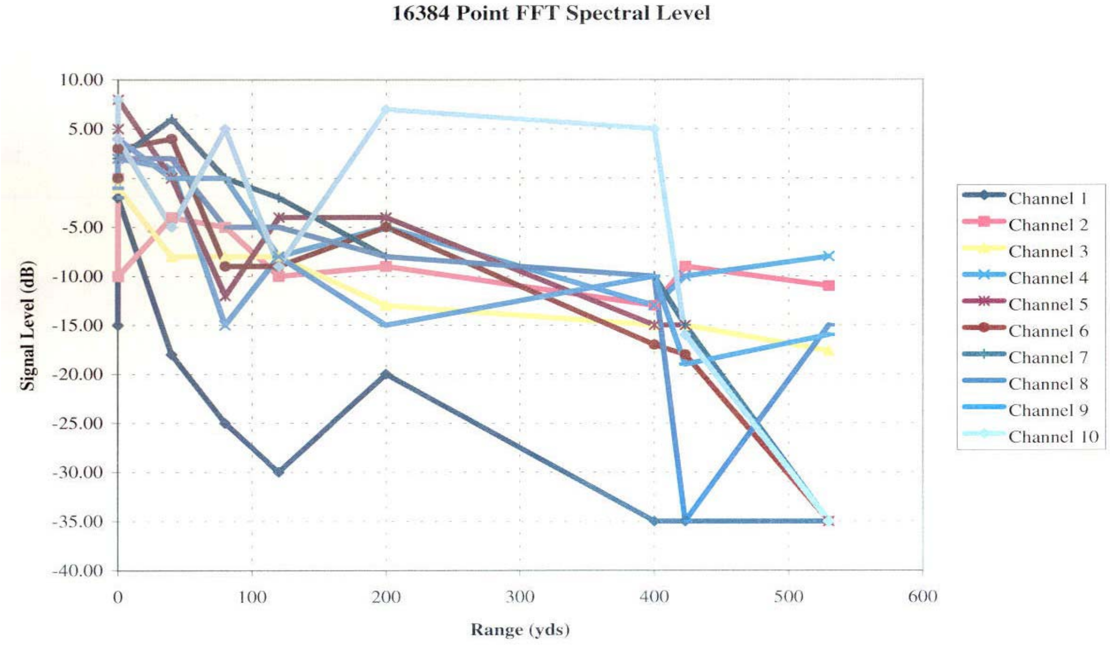

Figure 13. Signal Level versus Range for the 16,384 Point FFT Data

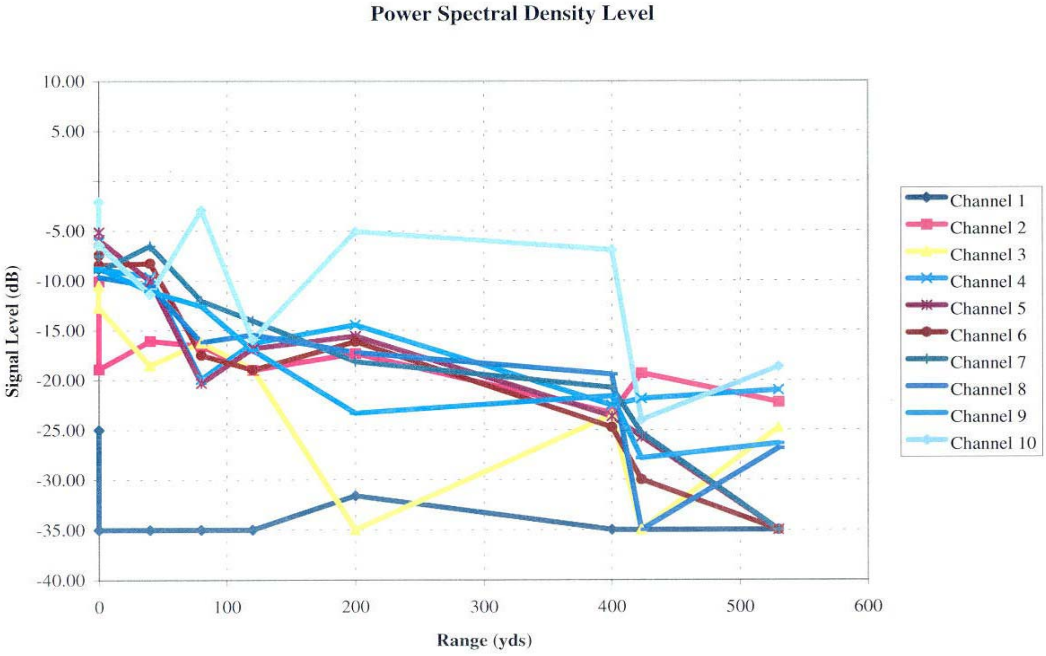

Figure 14. Signal Level versus Range for the Power Spectral Density Data

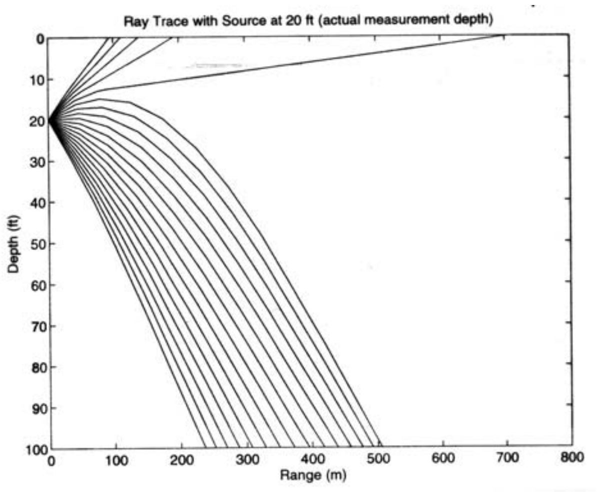

Figure 15. Propagation Conditions for the J-11 Underwater Source for a Depth of 20 ft.

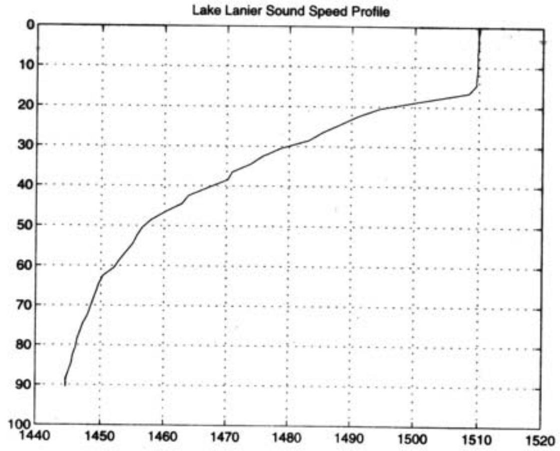

Figure 16. Sound Velocity Profile for the ALERT Lake Lanier Tests

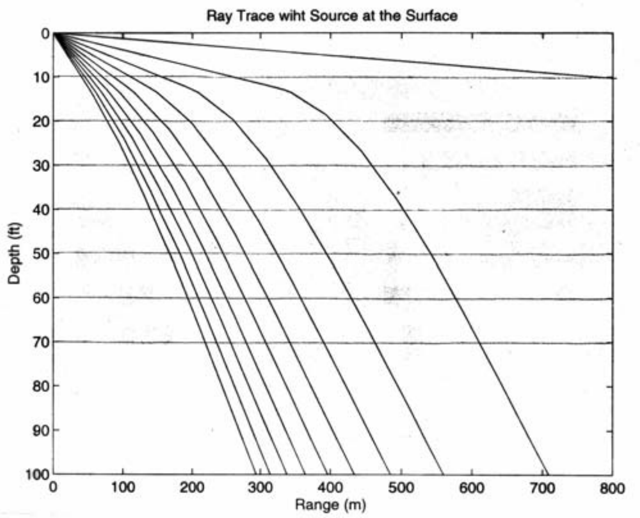

Figure 17. Propagation Conditions for the In-Air Source

5.0 SUMMARY AND CONCLUSIONS

The ALERT system provides a capability to overcome a near/mid-tern surface ship vulnerability to advanced anti-ship missile threats that arises from operations in the littoral environment. System requirements can be met with current state-of-the-art technology and, as miniaturization of components matures, many of the packaging and cost issues with be resolved.

The Acoustic Feasibility Measurements showed that signals from an in-air source could be detected with an underwater receiver at reasonable detection ranges for the ALERT concept. Analysis of the test data showed that the in-air signal could be detected at ranges of 2500m with an available 10 dB SNR for reliable signal detection and processing. When the source level of the in-air speaker was adjusted to be comparable to the missile radiated noise from Figure 5, a detection range for the ALERT sensor was computed to be approximately 2000m. Additional SNR and detection range could be obtained by processing the multiple channel receiver data as a line array rather than as individual receivers, which provides additional gain proportional to the number of elements used in the receiver line array. These acoustic measurements were conducted in sound propagation conditions typical of those to be experienced in the littoral regions.

The concept has addressed methods to discriminate between real targets, other targets of interest, and false alarms. Through signal processing, additional detection capabilities such as the detection of helicopters and submarines could be achieved. The remaining technical issues to be addressed include the lack of specific information about actual threat missile and other littoral contact signatures at various altitudes and speeds, overall affordability of the operational employment of the system, and operational security for the deployed sensors.

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