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Acoustic Event Signatures for Damage Control: Water Events and Shipboard Ambient Noise

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ACOUSTIC EVENT SIGNATURES FOR DAMAGE CONTROL: WATER EVENTS AND SHIPBOARD AMBIENT NOISE

I. INTRODUCTION

The objective of this report is to demonstrate the feasibility of detecting water-related, damage control (DC) events, specifically pipe ruptures and flooding, in a shipboard ambient noise environment and to document the data collected in support of that effort. This report is composed of seven sections. The first two are composed of introductory material.

The third section documents the acoustic measurements of water-related DC events made at the NAVSEA Damage Control Engineering Test Facility (DCETF) located at the Ft. McHenry Naval Reserve Center in Baltimore, MD. The measurements include both pipe rupture and flooding noises in different compartments of the facility. The fourth section characterizes the signals measured by their spectra and time histories, and provides some initial impressions on the relevant parameters that can be inferred from a given acoustic signature.

The fifth section documents the ambient noise measurements made aboard the USS RAMAGE (DDG-61) and the RV ENDEAVOR. The RAMAGE is an Arleigh Burke class destroyer, is 585 ft long and is powered by gas turbine engines. The ENDEAVOR is the research vessel of the University of Rhode Island, is 185 ft long and is powered by diesel engines.

The sixth section of the report compares the DC signals to the ambient noise background and demonstrates a basic ability to detect the DC signals in the ambient noise background. A fully developed detection algorithm that is immune to many types of false alarms is not the objective of the section, or the report, rather that it is possible to make reliable detections of the events.

The final section of the report summarizes the findings and makes recommendations.

II. BACKGROUND

This report documents some of the acoustic work done for the Advanced Volume Sensor (AVS) Project, Dr. Susan Rose-Pehrsson, NRL Code 6112. The AVS project is an element of the ONR FNC Advanced Damage Countermeasures (ADC) Program, managed at NRL by Dr. Fred Williams, Code 6180. The ADC program seeks to develop and demonstrate improved Damage Control (DC) capabilities to help ensure that reduced manning levels on future Naval vessels can still maintain an effective DC environment. The AVS project is an important element in that it seeks to develop a volume sensor with the capability to monitor an entire space without relying on long diffusion times and at the same time provides an enhanced false alarm rejection performance.

The Acoustics Task seeks to determine the best manner in which acoustic signals can be used as an integrated part of a volume sensor. The human ear and brain identifies individual events by comparing the time-frequency content of a signal with a stored database (memory) developed over time. The probability of a human falsely identifying a specific audio event decreases over time as the brain's database and comparative algorithms mature. In a similar fashion, a machine-based audio event detector will be successful if the time-frequency signature of the DC events such as pipe rupture and subsequent water flow can be uniquely distinguished from other broadband shipboard sounds.

Thus, to determine if an event represents a DC event or is just part of a normal shipboard ambient noise environment a database of sounds from a variety of DC scenarios must be acquired and analyzed to permit frequency and time-frequency signature characterizations. These characteristics must then be compared to common shipboard acoustic background sounds to determine if they can be distinguished in near-real time. To date, acoustic signals have been measured for fires, pipe ruptures and flooding, various events that cause false alarms in video systems, and a limited amount of shipboard ambient noise. The fire and false alarm measurements and analysis will be presented in a companion report.

III. WATER - NAVSEA DAMAGE CONTROL ENGINEERING TEST FACILITY MEASUREMENTS

A. The DCETF

The pipe rupture and flooding tests were conducted 14-15 May 2003 at the NAVSEA Damage Control Engineering Test Facility (DCETF) at the Ft. McHenry Naval Reserve Center in Baltimore, MD, shown in Fig. 1. Fifty-five events were run over two days. Each event typically lasted 2-3 minutes, except for the compartment flooding events, which took 5-6 minutes each.

As can be seen in Fig. 1 the building behind the DCETF was under construction. At the time of the tests workmen were chipping mortar from between the bricks preparatory to re-pointing the building. This was of some concern initially due to the noise generated by their work. However, the damage sounds proved to be much louder than the noise from their work inside the facility and have no effect on the results. While the ambient noise in the DCETF is of interest for this study, it should be noted for the record that it was a function of the level of activity of the workmen.

Figure 2 shows a view of the interior of a compartment and the "damages" and plumbing. A particular "damage" is selected by opening and closing the appropriate valves to cause water to flow through the damage. A large valve outside the compartment controls the water flow. The water supply, and pressure, is from the City of Baltimore's water system and is not necessarily the same pressure as might be found aboard a Naval ship. Two additional, related, observations are to be made about this setup. First, there is no actual sound of a pipe rupturing. Instead the pipe is already damaged and water simply flows out of it when present. Second, it was observed in most of the tests that one could hear the sound of water flowing in the pipes before it actually reached the rupture and began spraying into the compartment. This sound is probably not typical of a real rupture, as is the lack of an initial rupture sound, and has been ignored in our processing as far as is possible. A final observation is that there are no pipes near the deck. Thus, the objective of measuring damages at low, intermediate and high positions is to be interpreted as at mid-bulkhead, high-bulkhead and near-overhead heights. Further, only one event was run until the damage was submerged.

Fig. 1 – NAVSEA Damage Control Engineering Test Facility at the Ft. McHenry Naval Reserve Center, Baltimore MD. Tests were conducted in the various compartments inside the larger structure in the foreground. Recording took place inside the two sheds (one hidden) to the left rear.

Fig. 2 – DCETF interior view of compartment A1 showing some of the "damages" and plumbing. The hatch to A2 is at the top of the ladder.

During these tests the two microphones were installed in the test compartment inside the DCETF and cables were run to a recording station outside in a small shed. The microphones in Fig. 2 were located on the bulkhead behind the photographer. A two camera recording system was also installed and recorded to provide a visual record of the events and to test the response of fire alarm systems to the events. The results of the video recording and analysis are provided in a separate report [1]. Acoustic data were recorded on both a digital audio tape recorder and a computer. The video data were recorded on a VCR.

B. Test Equipment and Setup

Measurements at DCETF were made using the system shown in Fig. 3. Two microphones were used for redundancy. Both were placed near each other and the visual sensor systems in an upper corner of the compartments. The Brüel and Kjær 4141 is an extended frequency range microphone providing infrasonic and low ultrasonic signals to record signals for future analysis. The Shure MX-202 is more typical of low cost microphones, which would probably be used in an operational system. Each of these is driven by a conditioning amplifier that provides amplification and a DC bias voltage to the microphone. The signals were recorded on a Sony instrumentation DAT, 0-20,000 Hz (sampled at 48,000 Hz), and by the Micron lunchbox portable computer, 0-40,000 Hz (sampled at 100 kHz). Both units recorded the data as 16-bit integers. Results were monitored by the computer speakers and on the oscilloscope in real time. Besides the digital cassette tapes, captured data on the computer was transcribed to CDs for archival storage. Calibration of the system was achieved using a Brüel and Kjær Type 4231 calibrator. This unit provides a 1 kHz calibration tone at 94 dB // 20 μPa RMS which weas recorded on each of the microphones at various times throughout the exercise.

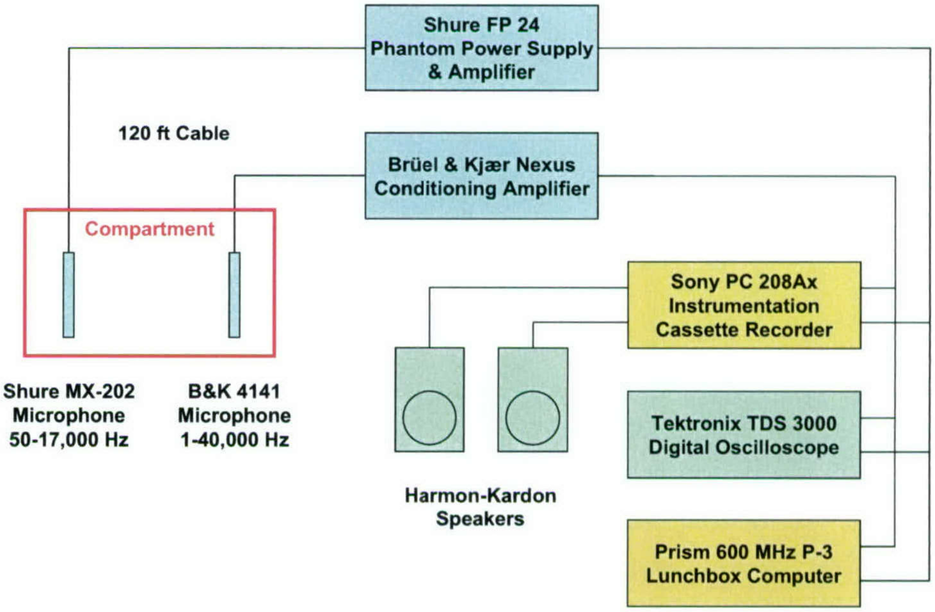

Fig. 3 – Measurement and recording system used to measure sounds due to water at the DCETF.

C. Test Design and Measurements Made

The tests were broken into five test groupings with the objective to capture the dependence of the flooding events on various parameters:

1. Flow rate, hole size, height of release, and water depth on deck
2. Hole shape, slit-to-circular
3. Special circumstances; hatch flooding, open valve, and leaky patch,
4. Compartment size, and
5. Compartment flooding level.

Test groups 1 to 3 are considered primary objectives of the test and test groups 4 and 5 are considered secondary. A sixth objective, to measure free field source levels at the rupture, was not done since it would have taken significant set up effort on the part of DCETF personnel, would have been contaminated by the noise of the workmen since it was outside, and was a secondary objective of the tests.

The tests called for the drain to be closed and each test to be run until the water level reached a certain point. For the first four test groups that point was reached when the water-on-water impact noise is no longer changing with increased water depth. This could be as little as an inch for sprays, but may be significantly more for streams, several inches to a foot. Generally, the tests were run for at least a few minutes. For a few of the lower flow rate tests, this extended to several minutes so that an adequate height of water was reached in the compartment to facilitate measuring the amount of water. Test group 5 was intended to test compartment-filling effects and the compartments were filled to 5 feet or more.

When the compartment had filled to a measurable height of water, the test was terminated and the drain was opened. The flow rate was calculated from the gallon markings on the bulkhead and the time of the run. The next test began after the compartment was completely drained. For the higher flow rates, these tests went fairly quickly.

The following test matrixes are provided to indicate the proposed sequence of tests. The stations were assigned during the experiment. In some of the later test groups a particular object was fulfilled by a previous test, when this happened it is indicated in the comments section and these tests were not repeated. The event number order in these matrixes is of actual execution. The complete log is provided in the Appendix along with times, heights, flow rates, and file numbers for the audio and video systems.

Test Group 1

1. Flow rate (x3)
2. Hole size (x3)
3. Height of release (x3)
4. Water depth on deck, none to a few inches (time)

The objective of this group of 27 tests, Table 1, is to characterize the gamut of dripping to spraying sounds.

Table 1 – Test Group 1 measurements for flow rate, hole size and height.

Test	Station	Hole Size	Height	Flow Rate	Comments
18	A1-PR3	Small slit	Low	High	
19				Medium	
20				Low	
21	A1-PR2	Small slit	Intermediate	High	
22				Medium	
23				Low	
24	A1-PR5	Small slit	High	High	
25				Medium	
26				Low	
27	A1-BH2	Large hole	Intermediate	High	
29				Low	
30	A1-PR1	Intermediate	High	High	
31				Medium	
32				Low	
33	B2-BH2	Large hole	Low	High	Run to 5 ft to satisfy test 52.
34				Medium	
35				Low	
36	B2-PR5	Large pipe break	High	High	
37				Medium	
38				Low	
39	B2-BH1	Intermediate – Many little holes	Low	High	
40				Medium	
41				Low	

Test Group 2

1. Hole shape, slit – irregular - circular (x3)
2. Flow rate (x3)

The objective of this group of nine tests, Table 2, was to characterize any differences due to the shape of the hole. That is, does a slit produce a different sound than a more circular hole? Casualty station B1-PR2 had multiple openings. A clamp with rubber sheeting was used to close off all of the openings except the one selected, a circular hole for Tests 1-3 and a small slit for Tests 7-9.

Table 2 – Test Group 2 measurements for hole shape.

Test	Station	Hole Shape	Flow Rate	Comments
1	B1-PR2	Small Circular	High	Circular hole only of this casualty.
2			Medium	
3			Low	
4	B1-BH1	Irregular	High	
5			Medium	
6			Low	
7	B1-PR2	Small Slit	High	Small slit only of this casualty.
8			Medium	
9			Low	

Test Group 3

1. Hatch flooding (3)
2. Open Valve (2)
3. Leaking Patch (3)

The objective of this group of eight tests, Table 3, was to characterize special circumstances at different flow rates.

Table 3 – Test Group 3 measurements for special cases.

Test	Station	Event Type	Flow Rate	Comments
10	B1 - Fire Main	Open Valve	High	
11			Low	
12	B1-PR1	Leaky Patch	High	
13			Medium	
14			Low	
15	B1 – Hatch from B2-BH2	Hatch Flooding	High	Run to 5.5 ft to satisfy test 51.
16			Medium	
17			Low	

Test Group 4

1. Compartment size (x3)
2. Scenarios (x2)

The objective of this test was to determine the effect of compartment acoustics on the sounds. In three different compartments, two tests that are as similar as possible between the compartments were run. However, only two compartment sizes existed, so the intermediate size did not exist. The objectives of this test were met by the various tests in groups 1-3, Table, 4, to the extent that that is possible. For instance comparing small slits in compartments A1 and B2, events 18-26 and 7-9, fulfills the stated objectives. However, even with similar sources, there may be significant differences caused by the source instead of the compartment, which will make separating the two causes difficult.

Table 4 – Test Group 4 measurements for compartment size.

Test	Station	Compartment	Flow Rate	Comments
45	B1 & B2	Small	High	Fulfilled by events 7–9.
46			Low	
49	A1	Large	High	Fulfilled by events 18–26.
50			Low	

Test Group 5

1. Flooding scenario (2)

The objective of this test is to determine how the compartment acoustics change as the compartment is more completely flooded. Two tests were run, Table 5, one from an overhead pipe and the other from a source near the deck, which was quickly submerged.

Table 5 – Test Group 5 measurements for flooding.

Test	Station	Height	Comments
51	B1	High	Fulfilled by test 15.
52	B2	Low	Fulfilled by test 33.

Test Group 6 and Additional Tests

A final Test Group 6 designed to measure the source level of the water flowing from a pipe rupture in a free field environment (outside) was canceled due to setup time, approaching rain, and the lateness during the day. This test group would have measured 3 hole shapes (slit, irregular and circular) at 2 flow rates (high and low). These would have constituted tests 53 to 58. Instead a final test inside, Table 6, was conducted.

Table 6 – Test Group 6 for a final measurement.

Test	Station	Hole Shape	Flow Rate	Comments
60	A2-BH1	Slit – Floor Level	High	Measured in A1 below. Hatch flooding.

IV. ANALYSIS OF WATER EVENT ACOUSTICS SIGNALS

The damage event data, and also the noise data described in Sections V and VI, were processed using Matlab and Fortran processing. Matlab was used for an initial analysis and some display work. Fortran programs were used for bulk processing of the data. Some results were displayed using Microsoft Excel.

The data was calibrated using the 1 kHz tone of the Brüel and Kjær 4231 sound level calibrator. This unit provides a 94 dB // 20 µPa (= 0 dB // 1 Pa = 120 dB // 1 µPa) signal which provides an end-to-end calibration of the system. Fortran and Matlab routines were used to calculate the factor necessary to adjust any given time series to a level directly corresponding to the level relative to 20 µPa, the standard reference level for airborne acoustics. The files were then processed to put them all in a common file format adjusted to this reference level. This facilitated a comparison between the different data sets as each of the measurements in this report (DCETF, RAMAGE and ENDEAVOR) had a different file format and recording level. The common file format included a header and a time series of 32-bit floating data, to prevent any loss of precision, at a 48 kHz sampling rate. For the DCETF tests, this involved digitally filtering the data to 20 kHz and resampling from 100 kHz to 48 kHz. 48 kHz is the standard sampling rate of digital audio tapes and provides a flat frequency response to 20 kHz.

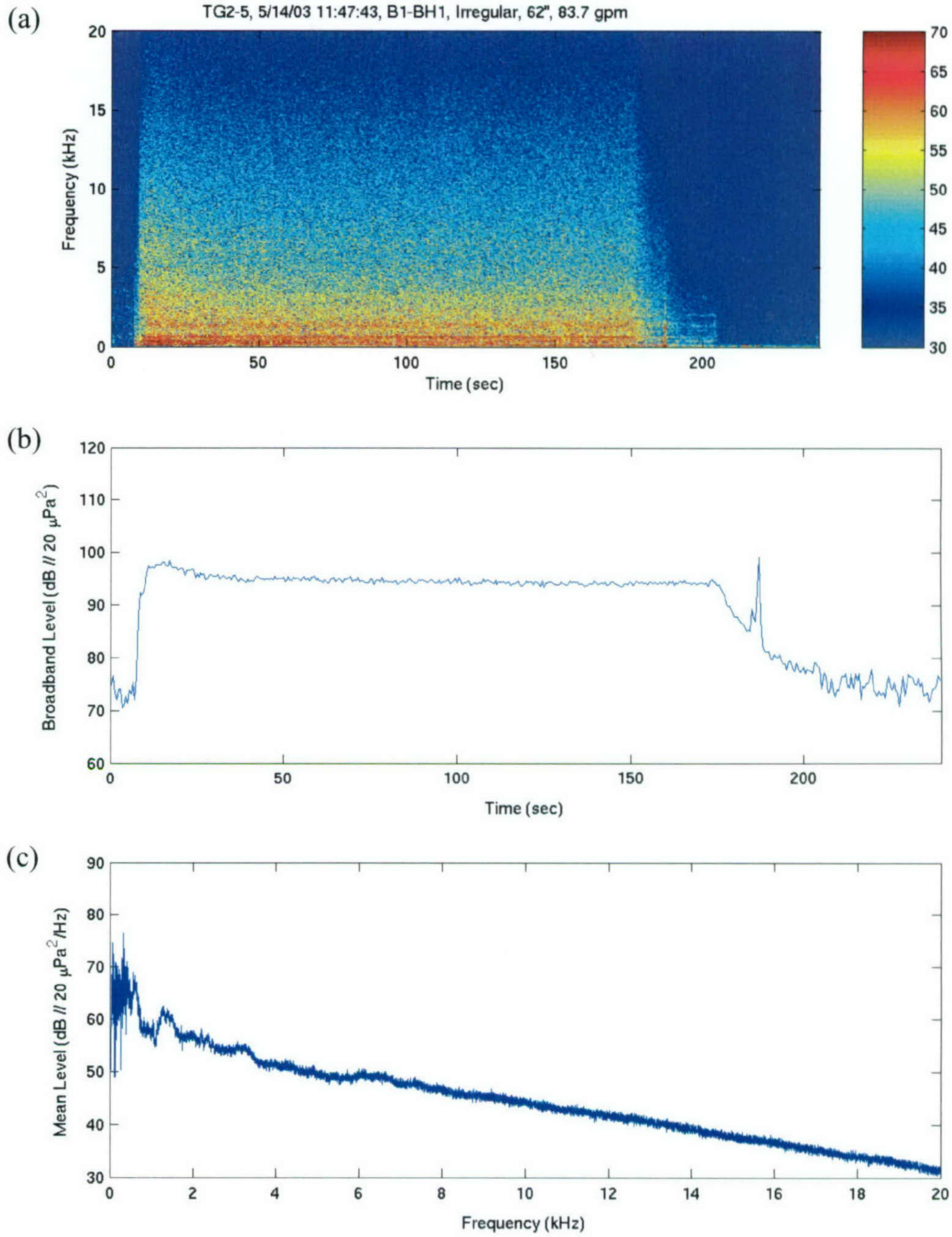

Fig. 4 – Typical damage event, (a) time-frequency spectrogram, (b) 0 – 20 kHz broadband level, and (c) averaged spectrum over the time interval 40-100 seconds.

Fig. 4 shows a typical example of a combined display of one of the events, in this case event 5, an irregular bulkhead breach in the bulkhead, 62" off of the deck, with a flow rate of 63.7 gpm. The figure is composed of three parts, a spectrogram on top, a broadband level plot in the middle and a spectrum on the bottom.

The uppermost part of Fig. 4 is a spectrogram with the units of dB // 20 $\mu Pa^2/Hz$. Initially the level is that of ambient noise in the compartment. Other events will follow this with an intermediate period and level of water flowing through the pipes as it approaches the damage. When the water emerges from the damage at about 10 seconds into the event and splashes on the steel deck the loudest sounds are usually measured for the event. As the deck is covered with water, water-on-water sounds predominate, but are remarkably similar to the water on the deck noise. Apparently much of the noise when striking the deck is also water-on-water in nature. The degree of difference in level varies from event to event. These sounds show little variation in time, varying only in a random sense as a nearly stationary statistical process. When the water is shut off the level begins to decay as the water finishes draining from the system. The spike at about 180 seconds is the hatch being opened to measure the water level. The water finishes draining from the damage shortly after 200 secs and the remainder of the event is noise, although with continued water sounds and people moving about on the facility. Possibly the workmen were also working at this time next door.

The middle part of Fig. 4 is a broadband level of the time series. The frequency band is from 0 to 20 kHz, although the levels below 1-3 Hz are significantly reduced due to microphone response. The broadband level is primarily a function the low frequency noise since it is generally much louder than the higher frequencies. The same sequence of events described for the spectrogram applies to this figure.

The bottom part of Fig. 4 is a spectrum extracted from the center portion of the event where the noise level is approximately constant in time. As can be seen the levels are loudest below 1 kHz, in the 60-70 dB range. Above about 6 kHz the levels decline linearly with frequency. It should be observed that this linear relation is not that of a power law dependence, which would drop off more rapidly for a fixed interval size at low frequencies than at high frequencies.

Figure 5 shows the third-octave spectra of all of the events measured. These were obtained by narrowband processing of the results from the calibrated files and collecting the spectra into third-octave levels. Thus, the points on the curve represent the total energy inside each standard third-octave band. Spectral levels, which are relative to a 1 Hz band, will be significantly lower varying linearly from 6.6 dB lower at 20 Hz to 36.6 dB lower at 20 kHz.

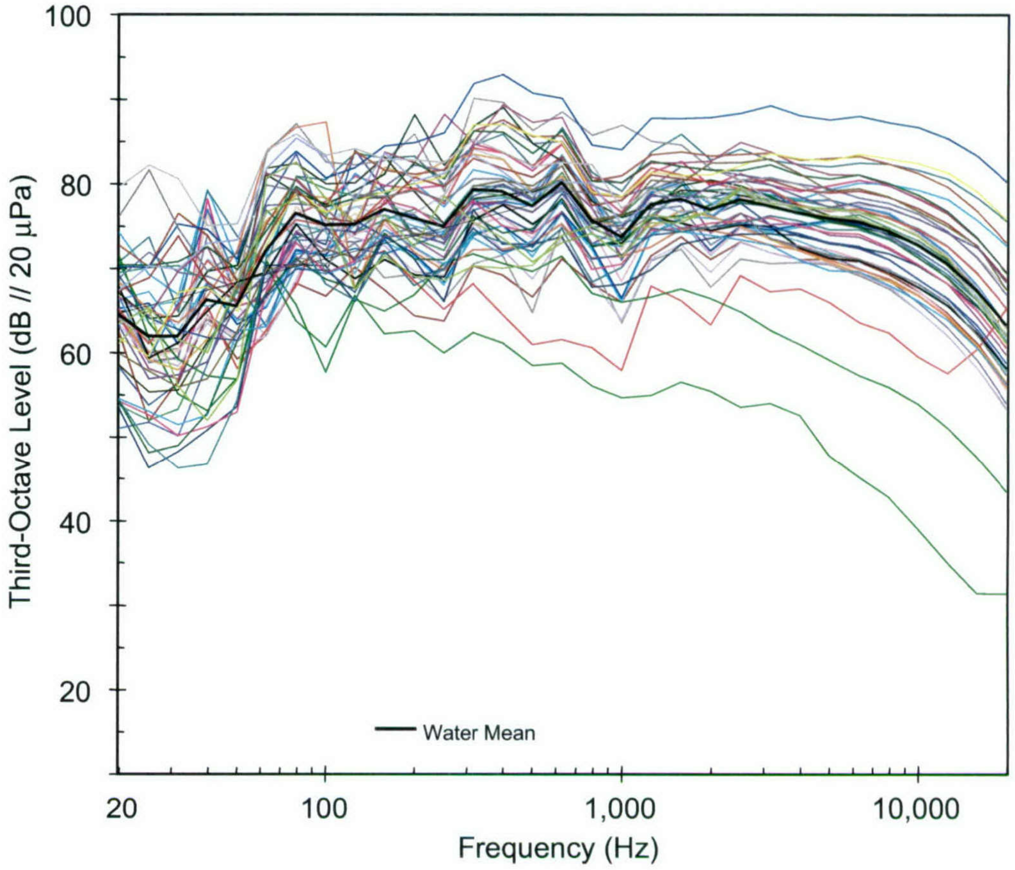

Fig. 5 – Third-octave spectra of the all of the damage events recorded. A few of the longer events have 2 or 3 curves. The heavy line represents the dB mean level of the measurements.

These curves are all very similar except for 3. First, the two green curves on the bottom, at high frequencies, are the second and third segments of a bulkhead rupture test, test 33, which was so long that it was recorded in three files of 4 minutes each. This test, which was one of the ones run to 5 ft, submerged the hole. In the upper of the two curves the hole is partially submerged during the course of the average, and in the lower curve it is completely submerged. The noise and particularly the high frequency component is significantly reduced. The other anomalous result is red curve, also below the main group above 500 Hz. This was test 29, a low flow of a low, 0.9 m high, large hole. The flow rate was approximately 7 gpm (gallons per minute), which was one of the lowest flow rates measured. It is believed that this was one of the few events to not produce significant splashing noise.+

+ This will be verified at a later date using the video recordings.

The loudest sound was from a small slit under full pressure. Because of the small hole size the flow from this slit was only 112 gpm, which is near the 100 gpm average flow rate for all events. Because of the pressure this event produced a significant amount of spray, but it also may have produced significant turbulent noise at the orifice as the water emerged [2]. This effect is generally discounted since the mechanism is a quadrupole, which is an inefficient radiation mechanism with the amplitude inversely proportional to the third power of distance from the source [3]. However, interaction of the turbulence with the surrounding environment may produce a more efficient source mechanism, so this cannot be discounted.

An immediate observation is that the levels are loud. Excluding the submerged event described above, the broadband levels range from 81.9 to 101.7 dB for the two events mentioned previously, with a dB mean of 91.2 dB and a standard deviation of 4.1 dB, over the 20 Hz – 20 kHz band.* These levels are similar to those of a noisy vacuum cleaner up to that of a pneumatic hammer and are in a region usually requiring hearing protection for prolonged exposure. Typical ambient noise levels run from 30 to 70 dB, an empty movie house to a busy street [4, 5]. 0 dB is considered a threshold of audibility and 120 dB the threshold of pain. This fact and the sustained nature of the event means that water damage events should be fairly easy to detect.

Also of interest are the levels above 6 kHz. With the exception of the three lower curves, the noise levels are fairly high, but not that high, given the adjustment from broadband level to spectral level. When that adjustment is made, the levels range from an average level of nearly 50 dB at 4 kHz down to 26 dB at 20 kHz. While not loud, these levels are louder than levels typically found in this frequency range. Also of interest is the way in which the levels seem to decreasing at higher frequencies. If the levels were declining as a power law of frequency, F^{-N}, in this region the spectrum would appear linear on this scale, even with the correction for the changing bandwidth, which would change the power law to F^{-N+1}. Instead, the levels are declining more rapidly at higher frequencies indicating an increasing dependence on frequency. This effect is not due to the microphone or recording system, which are both flat in this frequency regime, or to the digital filter used when the digital data was down sampled from the recorded rate of 100 kHz to the standard file rate of 48 kHz. That filter was also flat in this range even near 20 kHz. This rapid decline at the upper edge of the band indicates that it is unlikely that further analysis will demonstrate useful acoustic energy for this type of event in the low ultrasonic region. As will be seen in Section VI the audible high frequency region provides the most simple and direct method for detecting pipe rupture and flooding events based upon its level and sustained nature.

V. SHIPBOARD AMBIENT NOISE MEASUREMENTS

In order to evaluate any detection algorithm it is necessary to have, at a minimum, representative samples of the noise field against which the detections are to be made. In this case the noise field needed is that of shipboard ambient noise aboard a Naval vessel. Two opportunities present themselves as a way to acquire some shipboard ambient noise measurements. The first was during a Scientist-to-Sea cruise aboard the USS RAMAGE. The second was during a branch experiment aboard the RV ENDEAVOR.

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* These levels are unweighted and relative to 20 μPa as are all levels in this report.

The latter while not a Naval vessel shares many of the characteristics of any ship and the noise field was judged to sound very similar in many regards to that aboard the RAMAGE.

A. USS RAMAGE Noise Measurements

On 27-30 May 2003, shipboard noise measurements were conducted during a Scientist-to-Sea cruise aboard the USS RAMAGE, DDG-61, an Arleigh Burke class destroyer launched in 1995. The ship sailed from Norfolk and docked at Boston. During this cruise a sampling of noise measurements were made. Due to troubles with the recording system, the samples are not as long as desired, nor were as many made as originally intended.

For this set of measurements a Shure KSM-141 audio grade microphone (20 Hz – 20 kHz), powered and amplified by a Shure FP-23 conditioning amplifier, was used in conjunction with a portable Sony Walkman DAT recorder modified for extended low frequency response. (See Fig. 6.) The KSM-141 is a multifunction microphone with switchable low-end frequency response, directivity response pattern and sensitivity (0, -15 and –20 dB). Data calibration was provided using the Brüel and Kjær 4231 94 dB 1 kHz reference calibrator. Approximately 30 minutes of data was taken in 3-minute segments throughout the ship. Data recording was complicated by the exceptionally short battery lifetime of the Walkman and an inability to determine when levels were overloaded on the microphone.

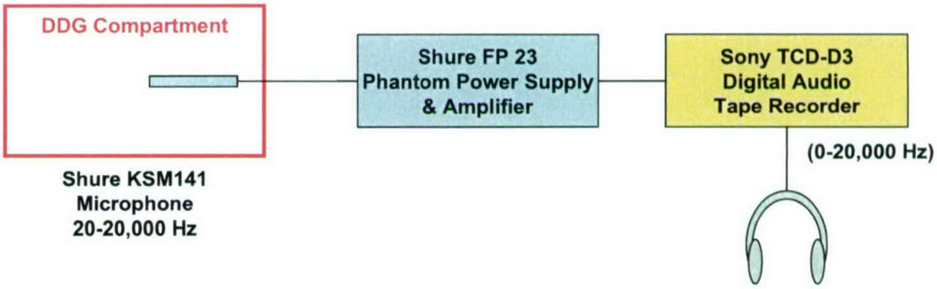

Fig. 6 – Recording system used to measure shipboard noise aboard the USS RAMAGE (DDG-61).

Compartments measured included sleeping spaces, passage ways, an engine room (on 2 levels), offices and the after missile compartment. (See Table 7.) It was noted that the noise was remarkably constant throughout the ship being primarily due to a low hum from the air circulation system. Only in compartments with mechanical machinery, such as the engine room, was there a significant difference in the character of the noise. There was a 20 dB variation between the quietest compartment measured, CPO berthing, and the noisiest, a passage way. The engine room measurements were overloaded due to the problems mentioned previously and hence cannot be further considered. Compartments with people present were generally ignored in the recording process.

Table 7 – USS RAMAGE shipboard ambient noise measurements, at least 3 minutes each.

Location and Comments	Level
Master Chief Berthing Space, 1-70-01-L, PA announcement	64.3
Passage way opposite 1-59-1, Transformers nearby	71.4
Passage way opposite 1-187-1, Hydraulic panel nearby, people passing	80.2
Engine Room, 4-254-0-E, Upper Level, overloaded.	> 85.8
Engine Room, 4-254-0-E, Lower Level, PA announcements, overloaded.	> 86.1
Officer's Wardroom	68.7
CSMC Tech Library, 01-130-1, 3 people talking on other side of the divider	71.7
Aft missile launcher, only partially filled out, upper level ~ 3' from bulkhead. Some clank of plates initially. Reportedly much quieter than normal since cooling fans were off.	74.8
Passage way opposite 1-300-01-L, only some traffic	84.4
Passage way opposite 1-254-6-L, long passage way	74.9

The tape made was returned to NRL where it was digitally dubbed from the tape to a set of computer files. Since a DAT records its data digitally at 48 kHz sampling rate, the sampling rate being used for the processing, these files did not need to be digitally filtered and resampled as was done for the DCETF data set. Instead, the appropriate calibration level was calculated, applied directly to the data and the files were rewritten in the standard file format. A complication in this process was that the calibration signal was also overloaded. This was overcome by histograming the calibration tone and determining the proportion that was not overloaded, about 24%. From this and the knowledge that the calibration tone is a sine wave, it is a straightforward calculation to estimate the rms level of the signal. However, while the DCETF and ENDEAVOR data can be said to be accurate to ±0.2 dB, the precision of the calibrator, this data is probably not reliable beyond 1-2 dB. The levels are consistent with those measured aboard the ENDEAVOR and the results are therefore believed to be accurate.

Figure 7 shows the noise spectra in third-octave bands for the compartments measured. As can be seen the noise levels are lower than those of the water events for frequencies above 75 Hz. The greatest difference is to be found at high frequencies above 2 kHz. Further, the frequency spectra in this region displays none of the smooth frequency dependence shown in the mean water curve and also in the individual water event curves of Fig. 5. From about 7 kHz up the mean water curve is nearly 20 dB above the shipboard ambient noise background of the RAMAGE, making detections very easy.

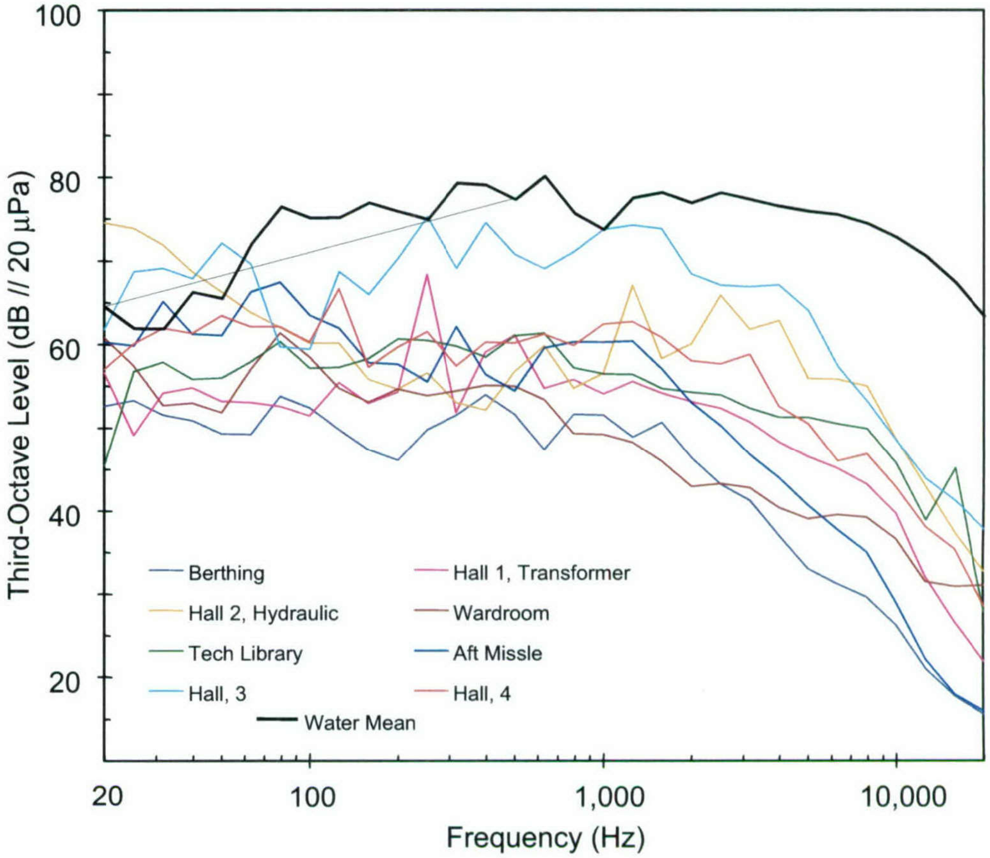

Fig. 7 – Third-octave spectra of the USS RAMAGE shipboard ambient noise measurements. The dark black line represents the dB mean water event noise level of Fig. 5.

B. RV ENDEAVOR Noise Measurements

After the recording difficulties aboard the RAMAGE a new recording setup was devised and acquired. For the measurements made aboard the RV ENDEAVOR in December 2003, the system shown in Fig. 8 was acquired. This system is composed of the Shure KSM-141 multifunction microphone along with an M-Audio Firewire 410 and an Apple laptop computer. The M-Audio unit not only provides the phantom power and amplification for the microphone, it also digitizes the result at 16 or 24 bits and sampling rates of up to 96 kHz. For the measurements aboard the ENDEAVOR the unit was set to provide 24-bit sampling at 48 kHz. Amadeus II software on the laptop provided the recording interface. It also permitted a checking of the levels prior to recording and an immediate examination of the results for overloads, dropouts etc. after the recording was done. The files were recorded as AIFF files, a standard audio file format used on Apple and SGI computers and audio CDs.

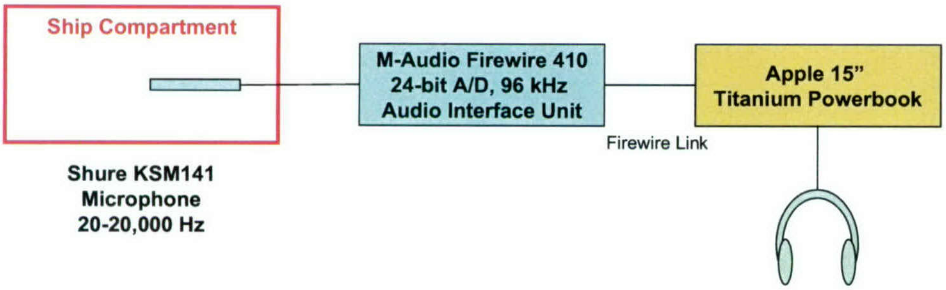

Fig. 8 – Recording system used to measure shipboard noise aboard the RV ENDEAVOR.

The processing for the ENDEAVOR data proceeded similar to the DCETF and RAMAGE data with the difference that these files were 24-bit AIFF files. Thus, it was necessary to write a routine to read AIFF files and to convert 24-bit integers to 32-bit floating point numbers. Like the RAMAGE data no filtering or resampling was necessary. The results are presented in Table 8. These measurements show a large variability of 33.3 dB from quietest to loudest. The engine room measurements are the loudest measured on either ship.

Table 8 – RV ENDEAVOR shipboard ambient noise measurements, 20 minutes each.

Compartment and Comments	Level
Control Pitch Compartment	95.76
Engine Room	104.02
Generator Compartment, open to Engine Room below	97.72
Main Laboratory, Talking	71.18
Main Laboratory, Quiet	70.69
Laundry Compartment, Forward	88.69
Scientific Storage, Stern, open to Steering Gear Compartment, aft, and Control Pitch Compartment, below	84.15
Stateroom, below decks, forward of Scientific Storage, ballast tanks below audible	77.93
Steering Gear Compartment	86.82

Figure 9 shows the noise spectra in third-octave bands for the compartments measured. As can be seen the noise levels are lower than those of the water events for frequencies above 250 Hz with three exceptions. The three exceptions are the main engine room (magenta) the generator compartment (gold) and the control-pitch compartment (dark blue). The first two compartments had heavy machinery running, the diesel engines driving the ship and the generators for the ship's power. The control-pitch compartment is located near the bottom aft end of the ship, in front of the propeller and is where the pitch of the propellers is controlled. Interestingly, the steering gear compartment (light blue) where the rudder is controlled by large hydraulic pistons was not one of the loudest compartments in the ship. This is somewhat surprising as it is situated directly above and slightly astern of the ship's propeller.

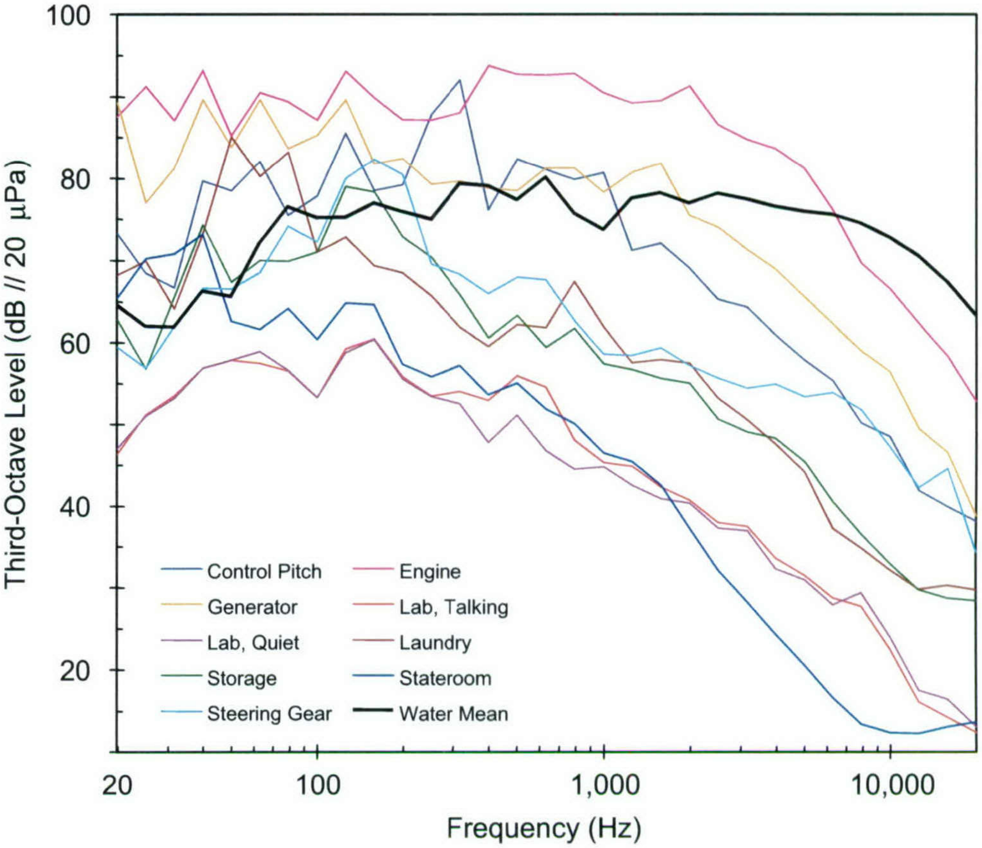

Fig. 9 – Third-octave spectra of the RV ENDEAVOR shipboard ambient noise measurements. The dark black line represents the dB mean water event noise level of Fig. 5.

The quietest compartment on either ship was the CPO berthing compartment aboard the RAMAGE by a small margin over the laboratory of the ENDEAVOR. The staterooms on the ENDEAVOR are down a deck and near the noise of the bottom of the ship, engine room forward and propeller aft. Further, they are situated over ballast tanks, which can be heard sloshing as the ship rolled from side to side. No such sounds were ever heard aboard the RAMAGE, which is a much larger ship. This may account for the higher low frequency noise levels in the ENDEAVOR's staterooms.

The data from the ENDEAVOR is very similar in character to that of the RAMAGE. The greatest difference between the water spectra and the shipboard ambient noise spectra is to be found at high frequencies above 2 kHz. Also again, the frequency spectra in this region displays none of the smooth frequency dependence shown in the mean water curve and also in the individual water event curves of Fig. 5. From about 7 kHz up the mean water curve is 15 dB above the shipboard ambient noise background of the ENDEAVOR, except for the engine room, making detections very easy. Even for the engine room the mean water curve exceeds the noise levels above 7 kHz making detections possible based upon level alone, if not as easily as for the other compartments.

VII. WATER DC EVENT DETECTABILITY

The discussion in the previous sections has suggested that water DC events are sufficiently loud that a simple energy detector applied to an appropriate high frequency band will yield an appropriate demonstration test. A final test might be more complex and look at the time-frequency content of the signal to determine whether the source of the noise is due to a pipe rupture or some other mechanism.

The first subsection will develop the test and present the results. As developed, the test ignores the differences in compartment size and absorption. Compartment size and absorption affect the apparent signal level and will be considered separately in the second subsection. The modifications to the results in the first section are readily apparent.

A. Simple Detection Example

The test to be used is a simple energy-ratio test of the ratio of the signal against the ambient background. Formally the test is the mean of the signal-to-noise ratio spectra, where the mean is over a frequency band and the noise is the long-term ambient background. For reasons of expediency, the entire 3 minute sample is used in the calculation of the ambient background. In actual practice the long-term ambient background would be calculated using a running exponential average of the data before the start of the event and would freeze until the event was over by some measure.

The frequency band selected for the test is 7 kHz to 17 kHz. The lower limit comes from an inspection of the third-octave frequency spectra of Figs. 5, 7 and 9. This limit is chosen to maximize the difference between the water spectra and the noise in the ship compartments. It also represents an approximate starting point for the linear behavior of the water event noise field in this region. The upper limit is selected as an upper limit of the frequency response for common microphones available on the market today at reasonable prices. The research and pro-audio grade microphones used to record the data extend to 40 and 20 kHz, respectively, but are relatively costly. The response of more common, and less costly microphones tends to drop off at around 17 kHz. Such microphones are also reasonably flat in the frequency range selected.

To mitigate the effects of transients in the data a 20 second exponential smoother is applied to the detection criteria. This will smooth over many short transient events, such as public address announcements and locker doors closing, but would not necessarily eliminate other events of short duration, arc-welding for instance. For those events a more sophisticated test will be needed.

The source event chosen for this example is event 5, which is shown in Fig. 4 of Section III. It was chosen because its spectrum is reasonably close to the mean curve of Fig. 5. The shipboard ambient noise measurements chosen are the RAMAGE CPO Berthing Space and the ENDEAVOR Engine Room for their extreme levels. The berthing space was among the quietest measured and the engine room was the loudest. The source event was added to the background noise and the test run on the quantity (S+N)/B as this is representative of reality where both signal and noise are present. (B is the long-term ambient noise.)

Figures 10 and 11 show the results of the tests. Figure 10 shows the berthing space result and Fig. 11 the engine room result. The upper part of each figure shows the spectrogram of the event. The lower part shows the test statistic as a function of time for the event. The red curve shows the test statistic value as a function of time when the signal is present and the lower blue curve the value for the noise only. For this test methodology the value of the latter is very nearly 1 throughout the test. In part, this is because of the way the test was constructed, however it would also be true in a more representative detection methodology as long as the noise background was nearly constant or very slowly varying.

As can be seen from the two tests, the test value rises to a much higher level, about 52 dB, for the berthing space than for the engine room, about 11 dB. This is to be expected since the engine room is much louder than the berthing space. The similar form of the two curves is a consequence of the same source being used for both examples. If different sources had been used there would be more differences, although they would retain a great deal of similarity due to the similarities among the events themselves. The large level of the berthing space means that a detection will be made almost regardless of the type of compartment if the noise background is at this level. On the other hand, the engine room level is such that the nature of the compartment must be considered when determining a detection threshold or whether a detection is even possible. This is the subject of the next sub-section.

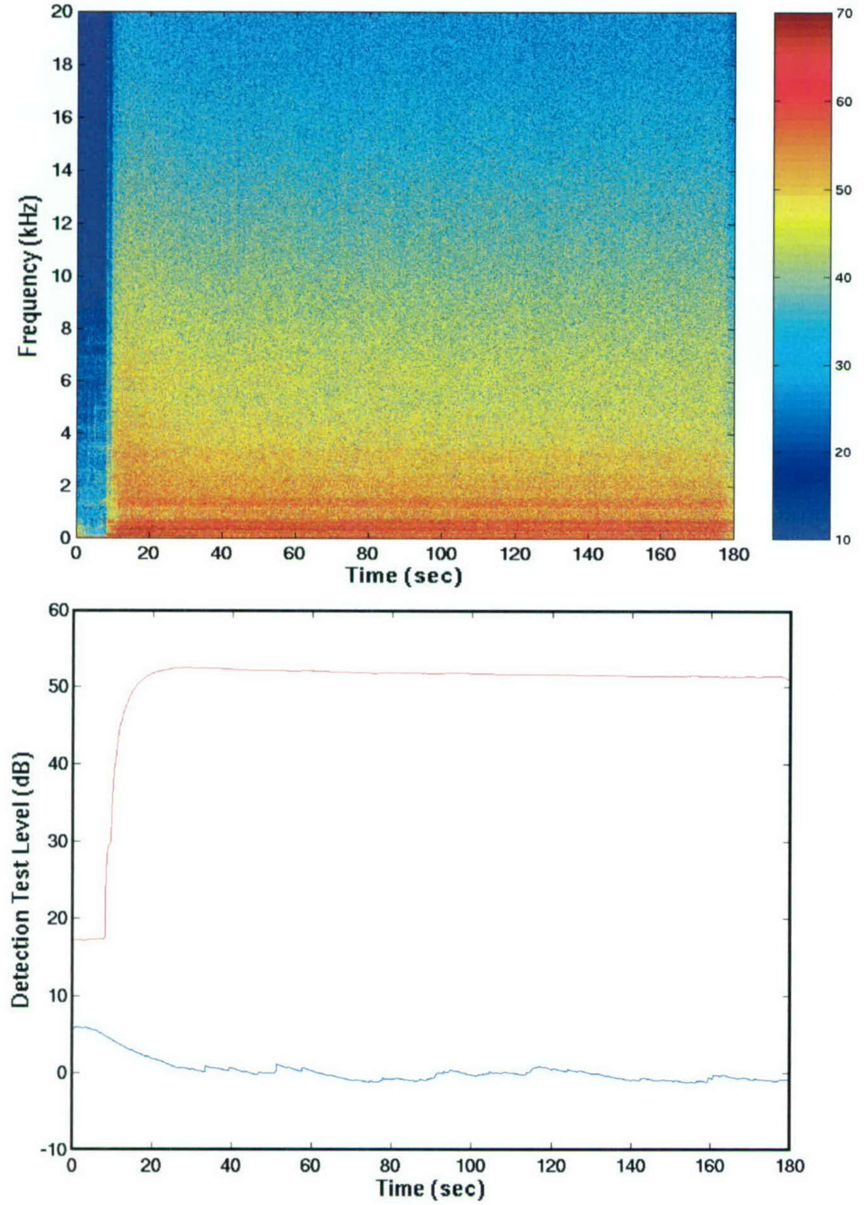

Fig. 10 – Pipe rupture test against RAMAGE CPO Berthing Space ambient noise background. Upper figure contains the spectrogram of the combined source and noise field. The lower figure contains a plot of the test level as a function of time in the presence of the signal + noise (red curve) and in for just the noise (blue curve).

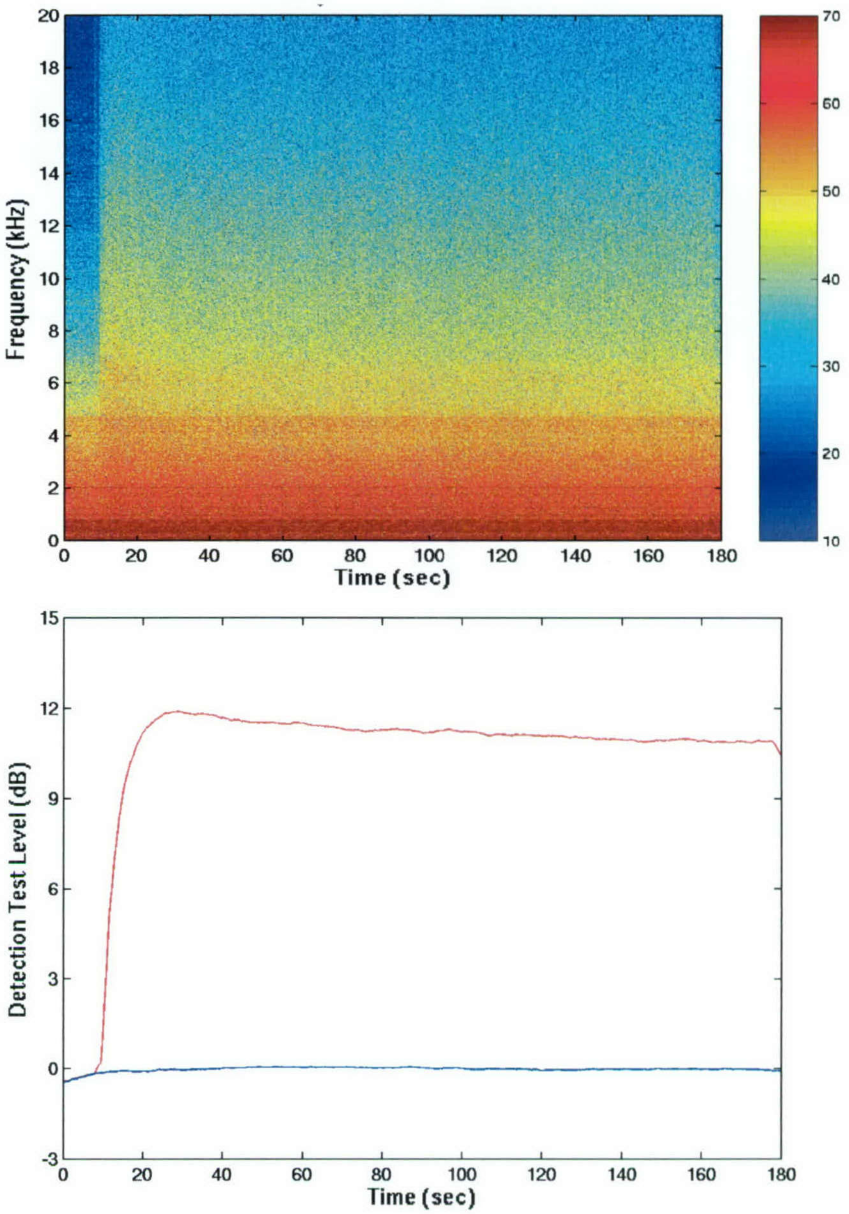

Fig. 11 – Pipe rupture test against ENDEAVOR Engine Room ambient noise background. Upper figure contains the spectrogram of the combined source and noise field. The lower figure contains a plot of the test level as a function of time in the presence of the signal + noise (red curve) and for just the noise (blue curve).

B. Test Result Modification Due to Compartment Differences

Given the high frequency range used in this test, the compartments may be characterized as many wavelengths in each of their dimensions. The wavelength at 7 kHz is only 5 cm. The compartment height, 2.44 m or 8 ft, is thus about 49 wavelengths. The relevant theory is Sabine's theory for large reverberant rooms [6,7]. These rooms are characterized by an even distribution of energy throughout the room, except in the immediate vicinity of the source where the direct path from the source may dominate. The dimensions of the compartments in which the water event measurements were made are given in Table 9.

Compartment	W x L x H	Volume	Surface	M. F. Path	Decay Time
A1	1.82 x 4.26 x 2.45 m	18.89 m^3	45.14 m^2	1.67 m	0.243 s
B1 & B2	1.21 x 2.44 x 2.45 m	7.19 m^3	23.71 m^2	1.21 m	0.176 s

Table 9 – Room properties of the spaces in which the water events were measured. M. F. Path is the mean free path of the room (see text) and the decay time was calculated assuming a surface loss of 0.02 for each reflection.

As can be seen these compartments are highly reverberant. The relevant equation describing the time dependence of the level in the room is given in Eq. 1 [8. This is the energy conservation equation for a compartment. The first term is the rate of change of the energy in the compartment and is zero when the level has reached steady state. The term on the right hand side of the equation is the source term and, thus, is a constant for any given source. The central term is the one that is of interest to the present discussion, since it describes how the results will scale with changing compartment characteristics.

$$V\frac{d\overline{w}}{dt}+\frac{c}{4}A_S\overline{w}=\overline{\mathcal{P}} \tag{1}$$

First the quantity $\overline{w}$ is the acoustic energy density in the compartment and is, as a decibel level, the measured quantity of each event. The sound speed, c, is nearly a constant, varying only a relatively small amount with temperature and humidity. The quantity A_S is the equivalent surface area through which energy is completely absorbed. It is given by the expression $A_S = \alpha S$, where α is the average reflection loss of the bulkheads, between 0 and 1, and S is the total surface area of the space. Clearly if A_S is larger, either through more loss or a larger surface area, then the energy density will of necessity be smaller since $\mathcal{P}$ is a constant for the purpose of this discussion. The compartments in which the measurements were made were both small and are assumed to have a low loss surface since all of the surfaces were steel. The two compartments in which the measurements are to be simulated are both larger than the source compartment, B1, by significant amount. Further, both have a larger surface area that must be added to the calculation. While no measurements were taken of either compartment some interesting estimates can be easily made. The berthing space was approximately the same height as the B1 test space, however, it was approximately 6 m by 7 m in deck area, and was divided by 6 bunks with solid sides with lockers backed up to the bunks. An estimate of the surface area is something near 220 m^2, or nearly 10 times the surface area of test space, B1. The bulkheads, overhead and decks were all hard surfaces, but there was bedding and other objects in the compartment. Assume a loss factor of about 0.05 as a reasonable approximation. The quantity A_S will thus be on the order of 11, approximately 23 times larger than that of the test space. The level measured in such a space will be 13.7 dB lower due to compartment differences. However, Fig. 10 indicates a signal-to-noise ratio of over 50 dB and hence in this environment the signal should be easily detectable. Indeed any of the signals recorded should be detectable.

A similar calculation for the ENDEAVOR's engine room is more difficult. The compartment was both wider and higher than the test space. Also it was open to the generator compartment on the next level. The engines sat in the middle of the compartment and must also be assumed to affect the absorption characteristics and surface area calculations somewhat. If the compartment is assumed to have the same surface area and attenuation characteristics as the berthing space, then a detection for this space would be harder, but nominally still possible. This is because the ratio plotted in Fig. 11 is really a signal-plus-noise to noise ratio and the detection test will still yield a ratio of about 2 dB. It would be difficult, but not necessarily impossible to make a detection under these circumstances. However, even slightly different assumptions about the compartment characteristics could cause the test statistic to fall to such a level that a detection could not be made.

VIII. SUMMARY AND RECOMMENDATIONS

This report has presented a study of the feasibility of detecting water-based, damage control events, specifically pipe ruptures and flooding and documented the data collection efforts in support of the objective.

It was shown that the water DC events recorded at the DCETF where all very loud with broadband levels ranging from 81.9 to 101.7 dB and a dB mean of 91.2 dB. The principal noise source mechanism is believed to be water-splashing sounds. The one case where the damage was completely submerged by the water resulted in a level reduction of 12.2 dB. The noise spectra are characterized by a variable, between events, low frequency spectra, below 2 kHz, and consistent high frequency spectra, above 6 kHz, which appears to fall off linearly in level. Depending on the event, the broadband level may show a slight initial peak before settling to a nearly constant level with time. The initial peak is believed to be due to the sounds of water on the deck and the later, stable level due to water-on-water sounds.

Measurements of shipboard ambient noise are also documented in this report. Measurements were made aboard two vessels, the USS RAMAGE and the RV ENDEAVOR. The USS RAMAGE (DDG-61) is a Navy Destroyer of the Arleigh Burke class, the most recent class of destroyers. The range of broadband levels, 64.3 to 84.4 dB, extended from considerably below those of the water DC events to as loud as some of the quieter events. The levels in the quietest spaces were due to a low frequency hum attributed to the ventilation system of the ship and in louder spaces due to machinery. RV ENDEAVOR is the University of Rhode Island's research vessel. The ENDEAVOR measurements showed many of the same features and variability as those made aboard the RAMAGE. The ENDEAVOR's levels ranged from 70.7 to 104.2 dB. Many of the louder of these measurements are of a broadband level similar to that of the water DC events. It is only by looking at the spectra that it is possible to identify a frequency region, frequencies greater than 5 kHz, in which detections can be made.

A basic detector was devised to detect the water DC events. This detector was formulated as an energy detector in the frequency range 7–17 kHz. The lower limit was chosen to optimize the signal-to-noise ratio. The upper limit was chosen as a reasonable frequency response limit for a standard low-cost microphone. Detections were demonstrated to be possible on the loudest and quietest of the ambient noise measurements. In the latter case, the mean signal-to-noise ratio of the detector was 12-15 dB, while it was in excess of 50 dB for the quietest space. A discussion of reverberant compartment effects indicates that it is possible for the detection in the engine room to be masked by the ambient noise. Whether it would be so masked or not depends on the physical size of the compartment and its attenuation characteristics, which have not been calculated. The signal-to-noise ratio for the quietest environments was more than enough to guarantee detection in even a larger, more highly attenuating space. It is concluded that an acoustic system to detect pipe ruptures and flooding is feasible in all but the loudest spaces.

VIII. ACKNOWLEDGMENTS

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X. APPENDIX - DCETF TEST LOGS

	Test #	Event Time		Audio Time				Video Time				Station	Event Type	Height	Flow Rate	Measured Gallons	Flow Rate GPM	Comments
		Start	Stop	Event #	Start	Stop	Length	Event #	Start	Stop	Dub #							
Test Group 2:																		
5/15/07	1	11:11:50	11:13:40	1	11:11:34	11:14:04	0:02:30	2	11:11:05	11:14:21	1-1	B1-PR2	Small Circular	82.75	High	360	196.4	Circular hole only of this casualty.
	2	11:20:00	11:21:33	2	11:19:45	11:22:18	0:02:33	3	11:19:38	11:22:18	1-2				Medium	240	154.8	
	3	11:27:45	11:32:25	3	11:27:25	11:33:55	0:06:30	4	11:27:03	11:32:55	1-3				Low	110	23.6	
	4	11:39:34	11:41:00	4	11:39:20	11:41:00	0:01:40	5	11:38:58	11:41:29	1-4	B1-BH1	Irregular	62	High	240	167.4	
	5	11:47:43	11:50:35	5	11:47:30	11:53:40	0:06:10	6	11:46:54	11:51:03	1-5				Medium	240	83.7	
	6	11:59:42	12:03:40	6	11:59:30	12:03:40	0:04:10	7	11:59:13	12:03:47	1-6				Low	120	30.3	
	7	12:09:36	12:11:45	7	12:09:29	12:12:00	0:02:31	8	12:09:08	12:12:04	1-7	B1-PR2	Small Slit	82.75	High	240	111.6	Slit only of this casualty.
	8	12:19:29	12:22:38	8	12:19:29	12:23:00	0:03:31	9	12:19:06	12:23:02	1-8				Medium	240	76.2	
	9	12:38:22	12:44:20	9	12:38:10	12:45:17	0:07:07	11	12:37:48	12:45:45	1-10				Low	70	11.7	
Test Group 3:																		
5/15/07	10	13:39:50	13:42:00	10	13:38:53	13:42:30	0:03:37	12	13:38:37	13:42:25	1-11	B1 - Fire Main	Open Valve	42	High	360	166.2	
	11	13:48:49	13:53:38	11	13:48:35	13:53:38	0:05:03	13	13:48:36	13:54:00	1-12				Low	120	24.9	
	12	14:00:19	14:02:55	12	13:59:50	14:03:25	0:03:35	14	14:00:21	14:03:18	1-12	B1-PR1	Leaky Patch	48.5	High	120	46.2	
	13	14:11:30	14:14:30	13	14:11:17	14:15:15	0:03:58	15	14:10:34	14:15:00	1-13				Medium	120	40.0	
	14	14:22:36	14:27:10	14	14:22:22	14:26:31	0:04:09	16	14:19:40	14:28:20	1-14				Low	65	14.2	
	15	15:04:00	15:10:15	15	15:04:36	15:12:45	0:08:09	17	15:04:04	15:16:38	1-15	B1 – Hatch from B2-BH2	Hatch Flooding	33 & 96.25	High	1200	192.0	Run to 5.5 ft to satisfy first test of test group 5.
	16	15:24:20	15:26:25	16	15:22:50	15:30:30	0:07:40	18	15:22:36	15:28:00	1-16				Medium	240	115.2	Used B2-BH2 as source in B2.
	17	15:32:40	15:38:45	17	15:32:25	15:39:24	0:06:59	19	15:32:44	15:40:03	1-16				Low	100	16.4	
Test Group 1:																		
5/15/07	18x-y	16:15:15	16:18:25	18	16:08:12	—	—	20 & 21	16:06:30	16:20:42	1-17	A1-PR3	Small slit	48.5 - Low	Low			Test aborted due to water on microphone - two attempts.
5/16/07	18	8:33:25	8:38:00	19	8:33:20	8:37:20	0:04:00	22	8:31:57	8:37:56	2-				Low	130	28.4	Not really that low.
	19	8:48:00	8:52:25	20	8:47:45	8:52:40	0:04:55	23	8:46:37	8:53:08	2-				Medium	430	97.4	
	20	9:08:35	9:10:50	21	9:08:25	9:12:25	0:04:00	24	9:03:46	9:11:30	2-				High	430	191.1	
	~~21~~						0:00:00					A1-PR2	Small slit	71.75 - Inter	~~High~~			
	22	9:26:05	9:29:10	22	9:25:53	9:29:55	0:04:02	25	9:24:48	9:29:48	2-3				Medium	160	51.9	
	23	9:39:25	9:42:30	23	9:39:17	9:43:17	0:04:00	26	9:38:04	9:43:30	2-4				Low	30	9.7	
	24	9:54:22	9:57:25	24	9:54:17	9:58:17	0:04:00	27	9:53:16	9:58:11	2-5	A1-PR5	Small slit	83 - High	High	475	155.7	
	25	10:13:55	10:19:15	25	10:13:35	10:19:30	0:05:55	28	10:12:04	10:18:42	2-6				Medium	220	41.2	
	26	10:32:15	10:36:05	26	10:32:00	10:36:00	0:04:00	29	10:31:24	10:36:49	2-7				Low	20	5.2	
	27	10:46:00	10:48:55	27	10:45:52	10:49:52	0:04:00	30	10:44:30	10:49:47	2-8	A1-BH2	Large hole	36	High	735	252.0	
	~~28~~														~~Medium~~			
	29	11:04:25	11:08:10	29	11:04:25	11:08:25	0:04:00	31	11:03:01	11:07:44	2-9				Low	25	6.7	
	30	11:18:45	11:21:45	30	11:18:33	11:22:33	0:04:00	32	11:12:28	11:22:18	2-10	A1-PR1	Intermediate	48.5	High	630	210.0	
	31	11:40:05	11:42:20	31	11:39:50	11:43:50	0:04:00	33	11:37:01	11:42:00	2-11				Medium	150	66.7	
	32	11:49:53	11:53:00	32	11:49:32	11:53:32	0:04:00	34	11:49:00	11:52:18	2-11				Low	50	16.0	
	33	12:44:10	12:49:00	34	12:42:18	12:53:45	0:11:27	36	12:41:08	12:50:10	2-13	B2-BH2	Large hole	33	High	1200	248.3	Run to 5 ft to satisfy second test of test group 5.
	34	13:43:42	13:45:10	35	13:43:33	13:46:37	0:03:04	37	13:41:06	13:46:19	2-14				Medium	280	190.9	
	35	13:51:21	13:53:33	36	13:51:07	13:54:00	0:02:53	38	13:50:00	13:52:00	2-15				Low	100	45.5	
	36	14:03:22	14:06:20	37	14:03:22	14:07:22	0:04:00	39	14:02:35	14:07:04	2-15	B2-PR5	Large pipe beak	66	High	620	209.0	
	37	14:14:10	14:16:10	38	14:13:47	14:17:47	0:04:00	40	14:11:51	14:21:49	2-16				Medium	200	100.0	
	38	14:33:35	14:36:15	39	14:33:07	14:37:07	0:04:00	41	14:32:30	14:35:57	2-16				Low	35	13.1	
	39	14:40:43	14:42:55	40	14:40:35	14:44:35	0:04:00	42	14:39:24	14:42:00	2-18	B2-BH1	Intermediate – 58 little holes	62	High	560	254.5	
	40	14:49:06	14:51:20	41	14:48:55	14:52:55	0:04:00	43	14:48:07	14:50:49	2-18				Medium	375	167.9	
	41	14:58:05	15:00:15	42	14:57:51	15:01:05	0:03:14	44	14:56:49	15:02:35	2-19				Low	120	55.4	
	~~42~~												~~Intermediate~~	~~Intermediate~~	~~High~~			
	~~43~~														~~Medium~~			
	~~44~~														~~Low~~			

	Test #	Event Time		Audio Time				Video Time				Station	Event Type	Height	Flow Rate	Measured Gallons	Flow Rate GPM	Comments
		Start	Stop	Event #	Start	Stop	Length	Event #	Start	Stop	Dub #							
Test Group 4:																		
5/16/07	45											B1 & B2	Small		High			Test objectives met by the various measurements in B1 & B2.
	46														Low			
	~~47~~												~~Medium~~		~~High~~			No intermediate size room exists between B1/B2 size and A1/A2 size.
	~~48~~														~~Low~~			
	49											A1	Large		High			Test objectives met by the various measurements in A1.
	50														Low			
Test Group 5:																		
	51	15:04:00	15:10:15	15	15:04:36	15:12:45	0:08:09	17	15:04:04	15:16:38	1-15	B1	Hatch flooding	High	High	1200	192.0	Fulfilled by test 15.
	52	12:44:10	12:49:00	34	12:42:18	12:53:45	0:11:27	36	12:41:08	12:50:10	2-11	B2	Large hole	Low	High	1200	248.3	Fulfilled by test 33.
Test Group 6:																		
	~~53~~												~~Slit~~		~~High~~			Tests canceled.
	~~54~~														~~Low~~			
	~~55~~												~~Irregular~~		~~High~~			
	~~56~~														~~Low~~			
	~~57~~												~~Circular~~		~~High~~			
	~~58~~														~~Low~~			
Additional Tests:																		
	~~59~~											A2-BH1	Slit - Hatch	3.5 & 96.25	~~Low~~			
	60	12:08:00	12:13:20	33	12:08:00	12:14:00	0:06:00	35	12:05:38	12:15:54	2-12				High	995	186.6	Measured in A1 below. Hatch flooding.

Total Time 3:20:58