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### THESIS

# EFFECTS OF A SUSPENDED SEDIMENT LAYER ON ACOUSTIC IMAGERY

by

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June 2004

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# EFFECTS OF A SUSPENDED SEDIMENT LAYER ON ACOUSTIC IMAGERY

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# ABSTRACT

The Navy's CASS/GRAB sonar model is used to accurately simulate a side-scan sonar image with a mine-like object present through its reverberation characteristics. The acoustic impact of a suspended sediment layer is investigated numerically using CASS/GRAB through changing the volume scattering characteristics of the lower water column. A range of critical values of volume scattering strength were discovered through repeated model simulations. An understanding of the acoustic characteristics of suspended sediment layers can aid the Navy in the detection of mines that might exist within these layers.

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# I. INTRODUCTION

In the fifteen years since the fall of the Berlin Wall and the end of the “Cold War”, United States Naval Forces are still transitioning from a large “blue water” navy to a smaller, more mobile force capable of combat in the littoral regions of the world. The looming specter of the Soviet Union has been replaced by smaller regional threats that utilize unconventional tactics to inflict damage on those they oppose.

One such tactic that was prevalent during Operation Iraqi Freedom was that of using sea mines to block waterways. Naval mines are inexpensive, easily deployed, and possess extraordinary destructive capability. Once deployed, mine fields require very little maintenance and can effectively block access to ports, deter amphibious operations, prevent humanitarian assistance and psychologically affect those assigned to patrol the waters in the vicinity of the minefield. The damage caused by naval mines to U.S. assets is well documented. The USS SAMUEL B. ROBERTS (FFG-59), USS TRIPOLI (LPH-10) and USS PRINCETON (CG-59) all struck mines and received severe damage. The costs to repair the SAMUEL B. ROBERTS and the PRINCETON totaled over $125 million, not to mention the loss of human life. This staggering figure compared to the cost of the mines that caused the damage highlights the cost effectiveness of mines. Most recently, during Operation Iraqi Freedom in March of 2003, three tugboats were stopped just south of the Iraqi port city of Umm Qasr. The vessels were acting suspiciously, and were found to be carrying 70 mines of different types. The tug boats and the barge they were towing were altered so that mines could be deployed through the hull to avoid detection. Some of the mines were moored mines that detonate on contact, and some were bottom influence mines that are detonated by a ship’s magnetic or acoustic signature.

Figure 1. U.S. troops inspecting mines found aboard Iraqi tug boats.

In the reverberation limiting acoustic environment of the littoral regions of the world (water depths less than 100 meters), mine detection can prove to be quite difficult. As proximity of the mine to the bottom increases, probability of detection decreases due to complex bathymetry and diverse sediment types. Further complicating the issue are “bottom boundary layers”, sometimes called “nepheloid layers” or “suspended sediment layers”. These layers consist of suspended sediments that occupy the lower water column, sometimes up to 10 m., and lasting for several weeks. Their effects on acoustic detection are undeniable. Bottom boundary layers can make a mine undetectable and increase the threat to personnel and equipment. Understanding exactly what the acoustic effects of bottom boundary layers are can lead to the development of acoustic sensors that can see through to the sea floor and aid in the detection of the potential hazards that lie within.

In this thesis, the effects of a suspended bottom sediment layer on high frequency acoustic imagery is studied using the Navy’s Comprehensive Acoustic Simulation System with the Gaussian Ray Bundle (CASS/GRAB). A side scan sonar image of a mine-like object on a silty clay bottom has been obtained along with the sound velocity profile and all bathymetric data corresponding to the image.

The CASS/GRAB model is run with the appropriate input file that incorporates the sound velocity profile, bottom type and bathymetric data and the scattering characteristics of a mine-like object. The bottom synthetic reverberation field calculated using CASS/GRAB is taken as the bottom reverberation as well as the echoes from the mine-like object. The volume scattering strength is used to model the reverberation caused by the suspended sediment boundary layer. The CASS/GRAB is run repeatedly while changing the value of the volume scattering strength until the modeled mine-like object disappears, which leads to a critical value representing the occurrence of the bottom suspended sediment layer, rendering the mine-like object undetectable. The critical values of volume scattering strength are then taken as a metric of the acoustic impact of the suspended bottom sediment layer.

The remainder of the thesis is organized as follows: Chapter II discusses the effects that suspended sediment has on acoustic propagation. Chapters III and IV describe the CASS/GRAB model and the input files that are required to run the model effectively. Chapters V, VI, and VII discuss the results of this work.

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# II. WORKING HYPOTHESIS AND PROCEDURE

## A. SUSPENDED SEDIMENT AND VOLUME REVERBERATION

One version of the active sonar equation, where there is zero signal excess, is given by

$$SL - 2TL + TS = RL + DT \qquad (1)$$

where SL represents the source level of the sonar, TL represents transmission loss, TS represents target strength, RL represents reverberation level and DT is the detection threshold of the sonar. Since no ambient noise information was available, the ambient noise level is assumed to be negligible. Transmission loss is multiplied by 2 because the radiated sound has to strike the target and then return, essentially making a round trip. In the detection of an object in the water, the source level and target strength must be large enough to overcome the losses of energy to transmission loss, the interference due to the reverberation, the ability of the sonar processor to enhance the signal-to-noise ratio and the ability of the operator to recognize objects.

Transmission loss is due to spreading and attenuation, and is a result of acoustic energy traveling through water (and possibly the ocean bottom) and reflecting from the ocean bottom and surface. There are three types of reverberation; volume reverberation, sea-surface reverberation and bottom reverberation. The most important factor that determines reverberation is scattering strength. (Urick, 1983) Scattering is the reflection of emitted sound from material in the water column, ocean bottom and ocean surface. The mechanisms that cause scattering can be biological, chemical or physical. The governing equation for volume scattering is:

$$S_v = 10\log\frac{I_{scat}}{I_{inc}} \qquad (2)$$

where $S_v$ represents the scattering coefficient, in decibels, $I_{scat}$ represents the scattered intensity of the sound by the unit volume, and $I_{inc}$ represents the incident intensity of the sound. When there are particles suspended in the water column, the scattering also depends on the size and shape of the scatterers. In this work, the particles were assumed to be spherical which yields:

$$S_v = 10\log\frac{m_v}{4\pi} \qquad (3)$$

where $S_v$ still represents the scattering coefficient and $m_v$ represents the backscattering cross section of a unit volume. The sum of all scattered energy in a region is defined as the reverberation (Urick, 1983). Not only does the size and shape of scatterers affect the reverberation, but the concentration of scatterers is also very important. The more scatterers there are in a unit volume, the more scattering will occur.

Volume reverberation is a function of the physical properties of the water column including any sediment, or biological material that may be suspended there. In a suspended bottom sediment layer, large quantities of sediment remain in the water column for up to several weeks. This layer significantly affects the acoustic characteristics of the water that it is suspended in. The thicker and denser a suspended sediment layer becomes, the harder it would be for a sonar to penetrate the layer. Another possible impact of a suspended bottom sediment layer would be changes in the temperature, density or salinity of the lower water column. These quantities would in turn alter the sound velocity profile and might prevent acoustic energy from reaching a possible mine. The focus of this work is on the effects of a suspended sediment layer on the volume scattering strength component of reverberation.

## B. PROCEDURE TO SIMULATE SUSPENDED SEDIMENT LAYER

The working hypothesis of this thesis is “the acoustic impact of a suspended sediment layer can be represented by high values of volume scattering in the lower water column”. Using an actual side-scan sonar image as a reference, an acoustic image can be created using CASS and the bottom can be effectively “stirred-up” to create a suspended sediment layer that did not previously exist in the image. The properties of this simulated layer can then be changed so the impact of the layer can be determined.

Figure 2 shows a representation of the procedure that was followed to recreate a side-scan sonar image using CASS. The bathymetry and sound velocity profile inputs to CASS were taken directly from the side-scan sonar image. Other inputs, including surface/bottom parameters and volume scattering were modeled to reflect real world conditions.

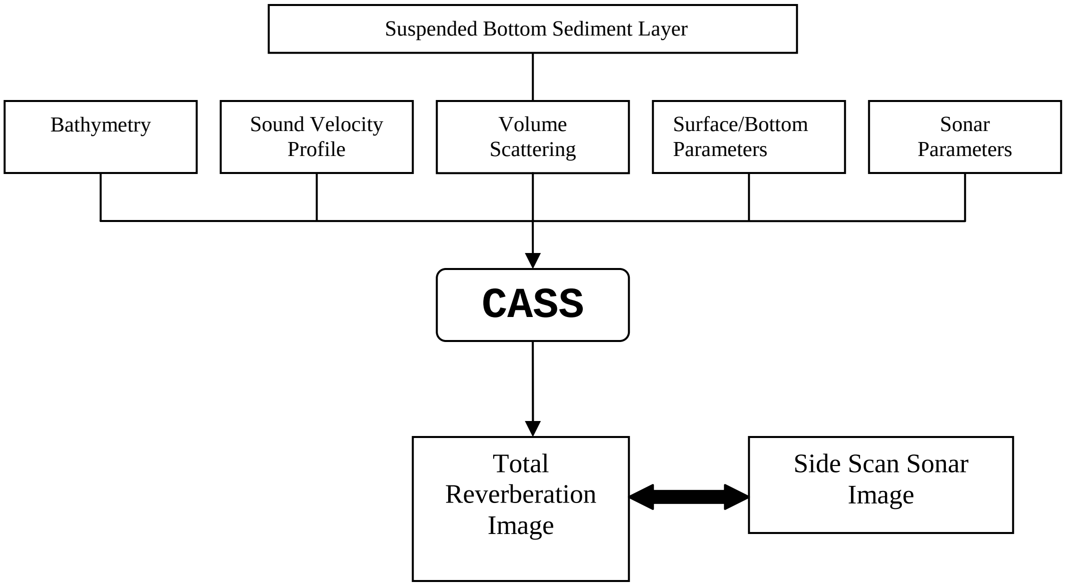

Figure 2. Steps taken to create a total reverberation image from CASS, compared to the side scan sonar image.

The total reverberation image is compared to the side-scan sonar image for accuracy before the suspended bottom sediment layer is inserted. Once a good comparison has been made, the volume scattering in the lower water column is increased to reflect the presence of the suspended sediment layer.

Figure 3 shows the decision making process that was used to determine if the chosen values of volume scattering were adequate. If the simulated mine object is still visible after increasing the volume scattering, then the simulated sediment layer is not strong enough to represent a layer that would hide a mine from a sonar. So the volume scattering was increased further. This procedure was performed several times until the mine object was no longer visible.

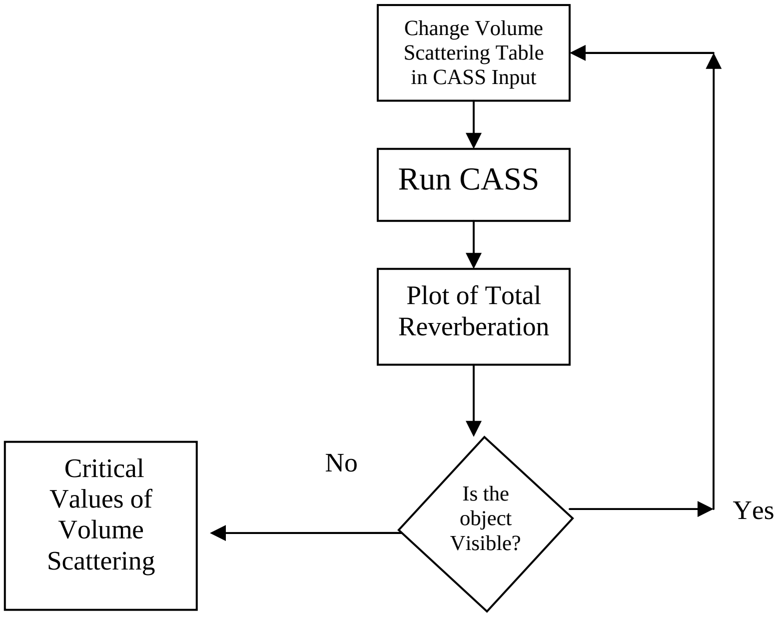

Figure 3. Procedure to determine whether object is obscured by suspended sediment layer

# III. COMPREHENSIVE ACOUSTIC SIMULATION SYSTEM/ GAUSSIAN RAY ACOUSTIC BUNDLE

## A. CASS MODEL FUNDAMENTALS

CASS/GRAB is one of the Navy's range-dependent propagation, reverberation, and signal excess acoustic models that can be used in both the active and passive sonar equations. The CASS model acts as the outer shell that computes range-independent monostatic and bistatic active signal excess calculations and calls on the GRAB subset for the computation of eigenrays and propagation loss (Figure 4).

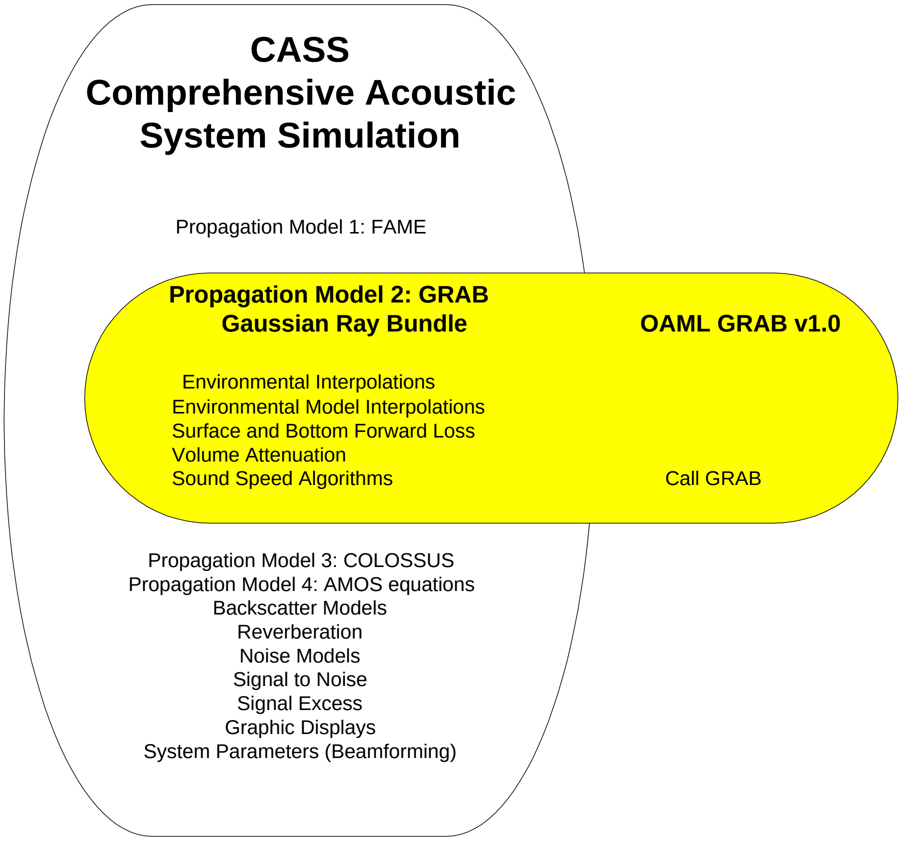

Figure 4. CASS/GRAB Overview (From Keenan et al.2000)

In the GRAB model, travel time, source angle, target angle, and phase of the ray bundles are similar to those values for a classic ray path. GRAB, however, uses ray bundles vice a ray path. This allows the amplitude of the Gaussian ray bundle to affect all depths to some degree, whereas with classic ray paths, amplitudes are local.

## B. BATCH FILE

A template for the input file that CASS requires to compute reverberation can be found in the files that come with the program. A more specific sample of the input file that was used in this work is included in Appendix A. Once created, the input file must be called “input.dat” for CASS to read it. This presented a slight problem since the bathymetric data was in 41 different “lines”. Each line represented one value of distance in the along track direction and had several values of cross track distance and depth associated with it. Hence, 41 different input files were created named “input1.dat” through “input41.dat”.

The output for the CASS input file is user specified. In this case, the output file was named “revout.dat” for “reverberation output”. The output file was also the same for each file and needed to be changed to something that made data retrieval more efficient.

A batch file was created that took “input1.dat” and renamed it “input.dat”. Then CASS was run on “input.dat”. The output file “revout.dat” was changed to “output1.dat”. This batch file continued to run each file until all 41 input files have a corresponding output file. This batch file was useful because it allowed for multiple runs of CASS with varying input files in a relatively short amount of time.

# IV. INPUT PARAMETERS

## A. ENVIRONMENTAL PARAMETERS

The environmental parameters for the CASS input file consisted primarily of data taken at the time of the side-scan sonar image. This image shows an object that, for the purposes of this work, represents a “mine-like” object. The object is assumed to be hollow steel and sits at 30 m above the lower boundary of the image and 27 meters to the left of the right boundary of the image. The extent of the image is approximately 60 meters in the y-direction and 50 meters in the x-direction. The following sections will address each part of the environmental parameters one at a time.

### 1. Bottom Depth Table

The values for the bottom depth were measured at the time the image was taken. After interpolating between adjacent values to improve the resolution, values were directly entered into the table. Values of depth ranged from 95 meters to 77 meters. A plot of bathymetry contours is included later in this work.

### 2. Sound Speed Table

The values for the sound velocity profile were also measured at the time of the image. Figure 5 shows a plot of the sound velocity vs. depth.

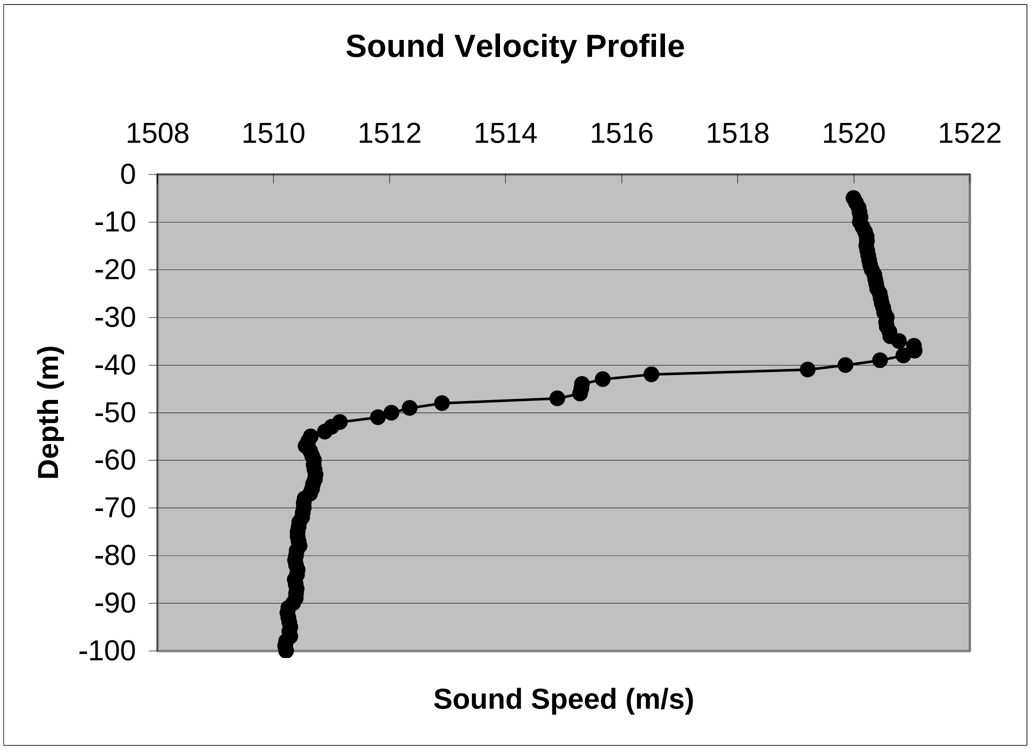

Figure 5. Sound Velocity Profile for region above“mine-like” object.

### 3. Bottom Parameters

Appendix B shows that the grain size index for a silty clay bottom is 8. APL/UW was the built-in model that was used to model bottom scattering. Bottom reflection effects were modeled using the Rayleigh scattering model.

### 4. Surface Parameters

Wind speed at the time the image was created was not recorded, so a nominal wind speed of 1 m/s was reasonable as no indication of significant winds were evidenced in the side scan image. APL/UW was the built in model that was chosen to model surface reflection and the surface scattering.

### 5. Volume Scattering Strength

For this work, the best way to model volume scattering strength was by a table that was directly entered into the input file. The water column was assumed to be relatively clear above 77 meters, with an initial suspended sediment layer characterized by a slightly stronger scattering strength below 78 meters.

VOLUME SCATTERING STRENGTH TABLE

| M | DB/M |
|---|---|
| 0.00 | -95.00 |
| 77.00 | -95.00 |
| 78.00 | -65.00 |
| 95.00 | -65.00 |

Table 1. Scattering strength table for CASS input file

#### 6. Volume Attenuation

Out of all the models available in CASS, Francois-Garrison was the model chosen for volume attenuation. This is due to the accuracy that this model handles at higher frequencies.

## B. SONAR PARAMETERS

The sonar parameters for this work were entered to reflect that of a high frequency side scan sonar at 100 kHz. The source level was 240 dB. The sonar was towed at a depth of 30.4 meters below the surface and had a pulse length of 0.001 seconds.

## C. MODEL PARAMETERS

The time increment for modeling should not exceed one half of the pulse length to achieve proper resolution of each time step. Since the total distance traveled from the sonar to the end of the image is approximately 50m, the total reverberation time is only 0.12 seconds. The maximum number of bottom and surface reflections modeled was set at 30 to allow for some interference by reflected eigenrays.

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# V. CASS REPRESENTATION OF SONAR IMAGE

The first task that was to be accomplished was to represent the side-scan sonar image (Figure 6) through reverberation output from CASS.

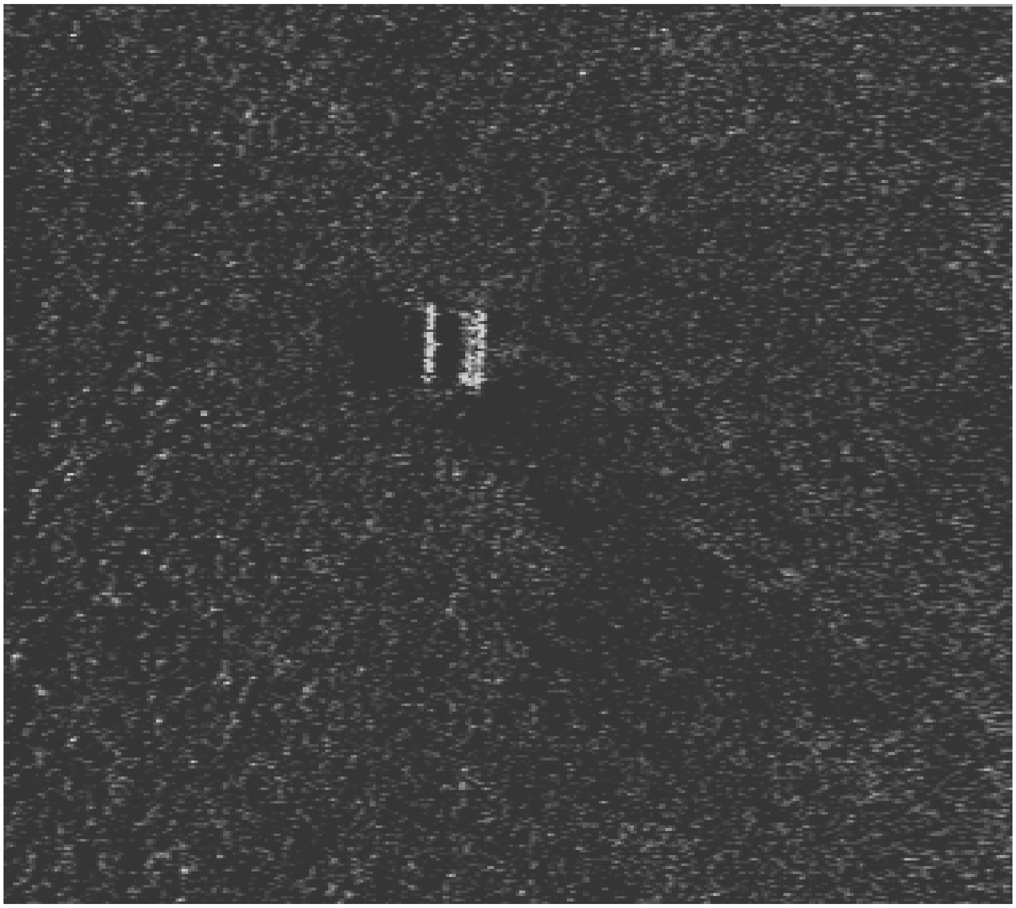

Figure 6. Klein 5000 image of "mine-like" object on silty clay bottom.

Using the input quantities from the previous section, the batch file, and a Matlab© m-file that searches through the output file and extracts the total reverberation data (Appendix C.), the following image was created that does not include the mine-like object:

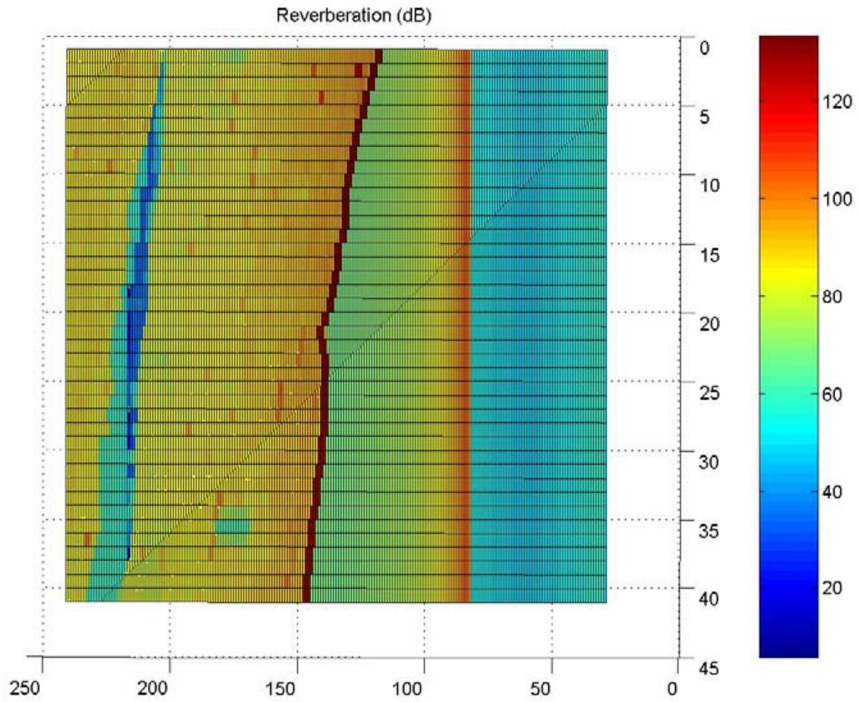

Figure 7. Reverberation plot of bottom without mine object inserted. X-axis is cross track indices represented by time and Y-axis is along track indices represented by distance.

The above plot shows that after the sound leaves the sonar, there is a brief time when no return has been received. The first blue shading is the return from volume reverberation. The first red line and the yellow field that follows is the return from the surface reverberation. The second red line is the initial return from the bottom (not unlike a fathometer). The final feature of note is the blue “trench” that appears near the far edge of the plot. This is because the sonar was located at a depth of 30.4 meters which was just above the thermocline. (Figure 5)

Now that there is an accurate depiction of the bottom, the next step is to insert the “mine-like” object. This is done in two steps. First, the bathymetry must be changed to reflect a mine that protrudes above the bottom. The water depth in the vicinity of the object is 87 meters. The size of the object in the image is 5 meters long, 3 meters wide and 2 meters high. Therefore, the depth in the vicinity of the mine will change to 85 meters. The width and length of the object will be exaggerated slightly to ensure that the object is hit with as many eigenrays as possible. (Figures 8 and 9)

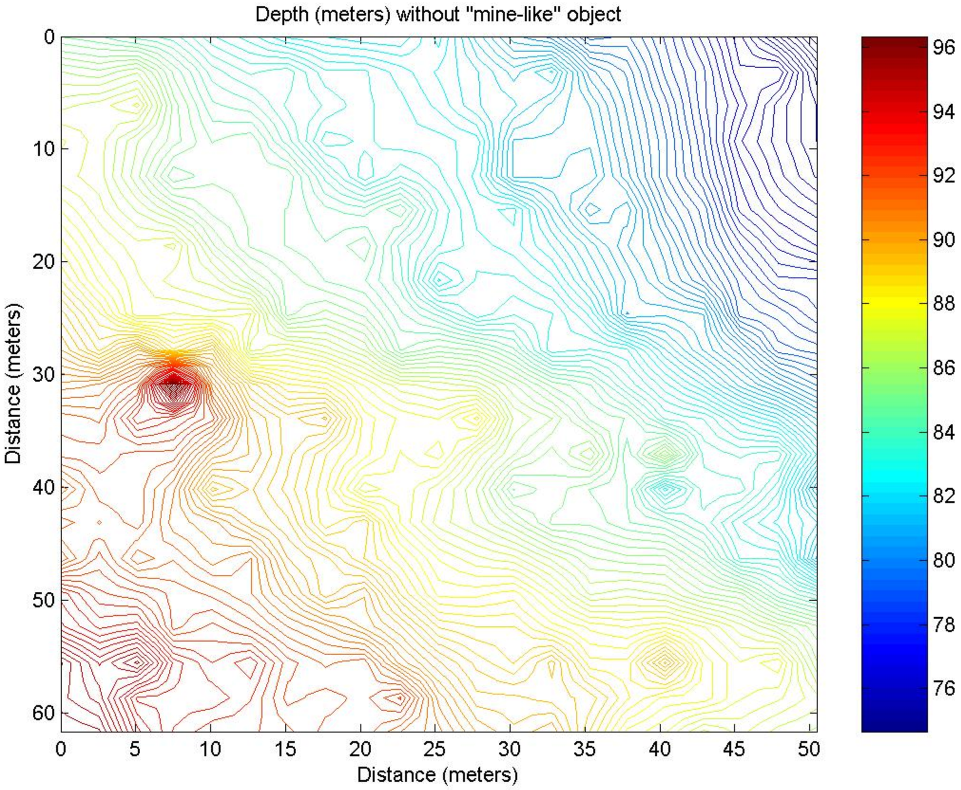

FIGURE 8. Bathymetry plot without mine object.

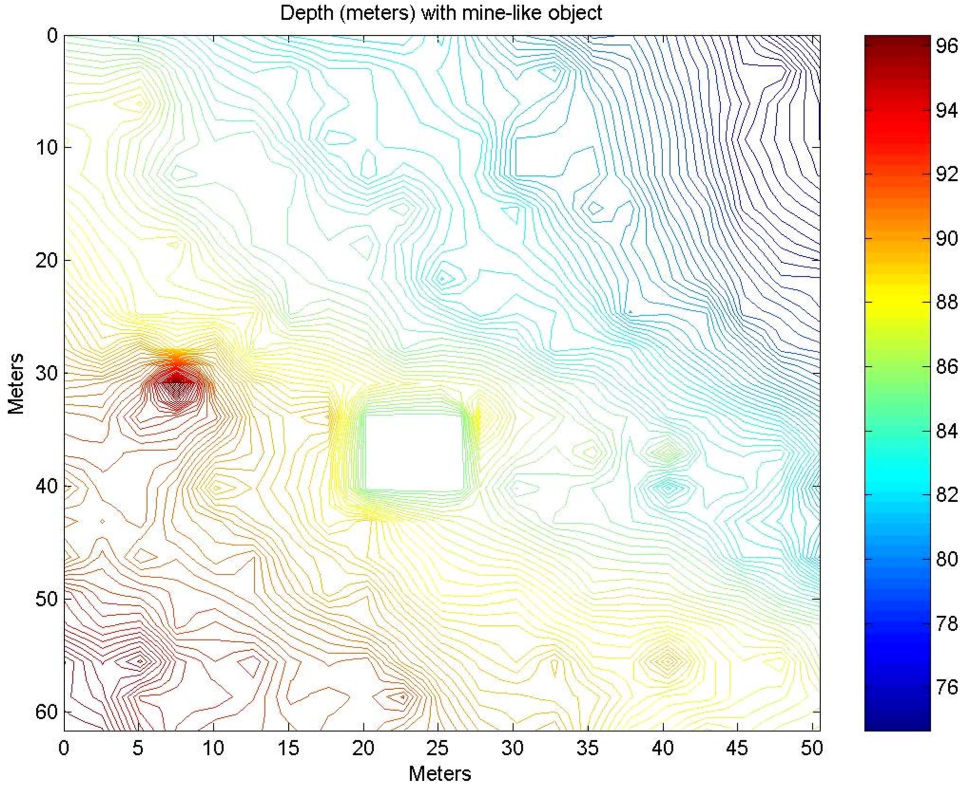

FIGURE 9. Bathymetry plot with mine object.

The second step to entering the synthetic “mine-like” object is to change the bottom parameters to reflect hollow steel instead of silty clay. This is done by means of inserting a bottom scattering strength table. (Table 1) This shows for all grazing angles, the scattering strength of the object is -1.13 dB/$m^3$. With no object inserted into the bathymetry, there was only one bottom parameter for the input file. To insert an object in the horizontal, there must be three “environments”. The first environment is the same as in the CASS run without the object. Files “output1” through “output17” cover this regime. The second “environment” is from files “output17” thorough “output22”. This corresponds to an object that is roughly 8 meters long in the y-direction. In the x-direction, the altered bottom scattering values occupy values from 27.8 meters to 32.8 meters, producing an image that is 5 meters wide. The original object was 5 meters long by 3 meters wide. This simulated image is slightly larger, but still representative of the original.

Now, CASS is run again with the altered files. The following image is the product of this attempt:

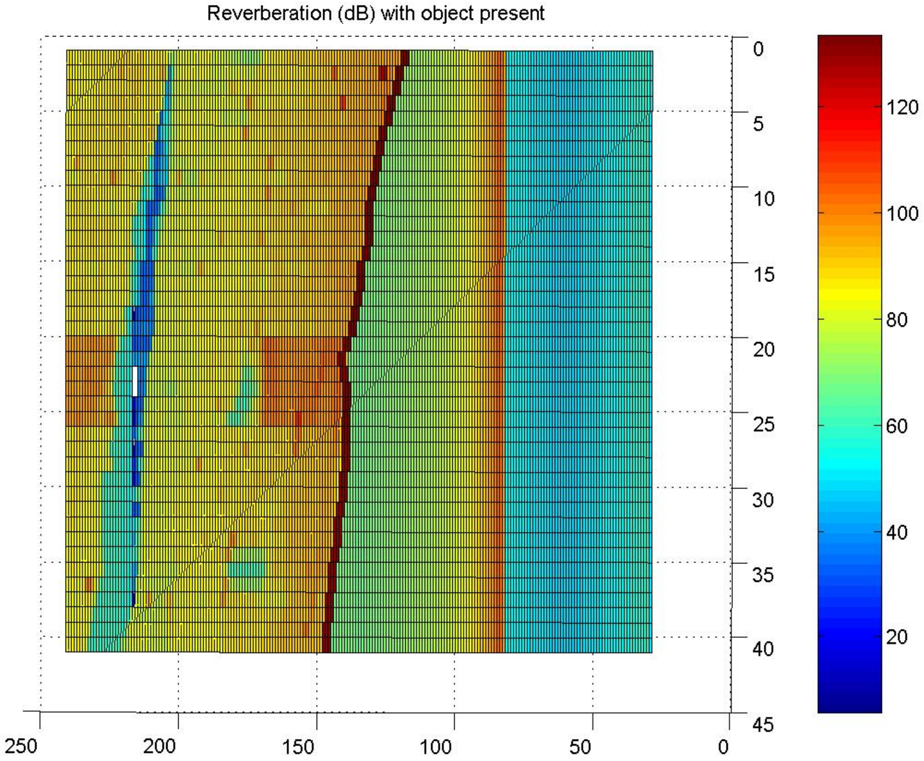

FIGURE 10. Reverberation plot of bottom with mine object inserted. X-axis is cross track indices represented by time and Y-axis is along track indices represented by distance

Clearly, the object is visible in the reverberation imagery. It is located at x-cooordinate 150, y-coordinate 23.  All of features that were in the image without the mine are still present, but now the object itself and even an echo from the object are visible. The echo is the orange shaded area located near the left edge of Figure 10. The value of this image is that now there exists a synthetic replica of a real image that inputs that can be changed to examine the effects of various parameters.

# VI. ACOUSTIC IMPACT OF SUSPENDED SEDIMENT LAYER

As shown in the input parameters section, the volume scattering table showed a slightly elevated scattering value for the depths below 78 meters (Table 1). This elevation was part of a typical volume scattering profile. Sediment in the water column would increase the volume scattering and ultimately the volume reverberation. Since the simulated side-scan sonar image with an object inserted has inputs that can be changed, a critical value can be determined as to how much volume scattering in a simulated suspended bottom sediment layer will render the “mine-like” object undetectable. Volume attenuation and changes in the sound velocity profile will also have an effect, but they are not addressed in this work.

Starting with the input files that had the object in place, the initial value of -65 dB/m$^3$ was changed to -60 dB/m$^3$. After plotting the output, little change was noted. For the next attempt, the volume scattering was changed to -50 dB/m$^3$. Changes to the plot began to appear. The reverberation values around the object, in the vicinity of where the bottom reverberation appeared before, were increasing. This was significant progress, but the object was still visible. Several more attempts were made until at -30 dB/m$^3$, the object was almost gone. (Figure 11)

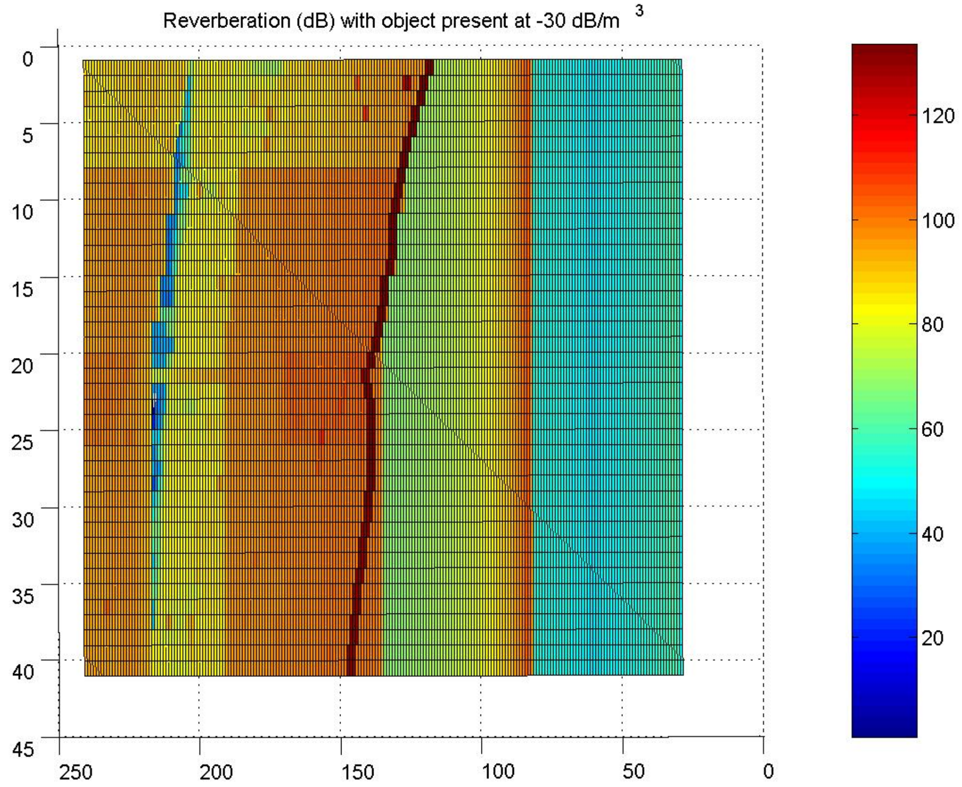

FIGURE 11. Reverberation plot of bottom with mine object inserted. X-axis is cross track indices represented by time and Y-axis is along track indices represented by distance with mine object inserted and suspended sediment layer with -30 dB/$m^3$ volume scattering strength.

The object is still visible in Figure 11, but it is beginning to approach that threshold where mine detection equipment might not be able to distinguish the object from the surrounding bathymetry. Still, the goal of the experiment was to find the values of volume scattering that rendered the object undetectable. Next, volume scattering values were changed and 1 dB/$m^3$ intervals until finally at -22 dB/$m^3$, the object was completely obscured by the suspended sediment layer. (Figure 12)

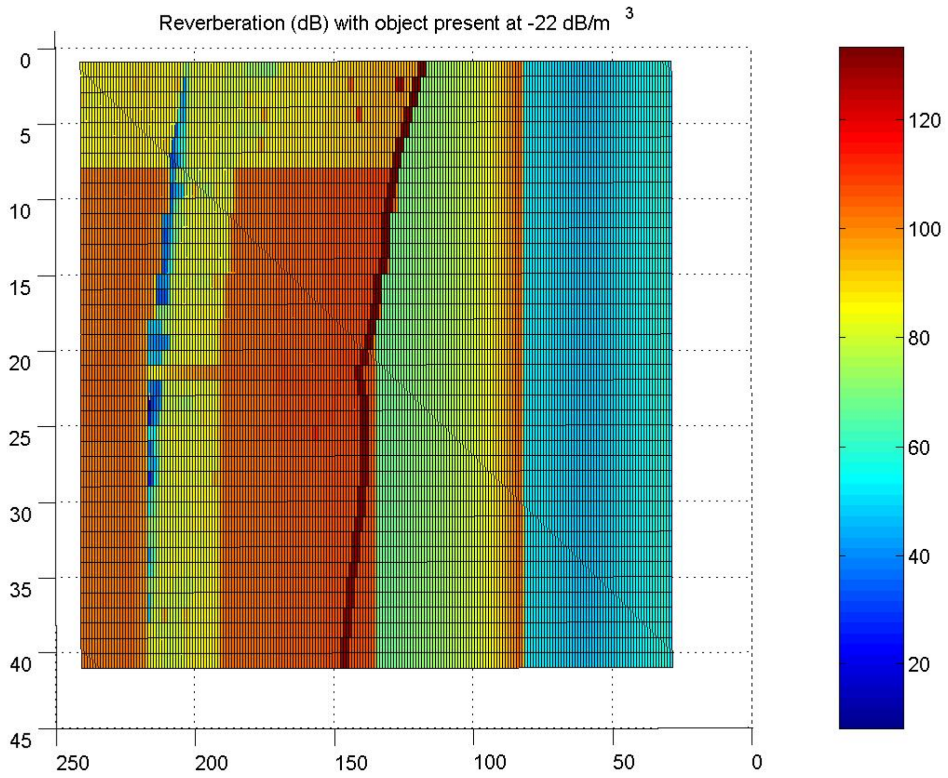

FIGURE 12. Reverberation plot of bottom with mine object inserted. X-axis is cross track indices represented by time and Y-axis is along track indices represented by distance with mine object inserted and suspended sediment layer with -22 dB/m$^3$ volume scattering strength

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# VII. CONCLUSIONS

It has been shown that the CASS/GRAB model can be used to create a side scan sonar image by mapping the modeled reverberation and that a synthetic mine-like object can be inserted into the input file to reflect a real object. Also, for this particular instance, volume scattering values of -30 dB/m$^3$ to -22 dB/m$^3$ render the object acoustically undetectable. These values are specific to this case only and do not represent universal values. The results of this study must also be tempered with the knowledge that changes in volume attenuation and sound speed, corresponding to the change in volume scattering, were not included.

This research was valuable because it provides a product that can model the effects of a suspended sediment layer on side scan sonar imagery. Given the appropriate inputs, this product can provide results for a tactically significant issue for the mine warfare community. While the development of this product is significant, several shortfalls remain. First, the process by which the environment and the object are modeled is cumbersome. Second, the appropriate volume attenuation and sound speed must also be used with into this product. Follow-on efforts should provide solutions to the two issues listed above. Equally (or more important) is a thorough study of the relationship between the suspended sediment layer density and type (e.g., sand, silt or clay), particle density in the layer, associated volume scattering and attenuation, and changes in the sound speed profile.

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# APPENDIX A. CASS/GRAB MODEL INPUT CARD FOR IMAGE WITHOUT MINE-LIKE OBJECT OR SUSPENDED SEDIMENT LAYER

```
  ------------------------------
  Direct Output
  ------------------------------

OUTPUT FILE = REVOUT
RESET OUTPUT DEVICE

VERTICAL ANGLE MINIMUM = 0 DEG
VERTICAL ANGLE MAXIMUM = 90 DEG
VERTICAL ANGLE INCREMENT = 1 DEG

  ------------------------------
  Frequency
  ------------------------------

FREQUENCY MINIMUM =  100000.00 HZ
FREQUENCY MAXIMUM =  100000.00 HZ
BANDWIDTH TABLE =        1.00 HZ

  ------------------------------
  BATHYMETRY
  ------------------------------

BOTTOM DEPTH TABLE
M        M        M
 0        0      84.94
 1.284     0       85.5
 2.568     0       86.06
 3.852     0       86.34
```

| | | |
|---|---|---|
| 5.136 | 0 | 86.62 |
| 6.345 | 0 | 86.905 |
| 7.554 | 0 | 87.19 |
| 8.838 | 0 | 87.095 |
| 10.122 | 0 | 87 |
| 11.406 | 0 | 87.28 |
| 12.691 | 0 | 87.56 |
| 13.899 | 0 | 87.845 |
| 15.105 | 0 | 88.13 |
| 16.392 | 0 | 88.41 |
| 17.676 | 0 | 88.69 |
| 18.960 | 0 | 89.065 |
| 20.245 | 0 | 89.44 |
| 21.453 | 0 | 89.72 |
| 22.662 | 0 | 90 |
| 23.946 | 0 | 90.47 |
| 25.230 | 0 | 90.94 |
| 26.515 | 0 | 91.41 |
| 27.799 | 0 | 91.88 |
| 29.008 | 0 | 91.97 |
| 30.216 | 0 | 92.06 |
| 31.500 | 0 | 91.5 |
| 32.785 | 0 | 90.94 |
| 34.069 | 0 | 91.41 |
| 35.353 | 0 | 91.88 |
| 36.562 | 0 | 91.505 |
| 37.770 | 0 | 91.13 |
| 39.055 | 0 | 92.16 |
| 40.339 | 0 | 93.19 |
| 41.623 | 0 | 93.375 |
| 42.907 | 0 | 93.56 |
| 44.116 | 0 | 94.31 |

```
45.325    0     95.06
46.609    0     94.97
47.893    0     94.88
49.177    0     95.065
50.461    0     95.25
EOT

  ------------------------------
  Sound speed Table
  ------------------------------

ENVIRONMENT X COORDINATE =   0.0 M
ENVIRONMENT Y COORDINATE =   0.0 M
SOUND SPEED TABLE
M         M/S
    0.00   1519.9981
    5.00   1519.9981
    6.00   1520.0421
    7.00   1520.0862
    8.00   1520.1026
    9.00   1520.1190
   10.00   1520.1076
   11.00   1520.1517
   12.00   1520.1958
   13.00   1520.2233
   14.00   1520.2285
   15.00   1520.2172
   16.00   1520.2336
   17.00   1520.2500
   18.00   1520.2664
   19.00   1520.2827
   20.00   1520.3103
```

| | |
|---|---|
| 21.00 | 1520.3543 |
| 22.00 | 1520.3707 |
| 23.00 | 1520.3871 |
| 24.00 | 1520.4035 |
| 25.00 | 1520.4475 |
| 26.00 | 1520.4639 |
| 27.00 | 1520.4803 |
| 28.00 | 1520.5078 |
| 29.00 | 1520.5242 |
| 30.00 | 1520.5683 |
| 31.00 | 1520.5570 |
| 32.00 | 1520.5734 |
| 33.00 | 1520.6174 |
| 34.00 | 1520.6338 |
| 35.00 | 1520.7830 |
| 36.00 | 1521.0372 |
| 37.00 | 1521.0483 |
| 38.00 | 1520.8550 |
| 39.00 | 1520.4563 |
| 40.00 | 1519.8601 |
| 41.00 | 1519.2093 |
| 42.00 | 1516.5164 |
| 43.00 | 1515.6759 |
| 44.00 | 1515.3182 |
| 45.00 | 1515.3036 |
| 46.00 | 1515.2825 |
| 47.00 | 1514.8935 |
| 48.00 | 1512.9059 |
| 49.00 | 1512.3495 |
| 50.00 | 1512.0346 |
| 51.00 | 1511.8022 |
| 52.00 | 1511.1448 |

| | |
|---|---|
| 53.00 | 1511.0015 |
| 54.00 | 1510.8884 |
| 55.00 | 1510.6417 |
| 56.00 | 1510.5972 |
| 57.00 | 1510.5563 |
| 58.00 | 1510.6303 |
| 59.00 | 1510.6662 |
| 60.00 | 1510.6980 |
| 61.00 | 1510.6953 |
| 62.00 | 1510.7117 |
| 63.00 | 1510.7281 |
| 64.00 | 1510.7139 |
| 65.00 | 1510.6805 |
| 66.00 | 1510.6662 |
| 67.00 | 1510.6327 |
| 68.00 | 1510.5377 |
| 69.00 | 1510.5234 |
| 70.00 | 1510.5206 |
| 71.00 | 1510.5063 |
| 72.00 | 1510.4919 |
| 73.00 | 1510.4467 |
| 74.00 | 1510.4324 |
| 75.00 | 1510.4180 |
| 76.00 | 1510.4151 |
| 77.00 | 1510.4316 |
| 78.00 | 1510.4480 |
| 79.00 | 1510.4027 |
| 80.00 | 1510.3883 |
| 81.00 | 1510.3739 |
| 82.00 | 1510.3903 |
| 83.00 | 1510.4183 |
| 84.00 | 1510.4039 |

| | |
|---|---|
| 85.00 | 1510.3701 |
| 86.00 | 1510.3865 |
| 87.00 | 1510.4029 |
| 88.00 | 1510.3885 |
| 89.00 | 1510.3856 |
| 90.00 | 1510.3402 |
| 91.00 | 1510.2561 |
| 92.00 | 1510.2416 |
| 93.00 | 1510.2580 |
| 94.00 | 1510.2744 |
| 95.00 | 1510.2909 |
| 96.00 | 1510.2763 |
| 97.00 | 1510.2928 |
| 98.00 | 1510.2163 |
| 99.00 | 1510.2017 |
| 100.00 | 1510.2182 |
| 101.00 | 1510.2036 |
| 102.00 | 1510.1890 |
| 103.00 | 1510.2054 |
| 104.00 | 1510.1599 |
| 105.00 | 1509.9590 |
| 106.00 | 1509.7888 |
| 107.00 | 1509.6496 |
| 108.00 | 1509.6348 |
| 109.00 | 1509.5577 |
| 110.00 | 1509.3868 |
| 111.00 | 1509.1334 |
| 112.00 | 1508.8560 |
| 113.00 | 1508.4836 |
| 114.00 | 1508.3856 |
| 115.00 | 1508.2643 |
| 116.00 | 1507.8065 |

```
  117.00   1507.4740
  118.00   1507.3517
  119.00   1507.1251
  120.00   1506.4675
  121.00   1505.7128
  122.00   1504.5219
  123.00   1498.3821
  124.00   1490.8919
  125.00   1485.0349
  126.00   1482.3583
  127.00   1480.0970
  128.00   1478.3381
EOT

  ------------------------------
  Surface Reflection Coefficient
  ------------------------------

WIND SPEED =   2.00 KNOTS
SURFACE REFLECTION COEFFICIENT MODEL = APL/UW
FUNCTION SYMBOL = SRF_RFL
FUNCTION UNIT = DB
PRINT FUNCTION VS VERTICAL ANGLE

  ------------------------------
  Volume Attenuation
  ------------------------------

VOLUME ATTENUATION MODEL = FRANCOIS
FUNCTION SYMBOL = VLM_ATN
FUNCTION UNIT = DB
PRINT FUNCTION VS VERTICAL ANGLE
```

```
  ------------------------------
  Surface Scattering
  ------------------------------

SURFACE SCATTERING STRENGTH MODEL = APL/UW
FUNCTION SYMBOL = SRF_STR
FUNCTION UNIT = DB
PRINT FUNCTION VS VERTICAL ANGLE


  ------------------------------
  Volume Scattering
  ------------------------------


VOLUME SCATTERING STRENGTH TABLE
M        DB//M
    0.00    -95.00
   77.00    -95.00
   78.00    -65.00
   95.00    -65.00
EOT
  ------------------------------
  Bottom Parameters
  ------------------------------

BOTTOM SEDIMENT GRAIN SIZE INDEX =  8
BOTTOM SCATTERING STRENGTH MODEL = APL/UW
FUNCTION SYMBOL = BTM_RFL
FUNCTION UNIT = DB
PRINT FUNCTION VS VERTICAL ANGLE
BOTTOM REFLECTION COEFFICIENT MODEL = RAYLEIGH
```

```
FUNCTION SYMBOL = BTM_STR
FUNCTION UNIT = DB
PRINT FUNCTION VS VERTICAL ANGLE

  ------------------------------
  Source parameters
  ------------------------------

SOURCE LEVEL TABLE = 240.00 DB
PULSE LENGTH =  0.001 S
TRANSMITTER DEPTH =  30.4 M
SOURCE DEPTH =       30.4 M

  ------------------------------
  Transmitter Beam Pattern
  ------------------------------

TRUE TRANSMITTER BEARING = 0 DEG
TRUE TRANSMITTER HEADING = 0 DEG
TRANSMITTER HORIZONTAL BEAMWIDTH MODEL = TABLE
TRANSMITTER HORIZONTAL BEAMWIDTH TABLE
KHZ       DEG
  100.00     .15
EOT
TRANSMITTER BEAM PATTERN MODEL = TABLE
TRANSMITTER BEAM PATTERN TABLE
DEG       DB
     -90.0   -900.00
     -86.0   -900.00
     -85.0    -20.00
     -28.0    -20.00
     -12.0      0.00
```

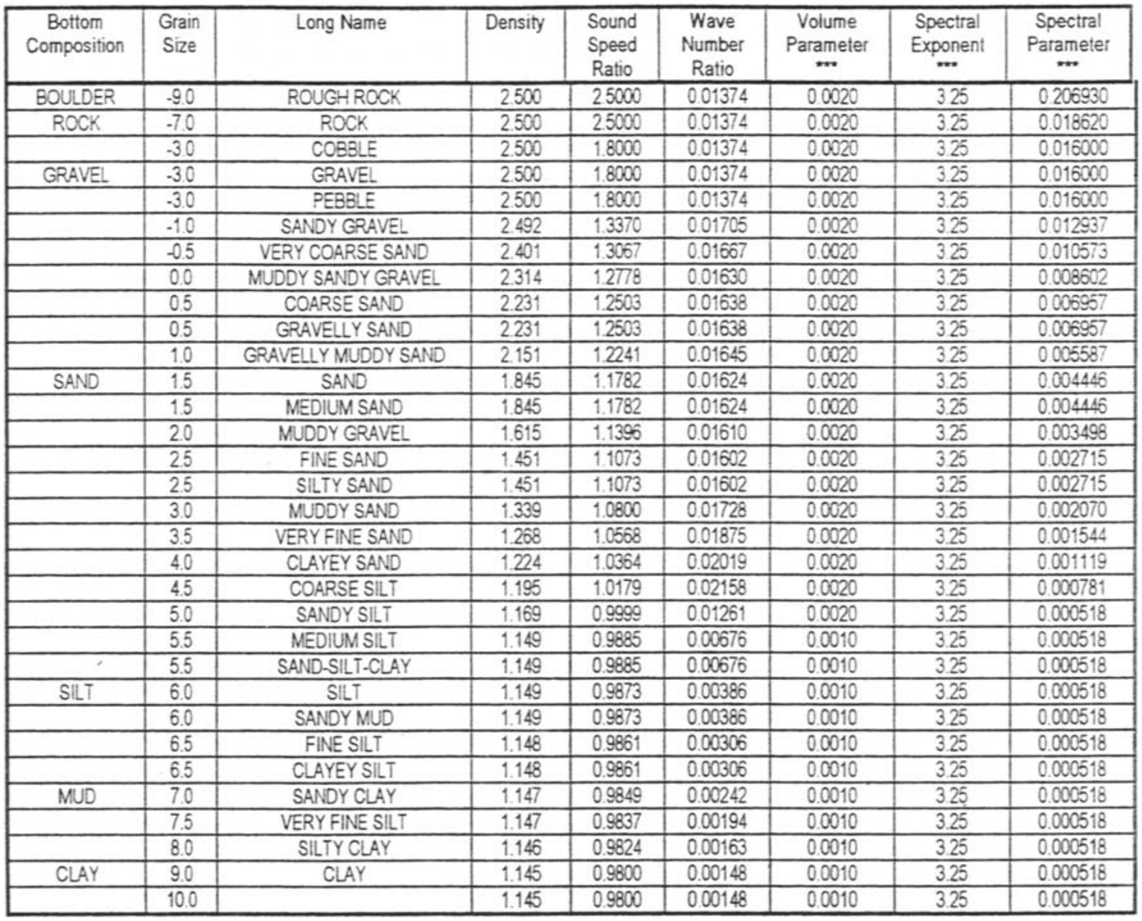
```
     4.0      0.00
    20.0      0.00
    36.0    -20.00
    90.0    -20.00
EOT

  -----------------------------
  Receiver Beam Pattern
  -----------------------------

BEARING ANGLE MINIMUM = 0 DEG
BEARING ANGLE MAXIMUM = 0 DEG
BEARING ANGLE INCREMENT = 1.0 DEG
RECEIVER HORIZONTAL BEAMWIDTH MODEL = TABLE
RECEIVER HORIZONTAL BEAMWIDTH TABLE
KHZ       DEG
   100.00     .15
EOT
RECEIVER BEAM PATTERN MODEL = TABLE
RECEIVER BEAM PATTERN TABLE
DEG       DB
   -90.0   -900.00
   -82.0   -900.00
   -81.0    -20.00
     0.0    -20.00
     1.0      0.00
    15.0      0.00
    16.0    -20.00
    90.0    -20.00
EOT

  -----------------------------
```

```
  Model and Run Parameters
  ------------------------------

EIGENRAY MODEL = GRAB
MAXIMUM BOTTOM REFLECTIONS = 30
MAXIMUM SURFACE REFLECTIONS = 30
TIME MINIMUM =       0.0 S
TIME MAXIMUM =       .12 S
TIME INCREMENT =     0.0005 S
RANGE MINIMUM =      0.0 M
RANGE MAXIMUM =     50.0 M
RANGE INCREMENT =    0.375 M
VERTICAL ANGLE MINIMUM   = -89 DEG
VERTICAL ANGLE MAXIMUM   =  89 DEG
VERTICAL ANGLE INCREMENT =   .1 DEG
ACTIVE MODE = MONOSTATIC

  ------------------------------
  bottom depth eigenray section
  ------------------------------

TARGET DEPTH = BOTTOM
EIGENRAY FILE = EIGBTM
EIGENRAY ADDITION = RANDOM
COMPUTE EIGENRAYS

  ------------------------------
  surface depth eigenray section
  ------------------------------

TARGET DEPTH = SURFACE
EIGENRAY FILE = EIGSRF
```

```
EIGENRAY ADDITION = RANDOM
COMPUTE EIGENRAYS

  ------------------------------
  Target depth eigenray section
  ------------------------------

TARGET DEPTH = 20.0 M
SCATTERING LAYER THICKNESS = 40.0 M
EIGENRAY FILE = EIG001
EIGENRAY ADDITION = RANDOM
COMPUTE EIGENRAYS
TARGET DEPTH = 60.0 M
SCATTERING LAYER THICKNESS = 40.0 M
EIGENRAY FILE = EIG002
EIGENRAY ADDITION = RANDOM
COMPUTE EIGENRAYS

TARGET DEPTH = 81 M
SCATTERING LAYER THICKNESS = 15.0 M
EIGENRAY FILE = EIG003
EIGENRAY ADDITION = RANDOM
COMPUTE EIGENRAYS
  ------------------------------
  Compute Reverberation
  ------------------------------
FATHOMETER RETURN MODEL = NB
REVERBERATION MODEL = NB
RESET REVERBERATION
COMPUTE FATHOMETER RETURNS
EIGENRAY FILE = EIGSRF
COMPUTE SURFACE REVERBERATION
```

```
EIGENRAY FILE = EIGBTM
COMPUTE BOTTOM REVERBERATION
EIGENRAY FILE = EIG001
COMPUTE VOLUME REVERBERATION
EIGENRAY FILE = EIG002
COMPUTE VOLUME REVERBERATION
EIGENRAY FILE = EIG003
COMPUTE VOLUME REVERBERATION

PRINT REVERBERATION VS TIME

END
```

# APPENDIX B. BOTTOM TYPE GEO-ACOUSTIC PROPERTIES FROM NAVO (1999)



| Bottom Composition | Grain Size | Long Name | Density | Sound Speed Ratio | Wave Number Ratio | Volume Parameter *** | Spectral Exponent *** | Spectral Parameter *** |
|---|---|---|---|---|---|---|---|---|
| BOULDER | -9.0 | ROUGH ROCK | 2.500 | 2.5000 | 0.01374 | 0.0020 | 3.25 | 0.206930 |
| ROCK | -7.0 | ROCK | 2.500 | 2.5000 | 0.01374 | 0.0020 | 3.25 | 0.018620 |
|  | -3.0 | COBBLE | 2.500 | 1.8000 | 0.01374 | 0.0020 | 3.25 | 0.016000 |
| GRAVEL | -3.0 | GRAVEL | 2.500 | 1.8000 | 0.01374 | 0.0020 | 3.25 | 0.016000 |
|  | -3.0 | PEBBLE | 2.500 | 1.8000 | 0.01374 | 0.0020 | 3.25 | 0.016000 |
|  | -1.0 | SANDY GRAVEL | 2.492 | 1.3370 | 0.01705 | 0.0020 | 3.25 | 0.012937 |
|  | -0.5 | VERY COARSE SAND | 2.401 | 1.3067 | 0.01667 | 0.0020 | 3.25 | 0.010573 |
|  | 0.0 | MUDDY SANDY GRAVEL | 2.314 | 1.2778 | 0.01630 | 0.0020 | 3.25 | 0.008602 |
|  | 0.5 | COARSE SAND | 2.231 | 1.2503 | 0.01638 | 0.0020 | 3.25 | 0.006957 |
|  | 0.5 | GRAVELLY SAND | 2.231 | 1.2503 | 0.01638 | 0.0020 | 3.25 | 0.006957 |
|  | 1.0 | GRAVELLY MUDDY SAND | 2.151 | 1.2241 | 0.01645 | 0.0020 | 3.25 | 0.005587 |
| SAND | 1.5 | SAND | 1.845 | 1.1782 | 0.01624 | 0.0020 | 3.25 | 0.004446 |
|  | 1.5 | MEDIUM SAND | 1.845 | 1.1782 | 0.01624 | 0.0020 | 3.25 | 0.004446 |
|  | 2.0 | MUDDY GRAVEL | 1.615 | 1.1396 | 0.01610 | 0.0020 | 3.25 | 0.003498 |
|  | 2.5 | FINE SAND | 1.451 | 1.1073 | 0.01602 | 0.0020 | 3.25 | 0.002715 |
|  | 2.5 | SILTY SAND | 1.451 | 1.1073 | 0.01602 | 0.0020 | 3.25 | 0.002715 |
|  | 3.0 | MUDDY SAND | 1.339 | 1.0800 | 0.01728 | 0.0020 | 3.25 | 0.002070 |
|  | 3.5 | VERY FINE SAND | 1.268 | 1.0568 | 0.01875 | 0.0020 | 3.25 | 0.001544 |
|  | 4.0 | CLAYEY SAND | 1.224 | 1.0364 | 0.02019 | 0.0020 | 3.25 | 0.001119 |
|  | 4.5 | COARSE SILT | 1.195 | 1.0179 | 0.02158 | 0.0020 | 3.25 | 0.000781 |
|  | 5.0 | SANDY SILT | 1.169 | 0.9999 | 0.01261 | 0.0020 | 3.25 | 0.000518 |
|  | 5.5 | MEDIUM SILT | 1.149 | 0.9885 | 0.00676 | 0.0010 | 3.25 | 0.000518 |
|  | 5.5 | SAND-SILT-CLAY | 1.149 | 0.9885 | 0.00676 | 0.0010 | 3.25 | 0.000518 |
| SILT | 6.0 | SILT | 1.149 | 0.9873 | 0.00386 | 0.0010 | 3.25 | 0.000518 |
|  | 6.0 | SANDY MUD | 1.149 | 0.9873 | 0.00386 | 0.0010 | 3.25 | 0.000518 |
|  | 6.5 | FINE SILT | 1.148 | 0.9861 | 0.00306 | 0.0010 | 3.25 | 0.000518 |
|  | 6.5 | CLAYEY SILT | 1.148 | 0.9861 | 0.00306 | 0.0010 | 3.25 | 0.000518 |
| MUD | 7.0 | SANDY CLAY | 1.147 | 0.9849 | 0.00242 | 0.0010 | 3.25 | 0.000518 |
|  | 7.5 | VERY FINE SILT | 1.147 | 0.9837 | 0.00194 | 0.0010 | 3.25 | 0.000518 |
|  | 8.0 | SILTY CLAY | 1.146 | 0.9824 | 0.00163 | 0.0010 | 3.25 | 0.000518 |
| CLAY | 9.0 | CLAY | 1.145 | 0.9800 | 0.00148 | 0.0010 | 3.25 | 0.000518 |
|  | 10.0 |  | 1.145 | 0.9800 | 0.00148 | 0.0010 | 3.25 | 0.000518 |

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# APPENDIX C. MATLAB© M-FILE TO RETRIEVE REVERBERATION INFORMATION

```
% file = PlotCASSReverb_all.m
%
clear
deflow = 0.0;                    % min value is Zero
for kk = 1:41
   fname = ['output' int2str(kk) '.DAT']
   fid = fopen(fname,'r');
   %
   % Acquire reverberation data.
   %
   string = fgetl(fid);
   boogie = 1;
   while boogie == 1
      string = fgetl(fid);
      if length(string) > 25
         if string(24:25) == 'NB'
            boogie = 0;
         end
      end
   end
   string = fgetl(fid);
   string = fgetl(fid);
   string = fgetl(fid);
   string = fgetl(fid);
   for j = 1:241
      string = fgetl(fid);
      A(1,j) = str2num(string(1:12));          % Col 1 -- Time
      A(2,j) = max(deflow,str2num(string(61:72)));      % Col 6
   end
```

```
  fclose(fid);
  Atime = A(1,:);        % Min time is 1st value in row (Left)
  index = find(A(2,:) == 0);      %  Find zeros
  A(2,index) = NaN;              % replace zero with NaN
  %Atotal(kk,:)  =  A(2,:);              %Left-to-right  row  vector  with
                                        A1 in Row 1 (top of matrix)
  Atotal(42-kk,:) = A(2,:);      %Left-to-right row vector
                          with A1 in Row 41 (bottom of
                          matrix)
End
```

# LIST OF REFERENCES

Keenan, R.E., *An Introduction to GRAB Eigenrays and CASS Reverberation and Signal Excess*. Science Applications International Corporation, MA, 2000.

Naval Oceanographic Office Systems Integration Division, *Software Design Document for the Gaussian Ray Bundle (GRAB) Eigenray Propagation Model.* OAML-SDD-74. Stennis Space Cneter, MS, 1999.

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