Detection of Suspended Sediment Effect on Sidescan Sonar Imagery Using the Navy's CASS-GRAB Model

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Abstract - Sidescan sonar detects objects buried in the seafloor through generating images of ordnance such as sea-mine buried in sediments. The sonar operates by illuminating a broad swath of the seabed using a line array of acoustic projectors while acoustic backscattering from the illuminated sediment volume is measured. The effect of suspended sediment on the sonar imagery depends on the volume scattering strength of the suspended sediment layer. Understanding the acoustic characteristics of suspended sediment layer can aid the Navy in the detection of mines using the sonar imagery. This study describes a combined experimental and modeling effort on the volume scattering strength on the burial object detection. A range of critical values of volume scattering strength for the buried object detection were discovered through repeated model simulations.

I. INTRODUCTION

Acoustic detection of undersea objects is quite difficult due to uncertain environment ([1], [2], [3]). However, acoustic detection of objects buried in the seabed is even much more difficult problem than detection of objects in water. First, sediments generate high backscattering noise due to volume scattering from heterogeneity within the sediments, and create surface scattering due to the roughness of sediment–water and sediment layer interfaces. Second, the acoustic wave attenuation in sediments is much higher than in water. Acoustic shadows make the buried targets absent in the sidescan images due to diffraction around the target, transmission through the target and relatively high acoustic noise due to backscattering from sediments surrounding the target. Classification of buried targets is also more difficult since shadows do not exist and since the images do not contain much information about target shape since scattering from oblique target surfaces is not detectable. Acoustic images of buried targets primarily consist of echoes from surfaces of the target that are normal to the incident acoustic ray path. Target surfaces with an oblique aspect to the incident ray path will backscatter much less energy at the lower operating frequencies of sub-bottom profilers since the acoustic wavelength is much longer than the surface roughness of most targets of interest.

The suspended sediment layer occupies the lower water column with the thickness may reach 10 m. and last several weeks. Presence of the suspended sediment layer changes the volume scattering strength and in turn affects the acoustic detection of objects. Understanding the acoustic effects of the suspended sediment layer leads to the development of acoustic sensors that has capability to scan the sea floor and to detect the ordnance such as mines.

Effect of suspended sediment layer on the sidescan sonar imagery can be investigated experimentally and numerically. For littoral zone, pure experimental study is difficult since it is hard to measure the volume scattering strength due to temporally varying concentration of the suspended sediments; pure numerical modeling study is also not suitable since the volume scattering strength due to suspended sediments is hard to determine. Combined experimental and numerical studies are necessary as the first step towards the solving this problem. This study is the demonstration of the combined experimental and modeling studies of the acoustic detection.

II. SONAR EQUATIONS

Sonar equations provide guidelines for system design [4]. The governing equation for the case where the volume reverberation noise dominates is given by

$$SL - TL_i - TL_r + TS - RL = SNR \qquad (1)$$

where SL is the source level; TL_i is the transmission loss of the incident wave; TL_r is the transmission loss of the reflected echo; TS is target strength; RL is the

reverberation level of sediments; SNR is the signal-to-noise ratio of the sonar data. The transmission losses of the incident and reflected waves, TL_i and TL_r, account for spherical spreading, acoustic attenuation and boundary losses. The reverberation level due to volume scattering is given by

$$RL = S\,L - TL_i - TL_r + S_v + 10\log V \qquad (2)$$
where

$$V = 0.5c\tau\psi r^2 m^3 \qquad (3)$$
is the volume of sediment illuminated at an instant in time by the processed acoustic pulse, and c is the sound speed; τ is the length of the processed pulse; ψ is the effective width in steradians of the two-way system beam illuminating the sediments; r is the range from the source to the center of the scatterers. The volume scattering coefficient of the sediments, S_v, is given by

$$S_v = 10\log(I_s / I_i) \qquad (4)$$
where I_i is the intensity of the incident acoustic wave and I_s is the intensity of the signal backscattered per cubic meter of sediment, illuminated at an instant in time, measured in the farfield of the scatterers and referenced 1 m from the scattering center ([5], [6]).

The most important design criterion for the buried object scanning sonar is to maximize the SNR, the target echo to scattering noise ratio in decibels. Equations (1)–(3) show that for a target at range r, SNR is improved by reducing the beamwidth ψ and/or reducing the processed pulse length τ. The system beamwidth can be reduced by increasing array size or increasing the operating frequency. Since reverberation level is proportional to the width of the zero-phase wavelet (the processed FM pulse), and the wavelet width is inversely proportional to the sonar bandwidth, volume scattering can also be reduced by increasing sonar bandwidth. The sonar described in this paper uses an unusually wide bandwidth to minimize scattering noise.

An additional consideration for minimizing reverberation noise is the number of array elements used to construct the array. The of reflection data at the output of a discrete element array for the case of a perfectly coherent signal in perfectly incoherent noise improves with the number of elements according to dB. This rule of thumb assumes the element spacing is sufficient so that the cross correlation coefficient of the output between any two array elements is zero ([6]). We selected 32 channels in the sonar design which appeared to be a breakpoint in the tradeoff between improvement and the increased complexity and cost of the added hardware and software needed for processing additional channels.

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 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 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.

III. EXPERIMENT

A nearshore location with silty clay bottom on the Louisiana shelf was selected. Horizontal extension of the area is 50 m×60 m. Total depth including water and sediment is around 100 m. Hydrographic survey was conducted in the area [7]. The sound speed increases a little from 1520 m s^{-1} near the ocean surface to 35 m depth, and reduces drastically to 1510.5 m s-1 at 55 m depth. Below 55 m depth, the sound speed decreases slightly with depth and reaches 1510 m s^{-1} at 100 m (Fig. 1).
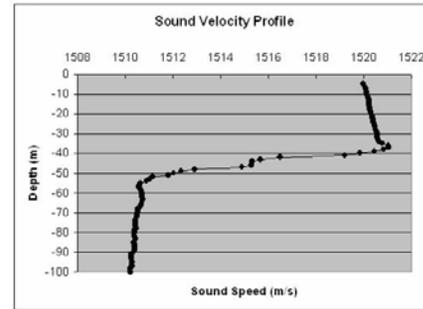

Fig. 1. Sound speed profile for region above a "mine-like" object.

The sonar parameters for this work were entered to reflect that of 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. 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 (Fig. 2). 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. The sidescan sonar develops a suitable tool for imaging buried objects, such as ordnance, cables, mines, pipelines and archeological sites. Commercial sonars such as multibeam and sidescan sonars usually have arrays oriented in the along track direction and the acoustic axis of the beams are orthogonal to the ship's track. This geometry usually prevents detection of buried objects when major target surfaces are not parallel to the ship's track; e.g., echoes from buried cylindrical objects would usually be undetectable in scattering noise unless the cylinders were oriented in the along track direction.

IV. MODELING

A. Sonra Model

Recently, a generic sonar model evolved into the Navy's Comprehensive Acoustic Simulation System (CASS) for acoustic and sonar analysis. It incorporates the Gaussian Ray Bundle (GRAB) eigenray modes to predict range- dependent acoustic propagation in the 600 Hz to 100 kHz frequency band ([8], [9]). Test rays are sorted into families of comparable numbers of turning points and boundary interactions. Ray properties are then power averaged for each ray family to produce a representative eigenray of that family. Target echo level and reverberation level are typically computed separately, subtracted to get signal-noise ratio in the absence of additive ambient noise – noise level is typically power summed with reverberation level to calculate total interference. A detection threshold is applied to compute SE, and then the peak signal is used to determine the signal/noise level (Fig. 3).
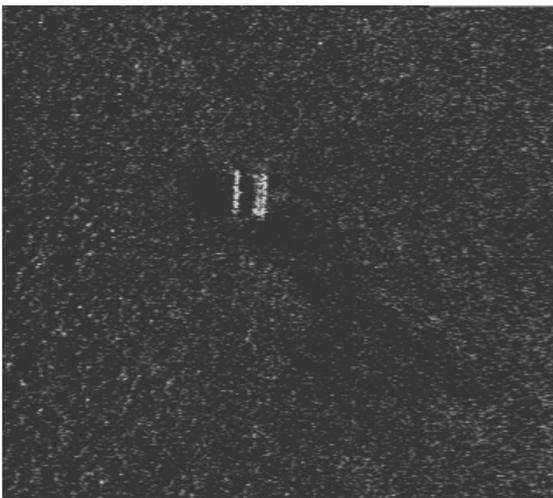
Fig. 2. Klein 5000 image of "mine-like" object on silty clay bottom.
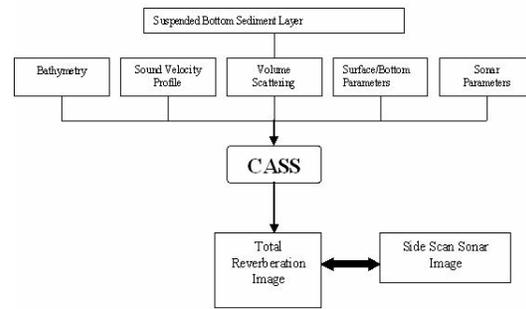
Fig. 3. Steps taken to create a total reverberation image from CASS, compared to the side scan sonar image.

CASS/GRAB simulates the sonar performance reasonably well in the littoral zone given accurate environmental input data, such as bottom type, sound speed profile and wind speed and accurate tilt angle of the sound source ([2], [3]). The CASS/GRAB has successfully modeled torpedo acoustic performance in shallow water exercises off the coast of Southern California and Cape Cod, and is currently being developed to simulate mine warfare systems performance in the fleet ([8]). Besides, the CASS/GRAB is a useful tool for the AN/SQQ-32 mine hunting detection and classification.

B. Parameters

CASS/GRAB contains sound speed conversion models such as Leroy equation [10] and Millero-Li equation [11] which is an adjustment to the original Chen-Millero [12] equation. The Wilson equation [6] for temperature-salinity-sound speed conversion is used. GRAB defaults to Leroy's equation for sound speed conversions, where numerically stable polynomials are fit to Wilson's data.

The environmental parameters for the CASS/GRAB 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.

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. The grain size index for a silty clay bottom is 8 from the Naval Oceanographic Office's standard. Bottom reflection effects were modeled using the Rayleigh scattering model.

The water column is assumed to be relatively clear above 77 m depth with a volume scattering strength of (-95 dB/m^3). An initial suspended sediment layer is present below 77 m depth characterized by a different scattering strength (-65 dB/m^3). The sonar parameters for this work were entered to reflect that of 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.

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.

V. MODEL-GENERATED SYTHETIC SONAR IMAGERY

A .Procedure

The CASS/GRAB model is integrated with the parameters of the sidescan sonar and the appropriate input file that incorporates, and SSP, bottom type, bathymetry, and the scattering characteristics. The model output of the seafloor reverberation is used to represent the model generated sonar imagery (MGSSI). 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.

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 is put at 30.4 m depth just above the thermocline (Fig. 1). There is an accurate depiction of the bottom. 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 m. The size of the object in the image is 5 m long, 3 m wide and 2 m high. Therefore, the depth in the vicinity of the mine is 85 m. The width and length of the object will be exaggerated slightly to ensure that the object is hit with as many eigenrays as possible (Figs. 4 and 5).
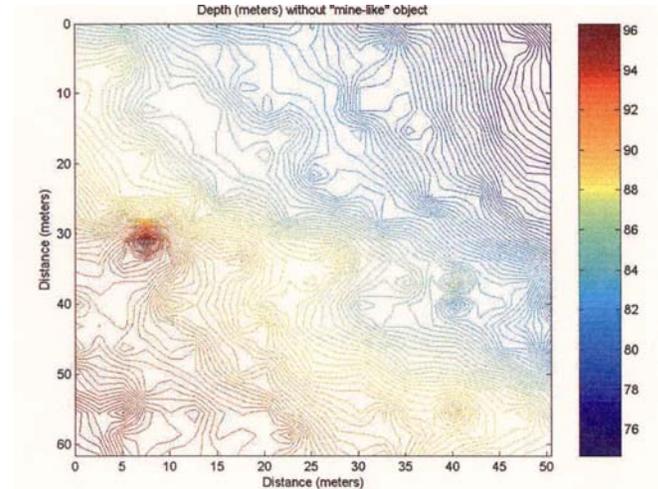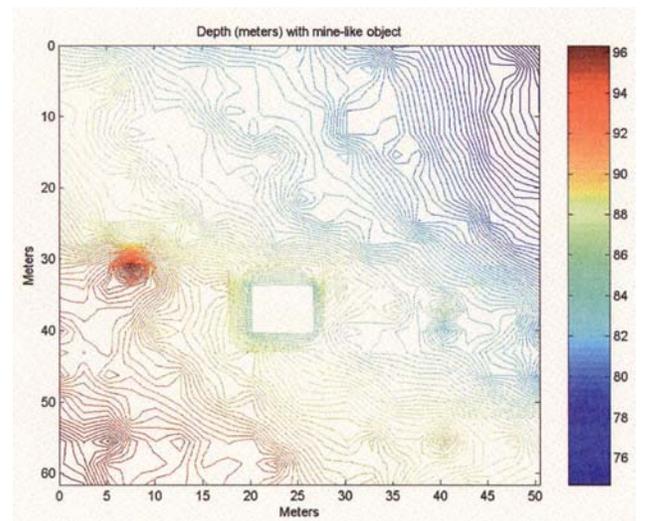

Fig.4. Bathymetry without mine-like object.

Fig. 5. Bathymetry with mine-like object.

B .Detection of Burial Object

When the synthetic "mine-like" object is inserted into the model, the bottom parameters to reflect hollow steel are used instead of silty clay. This is done by means of inserting a volume scattering strength of (-65 dB/m^3) at depths below 78 m depth. With no object inserted into the bathymetry, there is 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/GRAB run without the object. The second "environment" corresponds to an object that is roughly 8 m long in the *y*-direction (along-track). In the *x*-direction (cross-track), the altered bottom scattering values occupy values from 27.8 m to 32.8 m, producing an image that is 5 m wide. The original object is 5 m long and 3 m wide. MGSSI is slightly larger, but still representative of the original sidescan sonar imagery. Now, CASS/GRAB is run again with the altered files. The following image is the product of this attempt.

Clearly, the object is visible in the reverberation imagery. All of features that are 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 Fig. 6. The value of this image is that now there is a synthetic replica of a real image that inputs that can be changed to examine the effects of various parameters. The volume scattering strength due to suspended sediment layer is adjusted to a certain value that makes MGSSI fit the sidescan sonar imagery. This is called the modeled standard value of the 'true' volume scattering strength.

VI. EFFECT OF SEDIMENT ON SIDESCAN SONAR

Since MGSSI generated by CASS/GRAB fits the sidescan sonar imagery, the suspended sediment should have the volume scattering strength comparable to the modeled standard value. The effect of the suspended sediment on the sidescan sonar can be investigated through integrating the CASS/GRAB model with increasing the value of the volume scattering strength from the modeled standard value in the suspended sediment layer. The MGSSI changes and the object buried in the sediment is less identified. This process continues until the object is totally un-identifiable in the MGSSI. The critical values of volume scattering strength are then taken as a metric of the acoustic impact of the suspended bottom sediment layer.
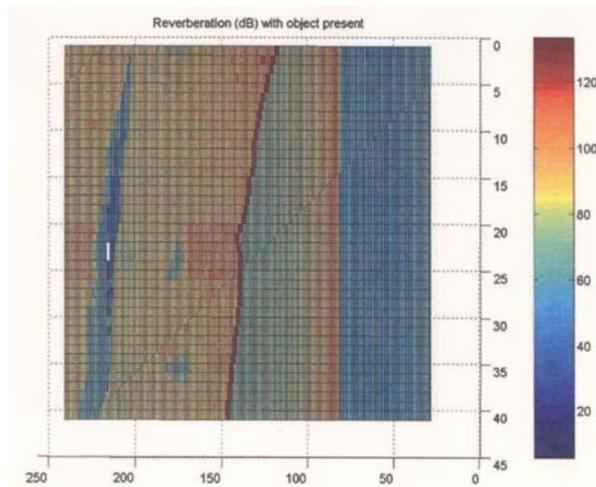

Fig. 6. Bottom reverberation with mine-like object inserted. Here, the horizontal-axis is cross track indices represented by time and the vertical-axis is along track indices represented by distance.

Fig. 7 shows the decision making process that was used to determine if the chosen values of volume scattering are 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 is increased further. This procedure was performed several times until the mine-like object is no longer visible. The water column is assumed to be relatively clear above 77 m depth, with an initial suspended sediment layer characterized by a slightly stronger scattering strength below 78 m.

Sediment in the water column would increase the volume scattering and ultimately the volume reverberation. Since MGSSI with an object inserted has changeable inputs, a critical value can be determined as to how much volume scattering strength in a simulated suspended bottom sediment layer (below 78 m depth) 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.
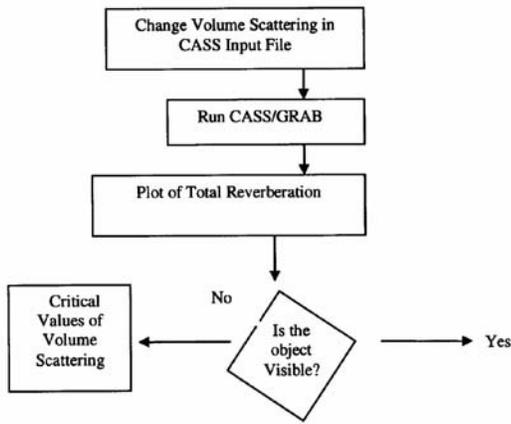
Fig. 7. Procedure to determine whether the mine-like object is obscured by suspended sediment layer.

The CASS/GRAB is integrated consecutively with all the input parameters unchanged except the volume scattering strength which is kept constant (-95 dB/m³) above 78 m depth and is increased by an increment of 5 dB/m³ from the value of -65 dB/m³ below 78 m depth. The reverberation around the object, in the vicinity of where the bottom reverberation appears, is increasing. As the volume scattering strength in the sediment layer (below 78 m depth) increases to a value of -30 dB/m³, the object becomes nearly undetectable (Fig. 8). It reaches a threshold that the mine detection equipment might not be able to distinguish the object from the surrounding bathymetry.

Still, the goal of the modeling effort is to find the criterion of the volume scattering strength that rendered the object undetectable. Thus, the CASS/GRAB modeling continues with the increase of a smaller increment of 1 dB/m³ from the value of -30 dB/m³ below 78 m depth. The mine-like object is completely obscured by the suspended sediment layer at a value of -22 dB/m³ (Fig. 9).
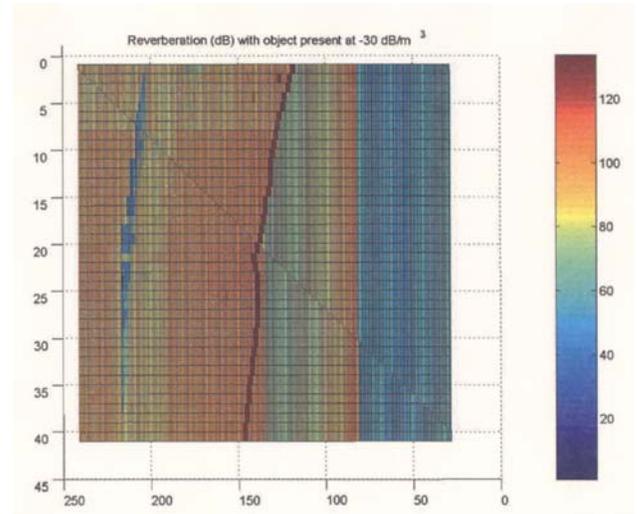

Fig. 8. Reverberation plot of bottom with mine-like object inserted. The horizontal axis is cross track indices represented by time and the vertical axis is along track indices represented by distance with mine object inserted and suspended sediment layer with -30 dB/m³ volume scattering strength.
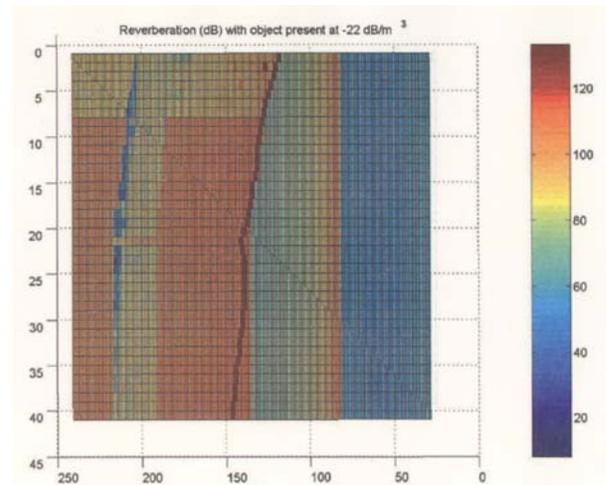

Fig. 9. Reverberation plot of bottom with mine object inserted. The horizontal axis is cross track indices represented by time and the vertical axis is along track indices represented by distance with mine object inserted and suspended sediment layer with -22 dB/m³ volume scattering strength.

VII. CONCLUSIONS

(1) A combined experiment and modeling effort is conducted to investigate the effect of suspended sediment on the burial object detection at the Louisiana shelf with water depth around 100 m and silty clay bottom. The sidescan sonar survey was conducted to detect a mine-like object buried in the sediment. Hydrographic and meteorological surveys were conducted to collect the

sound speed profile (SSP) data. The environmental data (wind and SSP) are taken as input into the Navy's CASS/GRAB to accurately simulate a side-scan sonar image with a mine-like object present through its reverberation characteristics.

(2) 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 for the buried object detection were discovered through repeated model simulations. When the volume scattering strength changes from -30 dB/m^3 to -22 dB/m^3, the buried object is acoustically undetectable. However, 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.

(3) This study shows the possibility to 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.

Acknowledgments

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