A MODEL FOR THE SIMULATION OF SIDESCAN SONAR

J.M. Bell, L.M. Linnett

Dept. of Computing and Electrical Engineering, Heriot Watt University, Riccarton, Edinburgh.

1. INTRODUCTION

The increasing demands on signal processing from sonar systems and their subsequent rise in complexity, has resulted in the requirement for the verification of such algorithms. To provide the required information, a computer-based model of the sidescan sonar process has been developed. This unique simulation model permits the pictorial visualisation of synthetic sidescan sonar images.

The simulation considers several of the deterministic variables associated with sidescan sonar and models these underlying physical processes. The main aspects investigated include :-

- seabed reverberation
- acoustic propagation
- transmission losses
- transducer directivity
- towfish motion and instabilities

Any of these effects can be considered independently or in combination, to permit the simulation of complex scenes. The simulated sidescan sonar images of these scenes are fully characterised by the input parameters describing the transducer and the environment. The model therefore provides a valuable tool for the testing and visualisation of complex processing algorithms and the isolation of the influence of individual parameters.

The aim of this paper is to provide an overview of the model and demonstrate the simulated images which can be generated to illustrate some of the above mentioned effects. The basic principles of the model will be explained prior to the discussion of the more complex features. Several of the simulated sidescan sonar images will then be presented as a comparison to real sidescan sonar data.

2. BASIC PRINCIPLES OF MODEL

The model attempts to replicate the actual process by which sidescan sonar images are created. These images are generated sequentially by emitting pulses of acoustical energy to the side of the towed sidescan device. The reflected energy returned to the transducer for each pulse is then used to create one line of the sidescan sonar image which provides a qualitative representation of the seabed.

To emulate this process, the model represents each acoustical pulse as a set of rays orthogonal to the expanding wavefronts of the emitted signal. These rays are emitted at preset angles from the transducer and their trajectories are traced until their subsequent interaction with the seabed, or any objects in the water column or on the seafloor. The energy backscattered to the transducer along an identical ray path to the incident ray is then computed.

For each ray traced two values are returned: the intensity of the returned signal and the two way travel time, or time of flight. The intensities occur at random samples in time and are not distributed evenly. These must therefore be processed to produce intensity values occurring at constant increments of time, without distorting the signal. These samples can then be displayed directly as one line of the image. The process can then be repeated iteratively to produce the subsequent lines of the sidescan sonar image.

The incorporation of the effects of the seabed reverberation, the refractive medium and the transducer characteristics into this simple model will be explained in the following sections.

3. SEABED REVERBERATION

To calculate the interaction of the acoustic energy with the seabed, a suitably complex and realistic representation of the seafloor topography and roughness is required. The simulation model employs stochastic models, based on the power spectral density, which have been observed to quantitatively characterise the seabed roughness on scales ranging from a few centimetres to several kilometres [1] [2]. This power law relationship can be characterised by the Brownian motion model, for which Mandelbrot [3] has produced a theoretical basis in terms of fractals and the fractal dimension.

The use of fractal models, which provide a good representation, both visually and statistically, of the seabed topography, permit the calculation of the interaction of the acoustic pulse with complex, yet controlled surfaces. Linnett [4] discusses the implementation of models to synthesise both isotropic and directional fractal surfaces. These fractal models are employed to generate images to represent the seabed topography for input to the simulation model.

The technique employed to calculate the intersection of the ray with the fractal seabed is similar to the technique of grid tracing developed by Musgrave for ray tracing fractal terrains in computer graphics [5] [6]. Both methods are based on the concept of height fields, where the input fractal terrain is transposed into a two dimensional grid array of altitude values which describe the surface. This technique removes any assumptions regarding flat seabeds and the seafloor can be represented as a random rough surface.

The method can also be used to simulate different seabed textures within the one image. A composite seabed image is created by defining fractal boundaries on an image, since naturally occurring boundaries do not usually occur as straight lines. Each of the segmented areas created by the boundaries are filled with different images to represent different sediment types or structures. The input image of a multi-texture seabed is illustrated as a height field in figure 1(a) and the corresponding simulated sidescan sonar image of this height field is displayed in figure 1(b). The period of no return has been removed from this image simply to permit more of the detail of the simulation to be visualised.

Procedurally defined objects can also be included to represent objects on the seabed, or in the water column. Thus, providing a general simulation model capable of synthesising many of the other applications of

Figure 1: (a) Fractal height field (b) Simulated sonar image of fractal seabed

sidescan sonar in addition to route survey.

The sonar simulation model has the ability to incorporate procedurally defined objects composed of any number of spheres and cylinders, in any orientation, within the scene. Planar objects on the seabed can also be modelled by manipulation of the input height field. The spheres and cylinders are defined using mathematical coordinates to specify their position and orientation relative to the other objects in the scene to be synthesised. More complex scenes can be constructed by the superposition of these primitives to model most of the commonly encountered underwater structures, and an example of the combination of cylinders to construct an object to represent a tethered mine is shown in figure 2(a). Figure 2(b) displays the simulated sidescan sonar image of this mine ensonified at a range of 32m, by a transducer flown at a constant height of 10m.

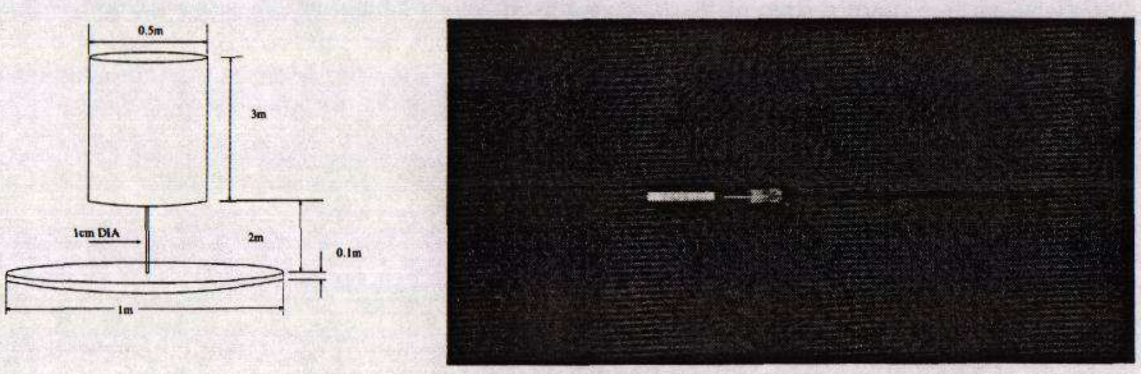

Figure 2: (a) Schematic diagram (b) Simulated sonar image of tethered mine

The simplest form of the model calculates the scattering of the acoustic energy from the random rough surfaces using a Lambertian diffuse scattering model. However the acoustic energy scattered from a rough surface is composed of a diffuse field scattered in all directions and a coherent field reflected in the specular direction. The relative magnitudes of the two fields are dependent on the surface roughness; a subjective term which in turn is dependent on the frequency and the angle of the incident energy.

The principal direction of the reflected energy tends to be in the specular direction, where the angle of reflection is equal to the angle of incidence. To model this effect, instead of effectively terminating the ray on intersection of the seabed (as described in section 2), the ray is traced in the specular direction from the point of intersection, to determine if it interacts with another part of the scene. If this specular ray does intersect an object, or another part of the seafloor, the diffuse energy from this intersection, scattered back to the transducer, will then be calculated.

A model is therefore required to determine the reverberation from a rough seabed. This model must have the capability to calculate the scattering from the seabed in any direction, as required by the sonar simulation model. Several solutions to the problem of calculating the scattering at a random rough interface have been formulated as solutions to the wave equation with the appropriate boundary conditions. The two main types of solution are the small roughness perturbation approximation and the Kirchhoff approximation [7]. Both of these techniques have limited domains of validity dependent on the approximations applied in the derivation of their solutions. The Kirchhoff and perturbation theories have been applied to several problems describing the scattering from the seabed, as has the composite roughness technique. The composite roughness technique is formed by the combination of the two techniques to account for the scattering from both large and small scale irregularities, by avoiding the shortcomings of the individual theories. Jackson [8] has developed a composite roughness model to describe the high frequency backscattering from the seabed which has found widespread application. This model, although valid over all grazing angles, cannot provide the specular reflection required by the sonar simulation model. Jackson has extended the backscatter model to calculate the bistatic scattering from the seabed [9] and the sonar simulation model applies this bistatic model developed by Jackson to the scattering problem inherent in the simulation.

The bistatic scattering model is composed of two terms to model the scattering due to the interface roughness and the scattering from volume inhomogeneities in the sediment. The output of the model is expressed in terms of the bistatic scattering strength $S_b(\theta_s, \phi_s, \theta_i)$ as stated in equation 1, where $\sigma_{br}(\theta_s, \phi_s, \theta_i)$ and $\sigma_{bv}(\theta_s, \phi_s, \theta_i)$ are the roughness and volume scattering cross sections per unit area. At the higher frequencies of interest for sidescan sonar, 10-100KHz, the acoustic penetration of the seabed is minimal and the volume scattering can be described as a surface process and quantified by the effective cross section, σ_{bv}.

$$S_b(\theta_s, \phi_s, \theta_i) = 10\log_{10}[\sigma_{br}(\theta_s, \phi_s, \theta_i) + \sigma_{bv}(\theta_s, \phi_s, \theta_i)] \quad (1)$$

4. ACOUSTIC PROPAGATION AND TRANSMISSION LOSS

The water column has two principal effects on the propagation of acoustic energy, as it influences both the direction of propagation and the losses incurred during propagation. The simulation model will apply a ray model to calculate the propagation of the acoustic energy through the water column. The principle motivation for the use of this type of model is its applicability to high frequency problems, as the sonar simulation model is typically synthesising high resolution sidescan sonars with operating frequencies of 100KHz and above. In addition, the ray model provides a simple, intuitive representation of the acoustic field which can be easily incorporated into the structure for the model.

The resulting curvature of the ray paths due to the sound velocity profile affects both of the parameters displayed in a sidescan sonar image, as it can influence both the two way travel times and the intensity values. The two way travel time, or time of return, is influenced by the actual path of the ray through the water column, which is related to the curvature of the ray within each layer. The two way travel time is also no longer directly proportional to the path length due to the variations in the velocity of propagation along the ray path. The second effect on the image is due to the alteration of the intensity values which are dependent on the grazing angles of the rays at the point of intersection and are therefore related to the curvature of the ray paths.

In addition to governing the direction of propagation, the water medium determines the loss of energy experienced by the acoustic signal as it propagates. The magnitude of the losses are particularly important in the simulation of sidescan sonar as the propagation losses must to be considered in two directions, both for the propagation of the emitted signal to the seabed and for the return propagation of the signal reflected from the seabed.

The loss of acoustic energy due to the propagation through the media is calculated in the model as the sum of the absorption and spreading losses. The absorption loss is obtained using the empirical model of Francois and Garrison [10] and the spreading loss is computed from the change in separation of the rays [11].

5. TRANSDUCER MOTION AND DIRECTIVITY CHARACTERISTICS

The simulation model incorporates the three dimensional directivity response of the transducer, which is modelled as a planar array composed of a grid of rectangular elements. The directivity response is included by applying weighting factors to the emitted rays. These rays are emitted in a three dimensional volume from the transducer for each pulse of emitted energy and not just in the plane perpendicular to the direction of travel of the transducer.

The resolution of the simulated images degrades with the inclusion of the three dimensional beam pattern and can result in the inability to distinguish two targets which are closely spaced in the along track direction. The transverse resolution also degrades with increasing range from the transducer due to the beam spreading.

As the transducer is towed through the water it is subject to translational and rotational motion instabilities which can alter the trajectory, speed and orientation of the towfish. This results in intensity and geometric distortions on the sidescan sonar images.

Within the simulation model, the motion instabilities will influence the actual position of the towfish from which the rays are traced and the orientation of the beam. This will alter the area of the seabed ensonified by each emitted pulse of acoustic energy. The model incorporates the motion of the transducer with six degrees of freedom and the effects of speed, rotational and translational distortions can be illustrated. Since the translational motion will generally result in a corresponding rotational motion, or vice-versa, it can be difficult to isolate the individual aspects of the motion. The model therefore considers the combined effects of yaw and sway and pitch and heave, although any of the motions can be considered in isolation.

The implementation of the motion characteristics within the simulation model assumes that the towfish trajectory, in three dimensional space, is read from an input file. The (x, y, z) coordinates within the file describe the position of the towfish from which each pulse of acoustic energy is emitted. The angular orientation of the towfish is obtained from the angular displacements between the consecutive points at which the signal is emitted.

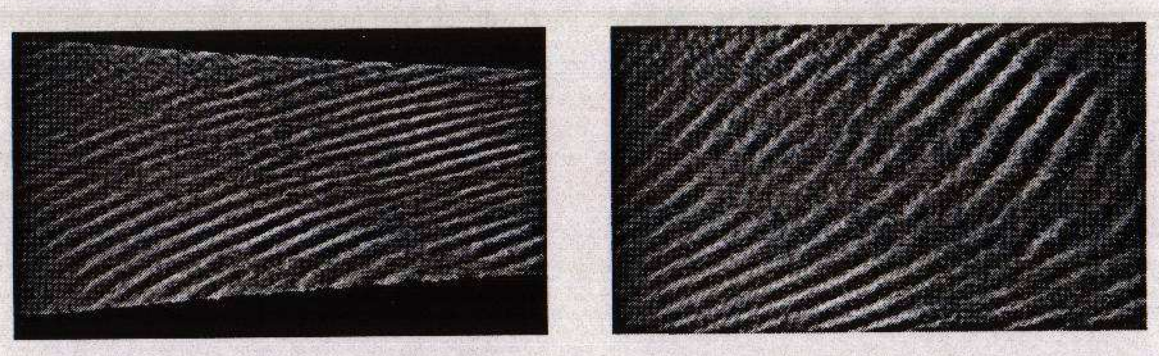

Figure 3: Simulated sidescan sonar images with towfish trajectory in (a) inward turn (b) outward turn

An example of geometric distortions introduced when the vessel turns to change the direction of survey is illustrated in figure 3, where the sonar is ensonifying sand ripples. Figure 3(a) simulates a shallow turn on the inward side of the towfish and displays the resulting compression of the sand ripples. The outward turn and resulting sweeping and expansion of the sand ripples is illustrated in figure 3(b).

6. COMPARISON OF REAL AND SIMULATED DATA

Having considered the implementation of the simulation model, the realism of the synthetic sidescan images will now be investigated. The sidescan sonar process, and the simulation model, produce qualitative representations in image form of the seabed. No closed form analytic expression exists to represent this complex process. This results in problems in testing and verifying the qualitative output of the sonar simulation model.

Sidescan sonar images can be considered as representing textures, with complex images composed of a number of regions of different textures, corresponding to different seafloor structures or sediments. The majority of image and texture analysis and processing produces subjective results where visual inspection and perception is often the most satisfactory method of testing.

Unfortunately, it was difficult to synthesise images which were visually identical to the existing sidescan sonar images, since insufficient information accompanied the real sidescan data. The quantitative input parameters required by the model cannot be derived in an inverse process from the qualitative sidescan image. Instead, only estimates of the seabed topography and typical medium characteristics and towfish characteristics can be applied. Although identical images cannot be synthesised, the correct representation of artifacts can be illustrated, and several examples will now be presented.

Sand ripples are commonly formed on the seafloor as a result of the current and tidal actions. These ripple features can produce distinctive features on sidescan sonar images. Figure 4(a) displays the sidescan sonar simulation of sand ripples, where fractals have been employed to represent the seafloor topography. Figure 4(b) displays a section of an actual sidescan sonar survey of an area of sand ripples. Similar features of highlights and shadows can be observed on both images. The images are not identical, though, as insufficient details regarding the height, composition, wavelength and shape of the ripple features on the seabed were available.

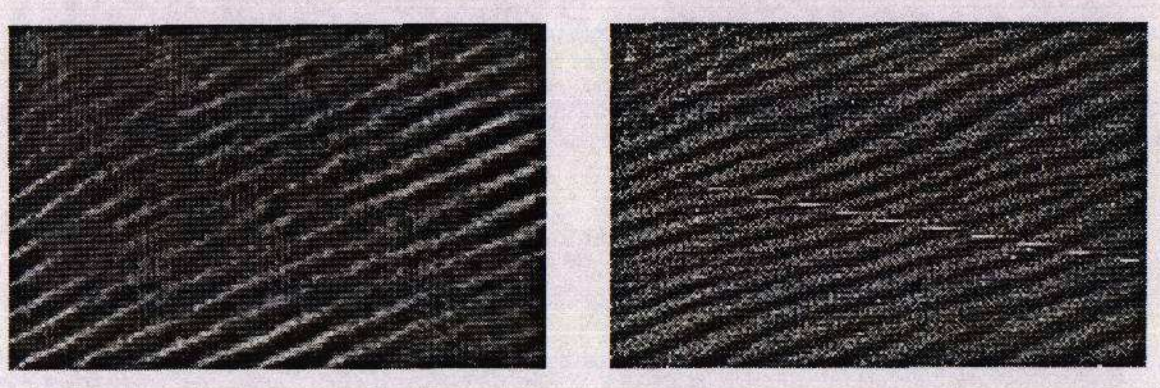

Figure 4:(a) Simulated sidescan sonar image (b) Actual sidescan image

Figure 5(a) illustrates the simulated sidescan sonar image of larger scale ripples on the seabed. At the beginning of the trace, when the towfish is directly above the area of the seabed ensonified, the ripples appear to bend, or curve, over. This is due to the slant range effects and the subsequent compression of the seabed features at close ranges. A similar effect is illustrated in figure 5(b) which represents an actual sidescan sonar trace of a sand ripple structure on the seafloor. The ripples again appear to bend at the beginning of the trace. Again, as a result of the previously described problem of insufficient data, the images of the sand ripples are not identical but do display similar features.

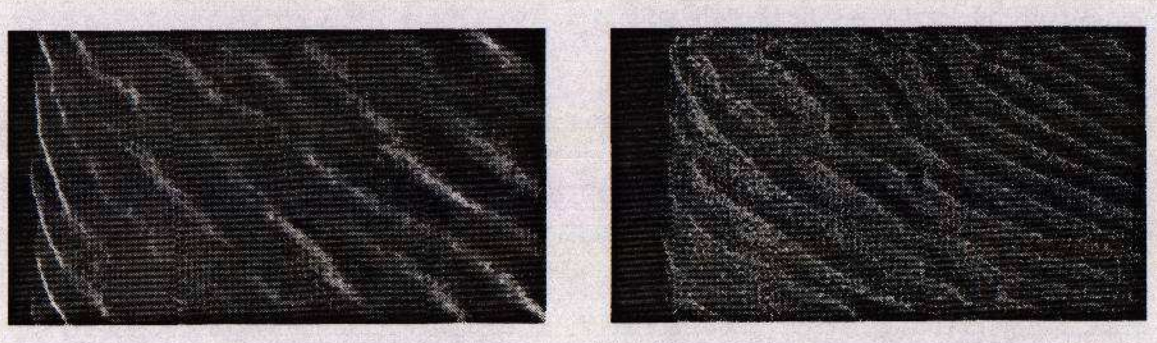

Figure 5:(a) Simulated sidescan sonar image (b) Actual sidescan image

Sidescan sonars are frequently employed to survey pipelines on the seabed. The objective of the surveys is to ascertain where sections of the pipe are unsupported by the seabed and spans have formed in the pipeline. This effect is simulated in figure 6(a) which represents a pipe on the seabed with an unsupported span in the centre of the image. The image of the pipeline and the associated shadow alters in this area.

This is similar to the image of the span illustrated in figure 6(b), which displays the actual sidescan survey of a pipeline in the North Sea.

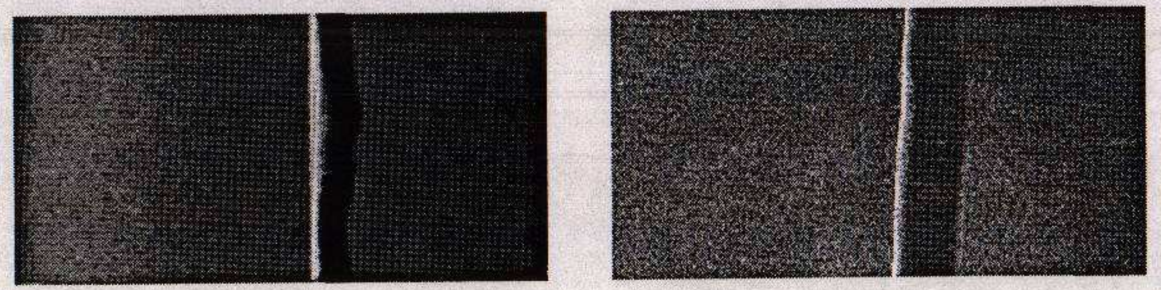

Figure 6:(a) Simulated sidescan sonar image (b) Actual sidescan image

Inspection of the figures 4 to 6 reveals similar representations of features on both the simulated and actual sidescan sonar images and visually realistic results can be produced by the model. Alternative techniques including statistical and spectral analysis have also been applied to investigate and verify the output of the model [12]. The application of these methods to the simulated and real sidescan sonar data have produced consistent results, where the simulated data exhibited similar characteristics and trends to the real data.

7. CONCLUSIONS

In conclusion, this paper has presented the initial development of a model for the simulation of sidescan sonar images. The model considers the main underlying physical processes including seabed reverberation, acoustic propagation through the water media, and the transducer characteristics. The output of the model is a simulated sidescan sonar image, comparable to the actual image which would be generated by a sidescan sonar operating under the specified conditions.

The main advantage of this model is the direct visualisation of the output of the simulated sidescan sonar process in image form. The model is one of the first to generate visually realistic sidescan sonar images of complex seabed topographies and features of the seafloor. This provides a direct advantage over existing models which generate only numerical or graphical results which are difficult to relate to the actual sidescan images.

A further advantage of the model is that it permits the visualisation of the influence of individual parameters on the sidescan sonar image. The parameters can either be explored in isolation or as a complex combination of phenomena. The model has proved to be a useful analysis tool in this respect and the effect of the sound velocity profile on the sidescan sonar images has already been investigated [13].

It is also envisaged that the model will provide a valuable tool for both training and visualisation, as it will permit the simulation of complex environments and artifacts of the sidescan sonar process. On a more sophisticated scale, it can provide a suitable platform for testing complex algorithms to improve the interpretation of sidescan sonar images.

On evaluation, the model has been demonstrated to replicate the deterministic aspects of the sidescan sonar process. Every simulated sidescan sonar image of a defined scene is therefore identical. However, sidescan records of a specified area have been observed to change slightly with time. This has been attributed to stochastic processes, such as volume reverberation, surface reverberation and noise, which can also result in the addition of speckle and clutter on the images. The model is currently limited in that it is unable to model these stochastic processes, but the framework of the deterministic model was necessary before stochastic features could be incorporated.

A further limitation of the model, at present, is that it is only capable of representing sidescan sonar. However, the propagation and reverberation sub-models are general for any sonar process and a recombination of the sub-models should permit the simulation of sonar systems with other architectures.

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