# Analysis and Problems of HF Acoustic Coherent and Incoherent Simulations in Shallow Water

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## Abstract

*Shallow water environments create complex scattering conditions due to the sea surface and bottom scattering mechanisms. An analysis of the effects of the scattering mechanisms on sonar images of simple targets in shallow water scenarios will be presented and will include a examination of both incoherent and coherent scattering. The analysis will use an incoherent model for the simulation of sidescan sonar images, as well as two dimensional coherent ray propagation and isovelocity models.*

## 1. Introduction

This paper aims to discuss the effects of incoherent and coherent scattering and the inclusion of such effects in sonar simulation models in shallow water environments. In shallow water environments, high resolution sonar images include contributions from many complex scattering mechanisms including the seabed, sea surface and target scattering and associated multi paths. Modelling of such scenarios often simplifies the calculations by assuming only incoherent scattering, or by limiting the number of paths calculated.

A model for the simulation of sidescan sonar and the images generated by such systems has been developed [1], and will be discussed in Section 2. This model attempts to replicate the underlying physical processes and create realistic synthetic sonar images. The processes incorporated include the transducer motion and directivity characteristics and the propagational effects and losses in a horizontally stratified media. In addition the model includes the scattering from complex, realistic seabeds and can include targets on the seabed or in the water column. The scattering from the seabed and sea surface includes the multi-path returns which can influence sonar images of targets and their associated shadows. These effects of the sea bottom and sea surface scattering with various target scenarios will be illustrated. This model however, is at present limited to the simulation of sidescan sonar as a result of the simplifying assumptions of a point source and the neglection of the phase. The implications of these assumptions will be examined in this paper, as well as introducing the concepts and complexity which arises from the inclusion of coherent effects.

The coherent effects will be illustrated using a simple two dimensional ray propagation model and an isovelocity model which can examine the various scattering paths. The coherent received signal is generated using versions of the same underlying seabed and sea surface scattering models as are used in the incoherent case, and summing many pulse replicas with relative phases and amplitudes as calculated from the ray trace and these models. The effects of small perturbations to both amplitude and phase of some of these replicas will be demonstrated for an idealistic environment (i.e. flat seabed and sea surface and very simple target) with the object of showing the possible effects of in-water inhomogenieties on high resolution sonar images. The consequences of the limitation of the current sonar image synthesis model will then be examined as result of the analysis of the coherent effects along with some of the problems envisaged in further developments.

The analysis will therefore consider three different models, viz. the sidescan simulation model, a 2D coherent ray propagation model and a coherent isovelocity model. Each of these models will be presented, along with details of their implementations and the results obtained from the application of the model. To permit comparison of the models and the effects of in-water inhomogeneities in high resolution models, the same scenario will be used in all three cases. This utilises the sound velocity profile of Figure 1, with the transducer positioned at a depth of 11m, and assumes a target with dimensions of 2m by 1m positioned on the seabed at a range of 150m from the transducer.

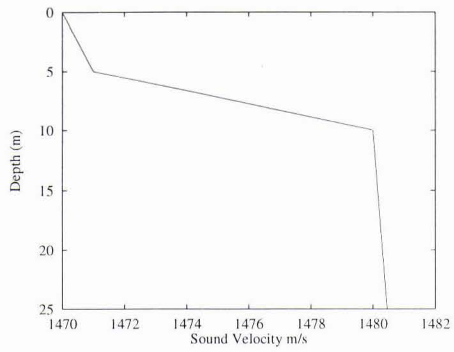


**Figure 1**

An analysis and comparison of the results obtained from the three models will also be presented. This will highlight the problems which are envisaged in extending a model, such as the model for the sidescan simulation, to a general coherent sonar simulation model capable of producing realistic high resolution sonar images.

## 2. Sidescan Simulation Model

A model for the simulation of sidescan sonar images which permits the direct visualisation of synthetic sonar images, generated by consideration of the underlying physical processes has been developed [1]. This model is based on ray theory and generates each line of the image by tracing a set of rays to represent each emitted pulse of acoustical energy. For each ray traced two values are calculated: the time for the ray to propagate through the water and be scattered back to the transducer and the intensity of sound received back at the transducer. These values are then processed to form one line of the image. The processing to form the image considers only the magnitude of the signals and neglects the phase [2].

The ray path is calculated assuming a horizontally stratified media, but can include any sound velocity profile. The intensity calculations include the effects of the spreading and absorption losses incurred during propagation, the three dimensional beam pattern for both the transmit and receive and the scattering from the seabed. The scattering can be calculated using the simple approximation of Lamberts Law or from the bistatic model of Jackson [3], which includes terms for both the scattering from the surface roughness and volume inhomogeneities in the sediment. The seabed is modelled as a realistic rough surface using fractals, which have been illustrated to provide a good representation of the seabed on a range of scales from centimeter to kilometer resolution [4 ] [5]. In addition targets can also be included in the scene using procedurally defined objects.

### 2.1 Simulation using backscatter only

In its simplest form the model calculates only the direct backscatter from the seabed and assumes the returning ray follows an identical trajectory to the outgoing ray. Part of a line of the image generated by calculating only the backscatter is displayed in Figure 2, for the scenario described previously, showing only the region in the vicinity of the target. A rough seabed surface has been used and the scattering model assumes a sandy sediment. The initial peak of the target in this signal is due to scattering from the face of the target orientated towards the transducer. The resulting shadow is clearly defined. This figure also shows the simulated signal if a totally flat seabed had been utilised in the modelling. This signal is unrealistic, and the advantage of the utilisation of complex fractals to model the topography and sediment roughness can be visualised. The fractal seabed was also used to generate the synthetic sidescan sonar image of Figure 3 which shows the target lying on the rough seafloor and the resulting pattern of highlights and shadows.

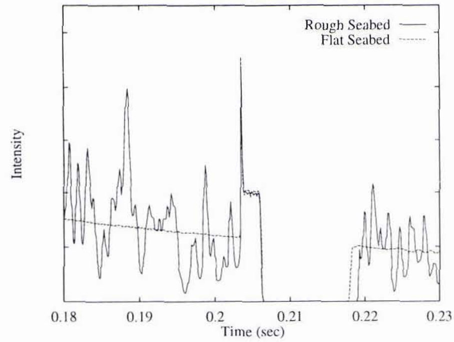


**Figure 2**

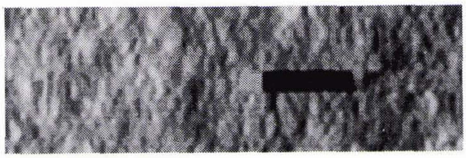

**Figure 3**

## 2.2 Seabed Multi-paths

The model can then be extended to include the multiple reflections from the seabed to account for the fact that the sound is scattered in all directions upon interaction with the seabed. The principle direction of the reflected energy tends to be in the specular direction, and the rays are traced in this direction upon intersection with the seabed or the target. The process of tracing the specular ray from each intersection can be repeated iteratively until the relative magnitude of the energy received at the transducer is no longer significant. With the use of Jackson's bistatic scattering model the magnitude of the signal can be easily calculated in both the specular and backscatter directions.

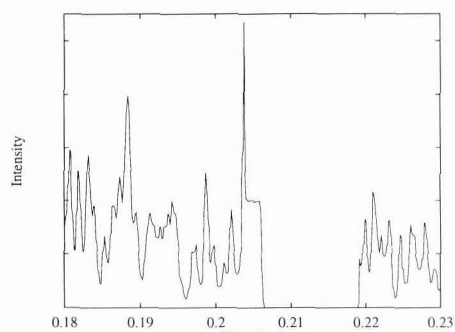


**Figure 4**

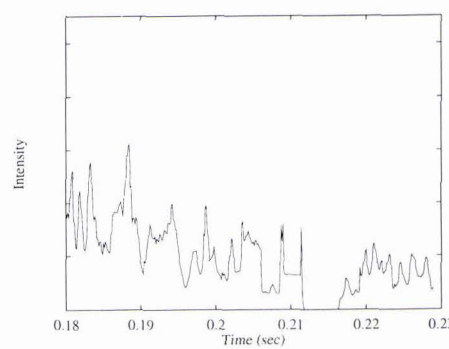


**Figure 5**

The effect of the multiple reflections is most pronounced in the area directly in front of the target, as the signal is reflected repeated between the seabed and the target. This produces a larger peak in the signal and subsequent smaller peaks where the target is detected, as can be seen in Figure 4. The bottom bounce only paths, have little other effect on the signal as the energy is reflected away from the scene without being reflected from any other objects.

## 2.3 Sea Surface Reflections

As has been illustrated in Section 2.2, the bottom only multi-paths have only a small effect on the signal in the vicinity of the target. In shallow water, the addition of the sea surface multi-paths has a greater effect on the signal. This is illustrated in Figure 5, which includes the influence of the sea surface reflections as well as the bottom reflections. The direct backscatter path produces the first image of the target and the first surface reflected path creates a clear multiple view of the target and a subsequent reduction in the shadow zone, due to the multiple images of the target. This effect can also be visualised in the simulated image of the target, shown in

Figure 6, where the visual detection of the object in the image becomes more difficult.

The simulated signal of Figure 5 assumed that the sea surface was a perfectly flat reflecting plane. The effect of the moving sea surface can be included by manipulating the surface normal of this plane to simulate the orientation of the sea surface waves at the point where the rays intersect the plane. This incorporated a more random effect into the simulated image as is illustrated in Figure 7.

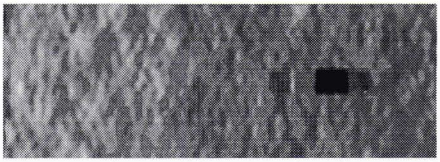

**Figure 6**

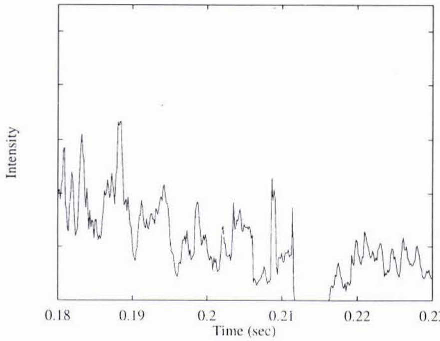


**Figure 7**

The model to produce the signals and images shown in the above figures has neglected the phase of the signals in the calculations and has assumed a point source and receiver. However, already the complexity of the model, to permit it to model realistic seabed topographies and roughness, ray refraction and 3D beam patterns, means that it can take several hours to generate the synthetic images shown. To extend the model to include the coherent scattering and beam forming at a realistic transducer could prove to be too computationally expensive. The effect of modelling the coherence is discussed in the following sections.

## 3. 2D Coherent Ray Propagation Model

To extend the investigation of the modelling to include the coherent effects, the study will use a very simple two dimensional raytrace model, which assumes a flat seabed and sea surface. The model has been modified to generate a spike array containing information about ray paths and arrival times at the target, seabed and sea surface. A time series is then generated by coherently adding pulse replicas modified by the time delays and information contained in the spike array. The amplitudes of the pulses summed are adjusted according to the source of the return, and the amplitude can also be given a small random perturbation to account for less than perfect surfaces. As no attempt is made to identify eigenrays, this approach for an active sonar simulation is only valid for direct path calculations and the assumption that the outward and return trajectory are identical.

Figure 8 shows the raytrace for the sound velocity profile shown in figure 1, and the resultant spike array and time series representing the calculated acoustic return for direct paths. On comparison with the flat seabed incoherent a-scan shown in Figure 2, the additional complexity and randomness introduced from the coherent addition is clearly visible.

### 3.1 Effect of velocity profile

As shown in the previous section it is desirable to include additional ray paths involving reflections from the seabed and sea surface in this study. The ray trace and resulting time series and spike array of Figure 8 was calculated for the profile previously discussed, this can be compared to Figure 9 which was calculated for the same target scenario but with isovelocity conditions. This shows that the effect of the profile on the spike array, as compared with that for isovelocity conditions, will only affect the sea surface returns and will not make a great deal of difference to the outcome, apart from in certain infrequently occurring conditions when the array beampattern and tilt should happen to be critical for the angle and range concerned.

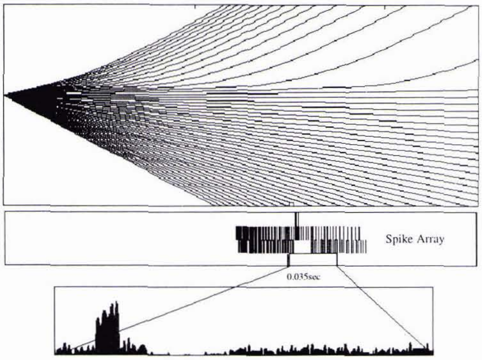


Figure 8

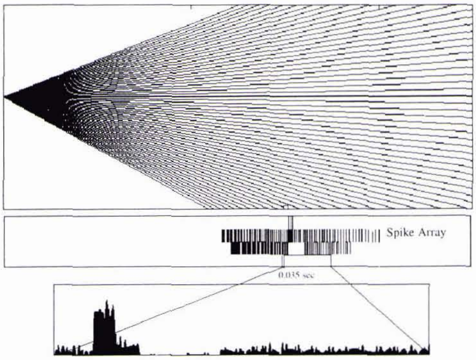


Figure 9

# 4. Coherent Isovelocity Model

As a result of the small effect of the sound velocity profile, as discussed in Section 3.1, a coherent isovelocity model has also been developed to simplify the calculations without distorting their accuracy. Limiting the environment to isovelocity conditions reduces the identification of eigenrays to simple geometry, making the study of the effects of the multiple paths considerably easier.

A two dimensional scenario is again considered initially for a single receive beam, as is illustrated in Figure 10, for a scene with a flat seabed and sea surface with the target positioned at a range of 150m and the transducer at a depth of 11m. The number of reflections can be limited to 0 or 1, thereby including direct paths only (e.g. Figure 10 path a) or those involving only one reflection from either the seabed or the sea surface (combinations of paths a, b and c). The model also has the ability to include up to two reflections, therefore calculating paths involving both a seabed and a sea surface reflection (paths d and e).

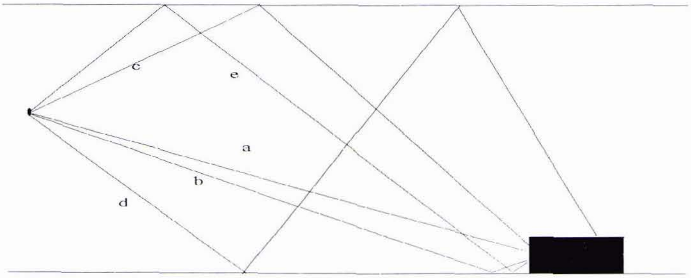


Figure 10

## 4.1 Comparison with Incoherent Modelling

The model is an extension of an isovelocity sonar equation model and uses the same underlying acoustic models to describe the level of the scattering from both seabed and sea-surface as the Sidescan Simulation Model, which was described in Section 2. It also includes the effects of the array beam patterns, beam steer and target size and position.

Once again a spike array is generated for all two way paths containing arrival time, cumulative path loss, and path type. Reflections at the sea surface undergo a phase reversal but those at the seabed do not [6]. Figure 11 compares (for a small time window in the target vicinity) seabed and sea surface reverberation levels and received signal level including target echo from the energy model (Figure 11a), with a plot of the information held in the spike array (Figure 11b). In addition, the time series data generated using that spike array is also illustrated in Figure 11c.

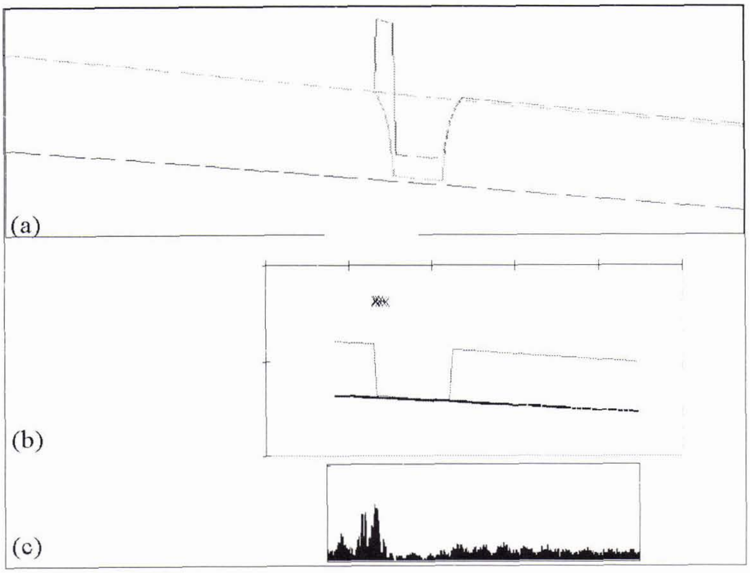


**Figure 11**

### 4.2 Time series simulation

This information is then used to coherently sum pulse replicas to give a simulated a-scan return. Provision has been made to allow the addition of a random phase shift or jitter to each pulse replica summed, but no alteration to the amplitude except as calculated from the cumulative path loss. This phase shift was included to allow a little variation between consecutive calculations using identical information and attempt to include the effects of sea surface movement, less than ideal surfaces, array movement, and through water inhomogenieties. The maximum size of this random shift can be chosen in terms of the wavelength from 0 upwards.

The summation is carried out in the time domain, as convolving the spike array timings with the transmit waveform would have involved a large number of dummy points in the spike array to retain the time structure, thus removing any speed advantage this method might have had. For simplicity a limit has been set on the size of the window that can be considered which in practice for a 100kHz simulation gives a window of 35msec.

### 4.3 Simulation Results

Figure 12 shows the effect on the simulated time series of including direct paths and reflected paths in the calculations. Figure 12a allowed only the direct paths in the calculations, whereas Figure 12b included the paths with one reflection and Figure 12c included paths with two reflections. As might be expected the obvious shadow in Figure 12a is filled in to the point of being obliterated as more reflection paths are included in this example. Figure 13 shows the sort of effect that might be expected by including different levels of phase jitter in the calculation of the time series using the same spike array.

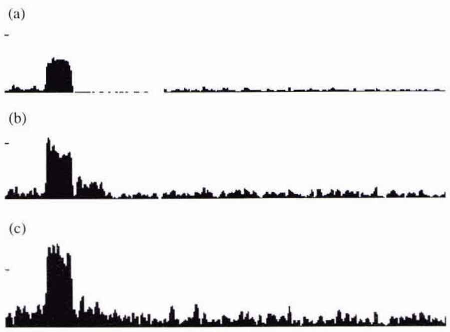


Figure 12

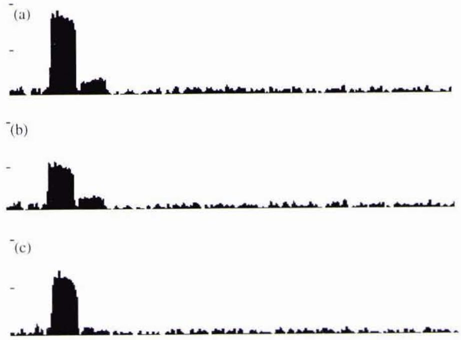


Figure 13

Figure 14 is an example of an image that can be built up by combining the time series for beams with different steer angles. Figure 14a shows examples of the coherent time series for different beams which were used to generate the image of Figure 14b, including examples in which the target was within and outwith the beam.

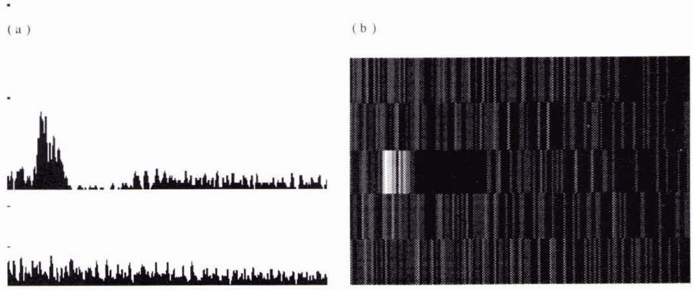


Figure 14

## 5. Analysis and Conclusions

It has been shown that inclusion of more realistic seabed descriptions to an incoherent model adds a great deal of confusion to the predicted time series data, and that the inclusion of bottom and surface reflected paths has a significant effect on these results. These results indicate that detailed bathymetry and sea surface description are important components in a realistic HF sonar simulation.

The simple coherent models add further degree of confusion even for assumed flat surfaces. Using these models the effect of including the forward reflected paths on the predicted time series data can be shown. Applying small perturbations to the amplitude or the phase of the components added into the time series might be a reasonable way of including effects of in-water inhomogenieties and less than perfect surfaces, and can have a noticeable effect on the predictions.

There has been a considerable amount of study of the effects and methods of including bottom topography and reflectivity [7], and in modelling 3D environments. Many of these studies have concentrated on rather longer ranges and wavelengths, and deeper water scenarios than are being considered here. It is apparent from the results presented here that the inclusion of seabed bathymetry and sea surface topography is essential in a realistic shallow water HF acoustic simulation, but as yet it is unclear whether it is realistic to model the complete scenario in a coherent manner.

Further work is currently being undertaken to investigate possible model architectures which are able to handle the additional complexity and permit the extension of the Sidescan Simulation Model to a coherent HF sonar model, since the original ray tracing approach may be too computationally expensive, as has been illustrated in this paper. This work will also require experimental data gathering for representative scenarios for comparison with the simulated data, and the development of methods for the comparison of real and simulated data.

## References

[1] J.M. Bell, " A Model for the Simulation of Sidescan Sonar", Ph.D Thesis, Heriot-Watt University, November 1995

[2] J.M. Bell," Application of Optical Ray Tracing Techniques to the Simulation of Sonar Images ",in Optical Engineering, in press.

[3] D.R. Jackson, "Models for scattering from the seabed", Proc. Inst. Acoustics, 16(6), Dec 1994

[4] K.B. Briggs, "Microtopographical Roughness of Shallow-Water Continental Shelves", IEEE J. Oceanic Eng., 14(4), pp. 360-367 (1989).

[5] C.G. Fox and D.E. Hayes, "Quantitative Methods for Analyzing the Roughness of the Seafloor", Rev. Geophysics, 23(1), pp. 1-48, 1985

[6] J.B. Keller and J.S. Papadakis, "Wave Propagation and Underwater Acoustics", Lecture Notes in Physics 70, Springer-Verlag Press.

[7] A.R. Robinson and D. Lee, "Oceanography and Acoustics Prediction and Propagation Models", (Chapter 9. J.F. Lynch, AE Newhall, CS Chiu and JH Miller) AIP Press