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TECHNIQUES FOR THE PHYSICAL MODELLING OF THE SONAR IMAGE GENERATION PROCESS

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Abstract

Modelling is widely recognised as playing a critical role in assessing the performance of systems and evaluating subsequent processing algorithms. However, few models exist which can fully represent entire sonar systems, including the signal transmission, propagation, scattering, reception and subsequent sonar image generation. This paper discusses one such model for the simulation of the sidescan process and possible techniques for its extension to a general sonar simulator capable of producing realistic synthetic sonar signals and images for any high frequency active sonar system.

Use of Modelling

The development and verification of processing techniques for sonar images, such as classification, segmentation and object detection, require accurate input data. However, there is great difficulty in obtaining fully ground-truthed data sets containing precise details of the scene, operating characteristics of the sonar and environmental details. Therefore, the use of an accurate model for assessing the performance of processing techniques can provide an alternative means of testing and evaluation.

There are already many accurate models for each of the individual aspects of the sonar process, for example propagation [1], scattering [2] and sensors, but few models encompass all aspects with the necessary detail. In addition, the majority of the models produce outputs in graphical or numerical form which are difficult to relate to the images/signals produced by the actual sonar systems. Sonar performance models, such as SEARAY[3] and INSIGHT[4], based around the application of the sonar equation, do combine all aspects but do not produce an output comparable to the output of a real sonar system. Therefore, the aim is to produce an accurate model for the simulation of sonar systems, which models the underlying physical processes but produces as its output synthetic images of the form created by real sonar systems.

In addition to its use for verifying complex processing algorithms, the model could also fulfil a number of important roles in the design and testing of sonar systems. To maximise the applicability of such a model, it is desired to create a general model which can simulate any form of active sonar system. Such a model, which is capable of representing the entire sonar process, must consider all aspects of the problem, including acoustic propagation, scattering at complex surfaces and the transducer operating characteristics.

This paper will briefly summarise the development of a model which was concentrated initially on the simulation of sidescan sonar, before discussing the extension of this model to a general sonar simulation system. The discussion will highlight the problems with the existing model structure before presenting two possible methods to overcome these limitations. A comparison of the two extension techniques, and their possible advantages and disadvantages, will then be presented.

Existing Sidescan Model

The initial model for the simulation of sidescan sonar [5] was developed based on the computer graphics technique of ray tracing, in which each pulse of acoustical energy is represented as a discrete set of rays. These rays are traced through the refractive water column until their subsequent intersection with the seabed. The time taken for each ray and the intensity returned are then calculated. The intensity calculations consider the spreading and absorption losses, the transducer directivity and the complex scattering at the seafloor [6]. These time and intensity values for each ray are then processed to form each line of the sidescan image [7].

The synthetic sidescan sonar images produced by the model are visually very realistic, as can be seen from figure 1. In addition, to permit further verification of the model, it has been demonstrated that the synthetic images posses similar statistical [5] and spectral characteristics [7] to real sonar images. The output of the model can also be viewed in terms of the A-scan showing the signal returned for each transmitted pulse. An example of a received signal is shown in Figure 2, which is the central horizontal line of the simulated image illustrated in Figure 1. The period of no return as the pulse propagates through the water column has been removed from both the image and the signal to permit greater visualisation of the data.

In producing realistic synthetic images through modelling the underlying physical processes, this model has a wide range of potential applications. Already it has found application in the analysis of the directional characteristics of sidescan images [8].

Limitations of Existing Model

This current model is however limited primarily to the simulation of sidescan sonar as a result of many simplifying assumptions used in its development. The most restricting of these assumptions is the use of a point source and receiver. The removal of this assumption and the simulation of the signals received from a distributed array would, with the necessary beamforming, permit the use of the model for the simulation of any sonar geometry (e.g. forward looking, multi-beam, synthetic aperture).

The motion of the transducer between the transmission and reception of the sonar signal was regarded as negligible for the sidescan model. This permitted the assumption that the returning ray trajectory was identical to the outward ray, and hence reduced the number of rays to trace. This assumption is not applicable for other forms of sonar, particularly when the direction of transmission is the same as the direction of travel (e.g. forward-looking).

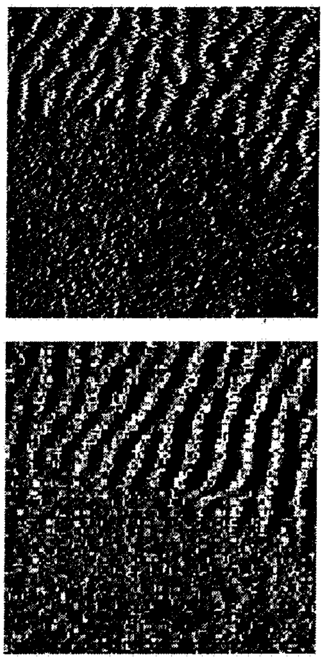


Figure 1: (top) Simulated sidescan sonar image (below) Visually similar real sidescan image

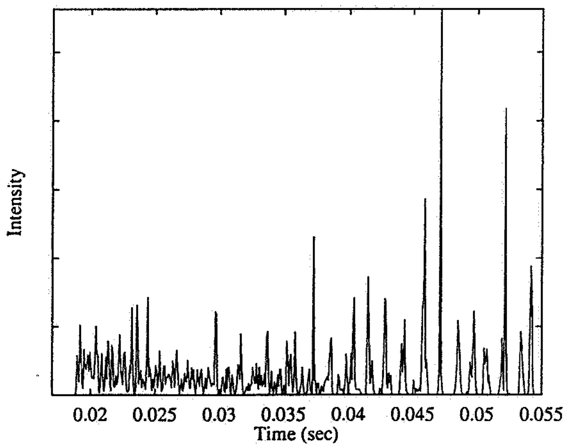


Figure 2: Simulated signal

In removing the first of these assumptions, a rapid explosion in the number of rays to trace would occur, dramatically increasing the already large processing time. This arises since the rays would be traced from every element to their interaction with the scene and then back to every element. Therefore, for an n element array, n^2 rays would require to be traced for every 1 ray traced in the current sidescan model.

A resulting artefact of tracing rays from one element to their interaction and back to every other element, is that rays can no longer be assumed to follow the same trajectory on return as the outward ray. Thus the rays returning to one element from another can only be found using an iterative trial and error technique as a result of using ray tracing in non-isovelocity conditions. This problem is compounded by removing the stationary receiver assumption.

The modified simulator must also be fully coherent and consider the phase rather than just the magnitude of the returned signals from the rays as currently implemented. This places much more stringent conditions on the accuracy to provide the correct phase.

The model is also limited since at present it considers the interaction of the acoustic pulse with complex seabed scenes and objects in the water column, but does not consider the sea surface. The main reason for this limitation is the complex post processing of the ray values required to produce the output signal. This arises as a result of representing the continuous sonar process with a discrete set of rays. The time and intensity values for each ray must be processed to produce samples at constant time increments to permit the formation of the time domain image. It is not possible to obtain directly samples at constant time increments because the ray times can not be predicted *a priori*, as a result of the refractive medium and rough surfaces. The required processing must not distort the highlights and shadows of the image. However, with the further extension of the simulator to include distributed arrays and the sea surface scattering this will require further examination to ascertain if the current technique is still valid.

This complex post processing has a direct influence on the ray tracing technique, since it dictates the numbers of rays to trace in order to satisfy sampling conditions. In the sidescan simulator this results in the tracing of many thousands of rays to cover a distance of only a few metres, and with the planned extensions to the model this is set to expand rapidly.

Extensions to the Model

To satisfy the requirements of producing a general simulation model for the sonar process, a model is obviously required which overcomes the limiting assumptions of the sidescan simulator discussed in the previous section. There are currently two different methods under consideration for this extension. The first approach is attempting to overcome the current limitations of the sidescan simulation, since ray tracing is seen to offer a conceptually simple technique for the representation of the sonar process. The second method is to model the entire process using a finite difference technique, which is felt to offer the advantage of treating all aspects of the problem as an inherent part of the model, but which is more difficult to devise.

Any developments made in extending the model must balance the effect of the change on the model's ability to produce accurate timing and phase information against the effect of the change on the complexity of the processing. The extension of the ray based solution and the development of the FD technique will be considered from this perspective.

using the approximation and the actual value was 23ns which is 1/87 of the period of a 500kHz signal. For a realistic profile the difference is reduced to 3ns.

Extended Ray Model The extended ray tracing model now has the capability to trace rays from every element of the array and estimate the return trajectory of each ray to every element of the array using the vector approximation technique. For an n element array this results in n^2 time and intensity values for every one ray of the old method. These time and intensity values obtained at each element of the array can then be combined by beamforming to produce a single line segment of the synthesised sonar record.

To illustrate that the extended model can reproduce the results of the initial model, the time series response for one line of a sidescan image is shown in Figure 4. This figure was generated using the same line of the input seabed employed in the creation of Figure 2. The resulting signal produces the expected response where the initial part is the energy backscattered from the isotropic region of the seabed and the later part from the sand ripples. Slight differences to Figure 2 can be attributed to the effective use of a knife edged beam pattern, rather than the full 3 dimensional simulation of the sidescan model.

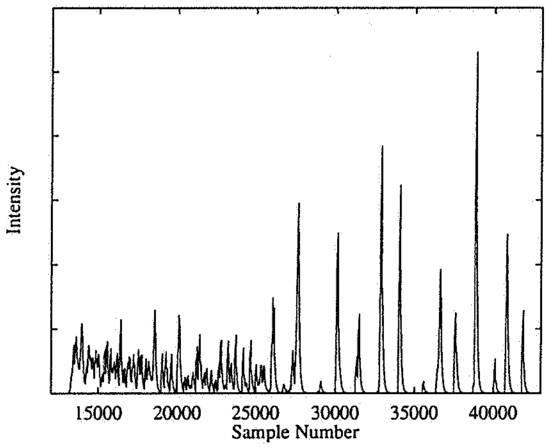


Figure 4: Simulated Impulse Response

These impulse responses, produced by the model, are under also under investigation using a technique whereby the impulses are modelled using the low-pass filtered method of Peterson [10]. It is anticipated that this will permit more accurate estimates of the returned signal to be obtained from the discrete time series produced by the model.

This extended ray technique still requires further expansion to provide the ability to produce the beamformed output of the entire signal rather than the time series impulse response of each element. However, the vector approximation technique has been demonstrated to provide adequate estimates of the time of flight without significantly increasing the computational complexity, thus allowing the removal of many of the limiting assumptions of the original sidescan model and therefore permitting the simulation of any form of active sonar system.

Finite Difference Methods

The other concurrent track for the extension of the model, is the investigation of a finite difference (FD) approach rather than the ray based technique. This is based on the discretisation of the wave equation in which the exact differential operators are replaced by local difference approximations over a discrete space-time grid [11]. These lead to a recurrence relation allowing the pressure at any point to be calculated from the values at the surrounding points (in space and time). This recurrence relation for a second order scheme is shown in equation 3 for a 2D environment.

$$p_{i,j}^{n+1} = r^2\left(p_{i-1,j}^n + p_{i+1,j}^n + p_{i,j-1}^n + p_{i,j+1}^n\right) + 2\left(1-2r^2\right)p_{i,j}^n - p_{i,j}^{n-1} \qquad (3)$$

where the mesh ratio

$$r = c\frac{\Delta t}{\Delta x} \qquad (4)$$

and $p_{i,j}^n = p(i\Delta x, j\Delta y, n\Delta t)$ is the pressure as a function of range ($i\Delta x$), depth ($j\Delta y$) and time ($n\Delta t$). Using this equation, the acoustic pressure field (in both the spatial and time dimensions) can thus be calculated everywhere through time.

The most significant advantage of this technique is its inherent capability to calculate all aspects of the sonar process, such as propagation, losses, refraction and other wave effects, as well as reflections at surfaces with appropriate boundary conditions. In addition, realistic source and receiver elements can be positioned within the scene and the time series obtained across the distributed array.

The main disadvantage of the FD method is the huge computational effort involved in its calculation. Sub-wavelength/period discretisation is necessary (in space/time) in order for the solution to remain stable, and typically at least 10 points per wavelength are required [11]. In addition, a further restriction is that this scheme is only conditionally stable, and to maintain stability the value of the mesh ratio, r, must satisfy the Courant-Freidrichs-Lewy (CFL) condition, as shown in equation 5. This is obtained by applying Von Neumann stability analysis to equation 3 [12] and it thus imposes limits on the possible values of the depth, range and time steps (Δx, Δy and Δt respectively).

$$r \le \frac{1}{\sqrt{2}} \qquad (5)$$

For the high frequency applications of interest, this requires a large amount of memory to store the spatial grid and many time steps to propagate a pulse across this grid. Historically, these factors have limited the method to small-scale low-frequency applications, however computers are now becoming sufficiently powerful that investigation of this approach for the model is feasible. However, even for a two way calculation over a range of 100m and depth of 20m for a 75kHz signal, approximately 300,000 time steps and 600MB of memory are required.

Even considering these disadvantages, initial results from the model look promising using this technique. Particularly since the time domain signal is obtained directly, for any number of array elements at any positions without the need for any post processing, as for the rays.

Initial results from the development of the model are shown in Figure 5, which illustrates the propagation of single pulse through a 2-D homogeneous medium with a rough boundary at the bottom and a flat pressure release sea surface. This simulation again used the same line of the seabed employed for the verification of the ray tracing technique. In Figure 5(a), the source/receiver point is positioned at the top left hand corner of the image, and the pulse can be seen to have undergone reflections from the rough bottom producing interference effects, which are characteristic of wave propagation. The resulting time series pressure signal at the transducer point is shown in Figure 5(b). The first part of the signal corresponding to the pulse transmission has been removed in order to illustrate the other characteristics of the signal, therefore the initial part is the first bottom return and the subsequent signals backscattered from the seabed are also indicated. Analysis of the data demonstrates that the spreading losses and phase changes (the latter due to reflection) occur as expected. It should be noted that Figure 5(b) includes the effect of the spreading loss, which has been compensated for with the application of time varying gain in Figures 2 and 4.

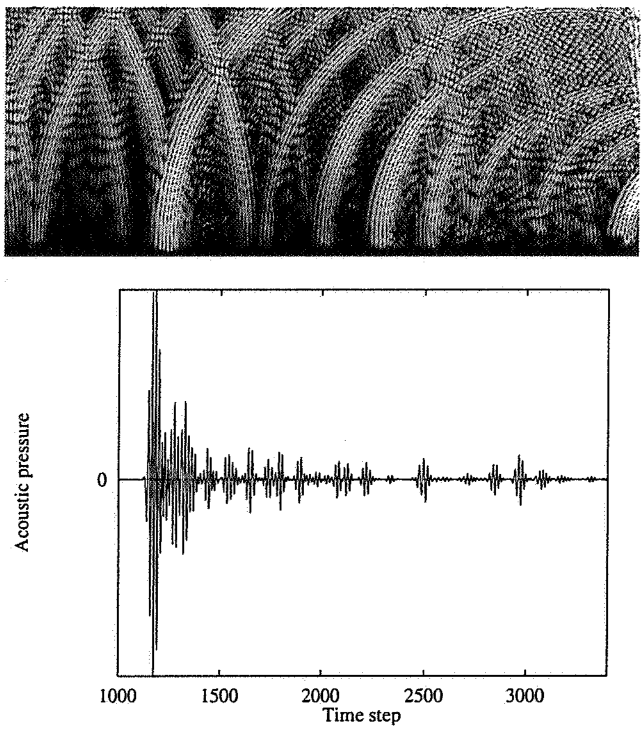
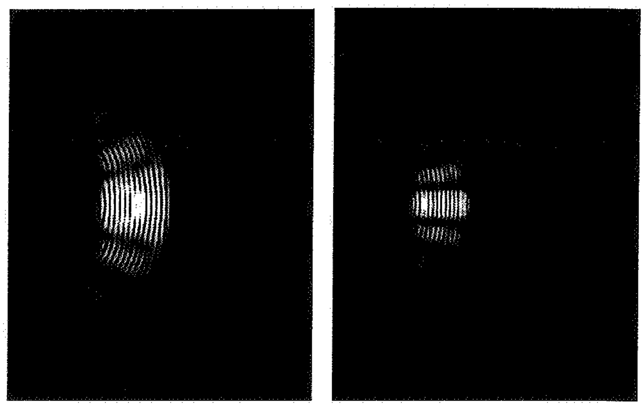


Figure 5: FD model output (top) Pulse propagation at time step 2000 (below) Received time series signal

The technique can then be extended to include any number of transducer elements and by varying the sound speed parameter in the mesh ratio, refraction due to variable sound speed profiles can also be incorporated. This is illustrated in Figure 6 for an array of 9 elements, transmitting in an isovelocity medium in Figure 6(a) and in an environment with a convergent SVP centred on the transducer position in Figure 6(b). In both cases, the propagation is shown after 500 time steps.

The time signals obtained from the transmission and subsequent reception of a pulse can be combined to produce a pseudo sonar image, by simply repeating the 2D modelling as discussed above for different slices of an input seabed. This was undertaken for the same input seabed as employed in the creation of Figure 1 and the resulting synthetic sidescan image formed in this way is illustrated in Figure 7. Although this produces a realistic output in comparison to Figure 1, more accurate simulations, which can consider the full three dimensional nature of the propagating pulse, will require the extension to a fully three dimensional model.



(a) (b)

Figure 6: Propagation from a source of 9 elements (a) through an isovelocity medium (b) in a convergent SVP

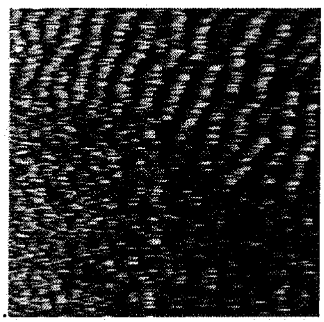


Figure 7: Pseudo sidescan image created using FD Technique

This is part of the future development of this FD model, as well as the incorporation of realistic boundary conditions. This will require the use of absorbing boundaries which can be implemented using a perfectly matched layer (PML)[13]. This will also allow the termination of the grid and permit the modelling of the pulse only over a specified area of interest. At present the results shown above have used perfectly reflecting boundaries to alleviate the problem of terminating the grid, but the use of a PML will permit the scattering from any sediments to be modelled accurately. In order to make such a 3D model tractable higher order finite difference schemes, such as the fourth order technique of Levander [14], will be considered as means to a more efficient and accurate implementation. To maintain the accuracy, but reduce the number of grid points to calculate, future work may consider varying the size of the grid depending on the area of interest.

Comparison of Techniques

Two very different techniques have now been suggested for the creation of a general sonar simulator, but yet each technique offers a range of advantages and disadvantages. For example, the use of a ray based technique will always suffer the disadvantage that it is representing a continuous process with a discrete set of rays, and requires complex post processing to produce constantly spaced samples in the time domain, suitable for display as an image. The FD technique however calculates the time domain signal as an integral part of its solution, thus requiring no processing.

The angular resolution of the FD method may however be limited by the grid size, as the number of grid cells surrounding the transducer will limit the angular resolving power, whereas rays can be traced and received accurately over all angles.

The FD model is liable to be the most accurate representation of the sonar process, but is hampered by the computational complexity required, especially for the modelling of high frequency signals propagating over ranges of several hundreds of metres. This computational complexity currently limits the FD method to working with ranges of only a few metres in only two dimensions. Rays can overcome many of the speed limitations by incorporating techniques such as the vector approximation, without significantly affecting the accuracy of the output.

The two methods are liable to have complimentary roles: FD providing accurate benchmark calculations and the rays finding application as a more operational approach. The FD method could then even be used as a means of verifying the simplifying assumptions employed within the ray tracing method.

The two complimentary techniques will therefore continue to be developed concurrently and in future this may result in a hybrid approach [15] combining the advantages of the two techniques. This would be liable to employ FD grids around the boundaries and the transducer (i.e. in the areas where most significant effects occur) but use rays to provide rapid propagation calculations. This would permit the time series signal to be obtained directly but would speed up the calculation by reducing the computational complexity.

Conclusions

The feasibility of developing a model capable of simulating the sonar process and producing realistic synthetic sonar images has been demonstrated with the creation of the sidescan sonar simulator. This model is however limited by the assumptions employed in its development.

Current work is aiming to extend this model to provide a general sonar simulator capable of modelling any high frequency active sonar system. However, in extending the model, the computational complexity introduced in removing the limiting assumptions must be balanced against the accuracy of the model output. Two concurrent avenues for the extension are being explored: extension of the ray approach and a finite difference based method. To provide a model which is not limited as a result of the computational complexity, the ray tracing approach has introduced some less limiting assumptions than the original model. The FD technique, however, is striving for accuracy and the removal of all assumptions but its application may be limited by the computational complexity. The results from both techniques currently appear promising and it is foreseen than the two approaches can fulfil complementary roles for the design, testing and visualisation of sonar systems: the FD approach providing accurate research benchmarking and the ray tracing providing a faster operational style model.

Acknowledgements

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