MODELLING OF HIGH FREQUENCY SONAR SYSTEMS

J Bell Ocean Systems Laboratory, EPS, Heriot-Watt University

1 INTRODUCTION

High frequency imaging sonars produce a representation in image, or signal, form of the seabed. However, no closed form analytic expression or direct modelling technique exists to represent this complex process. This paper presents a summary of work undertaken at the Ocean Systems Laboratory at Heriot-Watt to produce models capable of providing realistic synthetic sonar data as well as discussing the motivation behind the work and the subsequent applications of these models.

2 OVERVIEW OF MODELS

2.1 MOTIVATION FOR MODELLING

Modelling is widely regarded as playing a critical role in enhancing the understanding of underwater acoustics. Models have been created to fulfill a variety of different roles and have been applied to both the prediction and analysis of underwater acoustic phenomena. Within their role as a prediction tool, models can provide a systematic means of designing experiments, whether they are to investigate the complex environment itself or the effect of the environment on the acoustic signals. The output from the prediction may simply be the effective sonar range or may be a forecast of the actual results of the experiment. Models may also be used to increase the effectiveness of data analysis and interpretation, providing information on the oceanographic features and the effects of the complex environment on the acoustic signals. They can be used to assist the sonar designer in producing the optimum performance for the application by increasing their knowledge of how a desired pulse will propagate for a variety of source/receiver configurations and for different environmental conditions. Modelling can also enhance the development and testing of new processing techniques and algorithms, since a significant problem which can be overcome by modelling is the provision of fully ground truthed data with all parameters accurately known to permit the validation of algorithms for automated sonar processing. These models allow the operating scenarios to be easily controlled and individual parameters altered in isolation to assess their impact on the subsequent processing. This broad range of potential applications has differing requirements on the modelling, including the accuracy required, ease of use, flexibility and the computation time.

2.2 CATEGORIZATION OF MODELS

This broad range of potential applications has led to the creation of a diverse range of models for the calculation of underwater acoustic phenomena. Acoustic models exist at a range of complexities for use either in operational field activities or for complex research and investigative studies. Pure application, or operations models, are used to support field activities, and their main requirement is to generate results rapidly, often under demanding conditions, with the minimal amount of operator experience. Pure research models, on the other hand, are designed for investigative studies within the research environment. Here they are employed for more sophisticated purposes where accuracy is important and not run-time. These models tend to be complicated to operate, requiring the operator to select or input a variety of geoacoustical parameters to adequately describe the environment. Intermediary classes of models tend to be more generally available and are a trade-off between the research and applications models, combining the automated features of the pure applications models with the flexibility and input options of the pure research models.

A broad categorization illustrating some of the range of underwater acoustic models is presented in figure 1. The first division is between the modeling of individual features and specific aspects of the sonar process (such as acoustic propagation, reverberation, noise etc) and models which consider the entire process. Within each of these broad categories, several types of model have emerged and a range of these models is summarized by Etter [1].

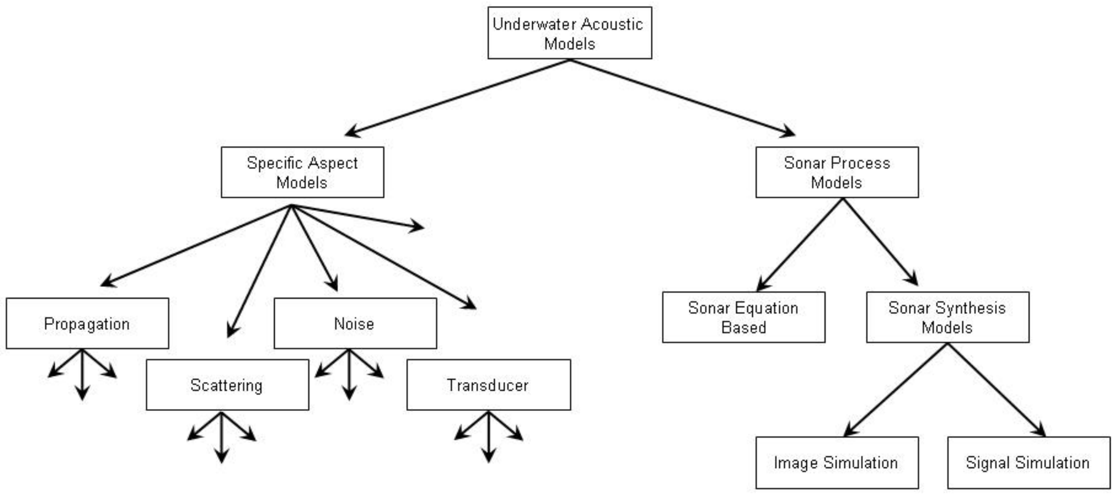

Figure 1. Broad categorization of models

The effects of the environmental models, propagation models and scattering models can be combined to produce some of the fundamental building blocks of active sonar models, or sonar performance prediction models. This class of active sonar models allows the prediction of the system signal, noise and reverberation levels in response to a particular environment. Sonar performance models tend to be based around the sonar equations which form the logical basis for calculations of the maximum range of sonar equipment and are similar to the equations used to describe radar performance. The outputs of these sonar performance models which combine the individual features are limited in that they tend to be in a graphical or numerical format, illustrating the effects of the individual parameters against terms such as the range or time or frequency. These results can be difficult to interpret and bear no direct resemblance to the typical outputs generated by sonar systems. This produces difficulties in attempting to correlate the expected and achieved performance.

2.3 AIM AND REQUIREMENTS OF DESIRED MODELS

The aim of the modelling discussed here has been to simulate the entire sonar process from signal transmission, through propagation, scattering and the subsequent reception of the signal at the receiver. However unlike the sonar performance models discussed above these models would produce realistic simulated data as their output which is directly comparable to the output of real sonar systems.

The main interest has been in high frequency imaging sonars, including sidescan, sector scan, bathymetric and synthetic aperture and has aimed at the production of synthetic data which is directly comparable to the output of real sonar systems. This has lead to two main classes of model: an “Image Simulation” model which aims to produce visually realistic simulated sonar images through modeling the underlying sonar process and the higher resolution “Signal Simulation” models which are more accurate coherent models producing synthetic data in the form of the received time series signal. Models which have been developed in both of these broad categories are discussed in the following sections.

3 IMAGE SIMULATION MODELS

3.1 AIM OF MODELS

As stated above the primary aim of these models is to create realistic synthetic sonar images of the specified environment using the desired sonar operating characteristics. The output is a qualitative image of the form generated by the actual sonar.

3.2 RAY TRACING MODEL

The first approach developed [2] is analogous to ray tracing in computer graphics and attempts to emulate the sidescan sonar process. It represents each emitted 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 position in three dimensional space and their trajectories are traced until they interact with the pre-defined underwater scene. For each ray traced two values are returned: the two way travel time for the signal to travel to the seabed and be scattered back to the transducer and the intensity of the signal received back. These time and intensity values for each set of rays, representing one emitted pulse, are processed to generate one line or `A' scan of the sidescan image. This process is then repeated for each pulse emitted to generate the subsequent lines of the sidescan image.

The calculation of the ray trajectories is derived from the ray solution to the Helmholtz equation and assumes a horizontally stratified water column. The ray trajectories are traced until they intersect the seabed defined in the 3D scene description. Fractal models, which are characterized by a roll-off of power spectral density with frequency, have been employed to provide complex, yet realistic, natural scenes. Seabed topographies, over a range of scales from centimetre to kilometre resolution, have been noted to exhibit this red power spectrum of fractals [3, 4]. To determine the intersection of the rays with the seabed the technique of height fields is applied, where the fractal terrain is transposed into a two dimensional grid array of altitude values which represent the surface. The scene can also include objects in the water column or on the seabed with the use of procedurally defined objects. Having determined the point of intersection with the defined scene, the amount of energy scattered back to the transducer must be calculated. This is determined using Jackson's bistatic scattering model [5] and incorporating the surface normal of the intersected facet. In addition, to reduce the complexity of the calculation without significantly altering the accuracy the scattering could instead be calculated using Lamberts law.

The directivity characteristics for both the transmission and reception of the acoustic signal also influence the received intensity level for each ray. Weighting factors are applied to each ray traced to account for the three dimensional beam patterns. The geometric and intensity distortions resulting from the motion of the towfish through the water are incorporated by updating the position and orientation of the transducer for each pulse of acoustic energy emitted. This alters the position from which the rays are traced and the orientation of the main lobe of the beam.

This technique can be amended to model forward look sonar in addition to the sidescan and example sidescan and forward look images produced by this model are shown in figure 2. The technique has also formed the basis for the development of models by Riordan and Toal [6]. Wendelboe et al. [7] have also extended the model for high frequency sector scan considering in more detail the calculation of the high frequency scattering and validation against real data.

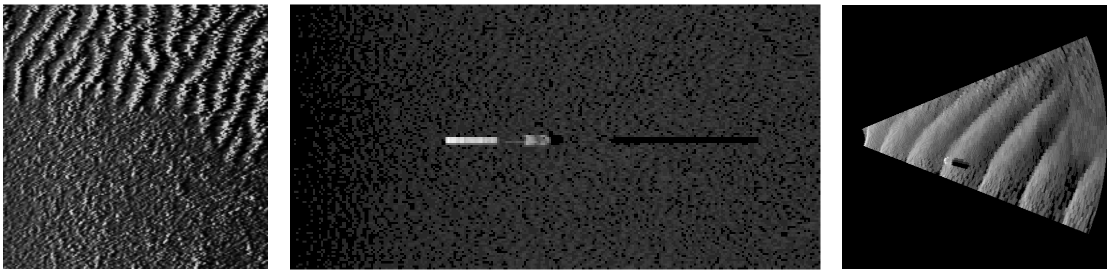

Figure 2. (a) Simulated sidescan image of boundary between sand ripples and silt sediment (b) simulated sidescan image of tethered object (c) simulated forward look image

3.3 AUGMENTED REALITY MODEL

3.3.1 REQUIREMENT FOR AUGMENTED REALITY MODEL

As mentioned in section 2.1, one application of simulation is for the development and analysis of automatic processing algorithms for sonar data. Without such models it can be difficult and costly to obtain sufficient databases of fully ground truthed sonar images. This is a particular problem in the development of automated target recognition algorithms, where large amounts of data are required to train supervised classification systems and to test both supervised and unsupervised systems.

To overcome the limited availability of real target images, synthetic images could be generated through the simulation process detailed above. The features and characteristics of man-made objects are well known and lead to accurate simulation. However, the ray tracing model can not effectively include the stochastic variability of sonar images introduced through system noise, environmental diversity and inhomogeneities. In addition, the computational complexity can also make it too time consuming.

A compromise between using real and synthetic data can be found in Augmented Reality (AR) simulation, where synthetic target models are embedded on a real image of the seafloor.

3.3.2 GENERATION OF AUGMENTED REALITY IMAGES

In contrast to the ray-tracing model which takes as input the description of the seabed topography, sediment types and the beam patterns, the augmented reality model estimates this information from real sidescan images using an inversion process. This scene data can then be manipulated to include target information and new sidescan images regenerated that realistically integrate the synthetic target within the observed scene.

The overall process is summarized in figure 3 which also illustrates the typical outputs of this technique. The first stage is the estimation of a 3D computer model of the observed scene, which is achieved through analysing the sidescan image and determining the particular characteristics and properties of the seafloor and the observing sensor which resulted in the formation of this image. It is assumed that these characteristics can be represented by a set of 3 parameters per image pixel: seabed altitude (Z), reflectivity of the seafloor (R) and intensity of the illuminating acoustic pulse at that point (Φ). It is then possible to realistically introduce simulated targets by locally modifying these maps according to the height and reflectivity of the target model in order to obtain new elevation and reflectivity maps. After calculating the new height map, the beam-pattern map has to be recomputed in order to account for the changes in elevation, since this map is the projection of the sonar beam-profile on the seafloor. Once the modified maps are obtained, the Augmented Reality image can be rendered.

A classical Lambertian diffuse illumination model has been employed for the AR model for both the inversion and the rendering. In the forward model this is used to calculate the intensity of the point in sonar image using the provided scene parameters. The inverse problem, that of obtaining the scene parameters from a given real sidescan image, is much more complex and requires the utilization of statistical optimization techniques for the inversion which are detailed in [8].

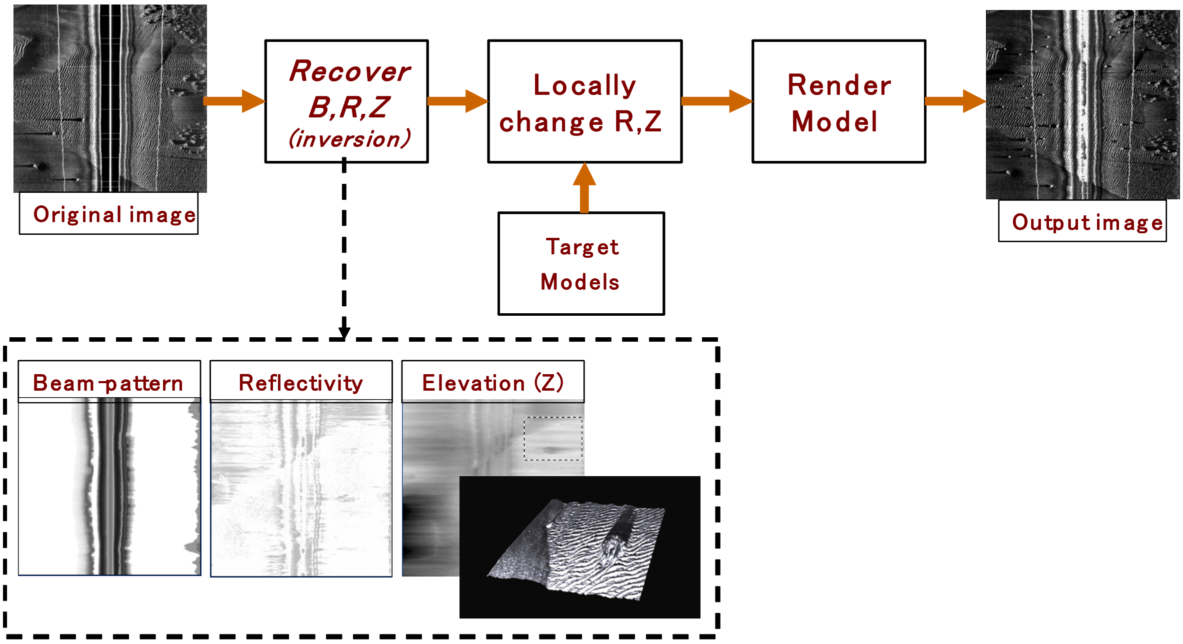

Figure 3. Augmented Reality system.

3.4 APPLICATION OF IMAGE SIMULATION MODELS

The ray tracing and AR models both have a wide range of potential applications. The first can be used in a more general context and the second more suited to automatic target recognition scenarios. Indeed the AR model has been widely used both to train classification systems and to quantify their success [9][10]. The more general model has also been widely used to verify and develop algorithms including the classification of targets [11], orientation dependant classification of sonar imagery [12], tracking for AUV navigation [13] and concurrent mapping and localisation[14].

3.5 ADVANTAGES AND DISADVANTAGES

The advantages of this type of imaging model are apparent from the range of applications discussed above. However there are a number of significant disadvantages of these techniques. One of these is the inability of the ray tracing to accurately consider the stochastic influences. Identical images will always be produced for the same input scene and operating characteristics, a trait which is not witnessed in real data.

An additional disadvantage of the ray based technique arises from the representation of a continuous process with a discrete set of rays. Each ray trajectory is calculated in space and then complex post processing of the computed values for the set of rays representing each transmitted pulse is required to produce the received signal in the time domain.

Although both techniques produce visually realistic synthetic data the accuracy of the output must be considered. Qualitative visual verification suggests that the techniques correctly mimic the characteristics of sonar images, and some statistical verification has also been undertaken [2]. However the resolution of the data which can be achieved is limited. Visually the images appear realistic but since the techniques cannot provide accurate phase information, the signal level data which can be produced is limited. To overcome these limitations the second class of “signal simulation” models for sonar synthesis was developed.

4 SIGNAL SIMULATION MODELS

The aim of this class of models was to produce a complimentary technique providing a complex research tool which can provide accurate calculations of the signal data compared to the more operational approach provided by the ray and AR techniques. The techniques discussed here are based on finite difference time domain (FDTD) modelling.

FDTD methods discretise the wave equation by replacing the exact differential operators with local difference approximations over a discrete space-time grid. This leads to a recurrence relation which relates the pressure at any point within the grid to the pressures at neighbouring points in both space and time. Iteration of this recurrence relation yields a numerical solution to the full spatial and temporal evolution of the acoustic field.

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 (including diffraction); and reflections and scattering at surfaces with appropriate boundary conditions. In addition, realistic source and receiver elements can be positioned anywhere within the scene and the time series obtained. This permits the calculation of a received signal across a distributed array as well as the simulation of multi-static scenarios.

Two forms of this model have been implemented: the Pseudospectral time domain (PSTD) model for the calculation of acoustic fields in fluid environments and a finite difference time domain (FDTD) model for calculations which include solid objects and shear effects.

4.1 PSEUDOSPECTRAL TIME DOMAIN

Elston and Bell [15] originally developed a model based on pseudospectral time domain (PSTD) methods with the aim of simulating the entire sonar process. The pseudospectal time-domain model is strongly related to finite-difference time-domain (FDTD) techniques and essentially represents the “infinite-order” limit of FDTD schemes [16] remaining stable and accurate up to the Nyquist limit of 2 points per wavelength.

Undoubtedly the PSTD model has several attractive features, especially for simulating the sonar responses of seafloors with fluid-like properties (e.g. sand, silt etc). Most of the required aspects, including viscous absorption and attenuation, are automatically included while the propagation model remains relatively simple. Any desired accuracy can be attained with a computational time inversely proportional to the time step as a result of the PSTD algorithm. Example outputs are illustrated in figure 4 which shows a simulated signal, the signal envelope and the combination of several such envelopes to produce a simulated sidescan image. In addition the model can provide an illustration of the acoustic field at any time step which can be useful for analysis and visualisation of the propagating acoustic field.

Its main drawback, however, is the inability to model solid objects and seabeds. This is because solids, unlike fluids and gases, can support shear stresses in addition to the compressional stresses (pressure) supported by all elastic media. The acoustic wave equation is therefore inadequate for modelling the sonar responses of hard seafloors or solid targets (e.g mines). Extension to include elastic scattering is not straight forward as a result of the technique employed to calculate the differences. Within the PSTD method, derivatives are evaluated as multiplication in the frequency domain through the discrete Fourier transform. However in heterogeneous media with large jumps in the values of the material parameters and in particular the shear modulus at object boundaries, the attempt to represent derivatives near such interfaces by a Fourier series results in significant Gibbs phenomena which corrupts the propagating signals and leads to instability.

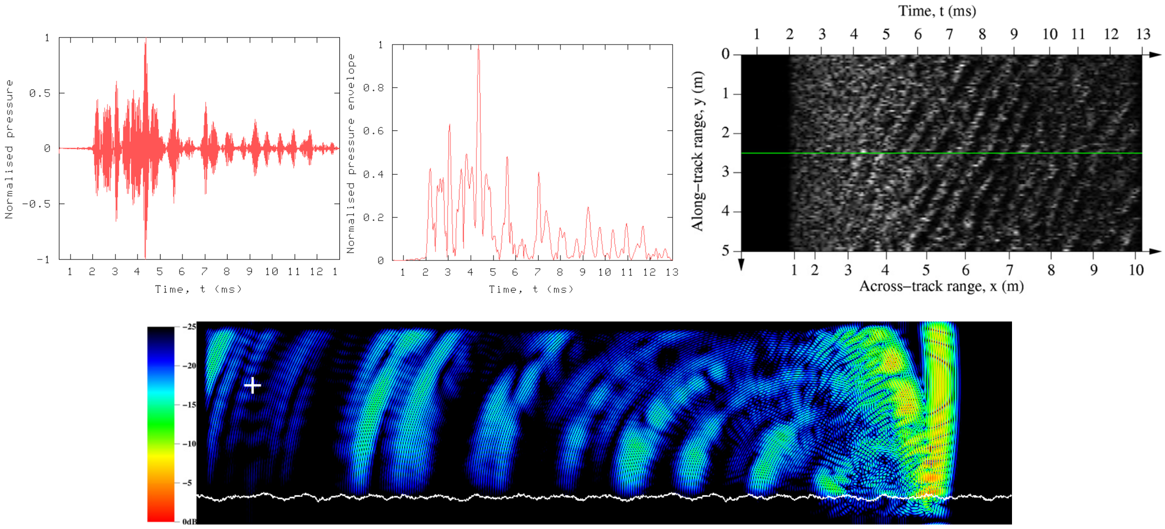

Figure 4. Simulation outputs (a) received signal (b) signal envelope (c) combination of successive signals to form simulated image (d) visualization of acoustic field after 6ms.

4.1.1 FINITE DIFFERENCE TIME DOMAIN (FDTD) MODEL

As a result of this limitation of the PSTD model to accurately model elastic effects, an FDTD model has been developed. The overall structure of this model and its implementation are similar to the PSTD apart from the calculation of the derivatives. The velocity-stress formulation of the elastic wave equation has been used as the propagation model. This model, first introduced by Virieux [17], is described by a first-order system of equations in terms of the velocity and stress rather than the more common second-order form of the elastic wave equation expressed in terms of the displacement vector. This formulation is the most suitable for modelling elastic propagation in isotropic, heterogeneous media as the equation coefficients, expressed in terms of the material parameters, do not need to be continuous. Media interfaces, for example sediment/target/water, can thus be incorporated in the model, represented by changes in the material parameters.

One issue with FDTD based models is the termination of the calculation at the boundary of the computation domain. This is generally an artificial boundary since only a small part of the unbounded underwater scene is considered. However the model considers this boundary to be perfectly reflecting and produces artificial reflections which corrupt the signal of interest. One of the most efficient ways to get round this problem for computational purposes is to impose an *absorbing boundary condition* along part or the entire boundary. The Perfectly Matched Layer (PML) absorbing boundary condition was employed producing a system where no reflection occurs at the interface between the absorbing and main computational cells and the solution decreases exponentially inside the layer of absorbing cells.

A staggered grid, finite difference scheme with second order centred approximation was used to discretise the PML model for the elastic wave equation. The full equations are listed by Lianantonakis [18]. A space-time staggered grid on which the different components of the velocity and stress fields are defined at different neighbouring points was necessary in order to approximate derivatives by central differences. Material averaging [19] was also included to ensure stability and improve accuracy since an offset of half a grid point occurs in the discretised versions of the equations.

The inclusion of elastic scattering increases the range of potential applications and in particular permits the analysis of target scattering. Figure 5 illustrates a very simple scenario of a target on a flat seabed ensonified by a 15kHz pulse and the subsequent outputs if elastic scattering is ignored (Fig 5(b-c)) and when it is included (Fig 5(d-e)).

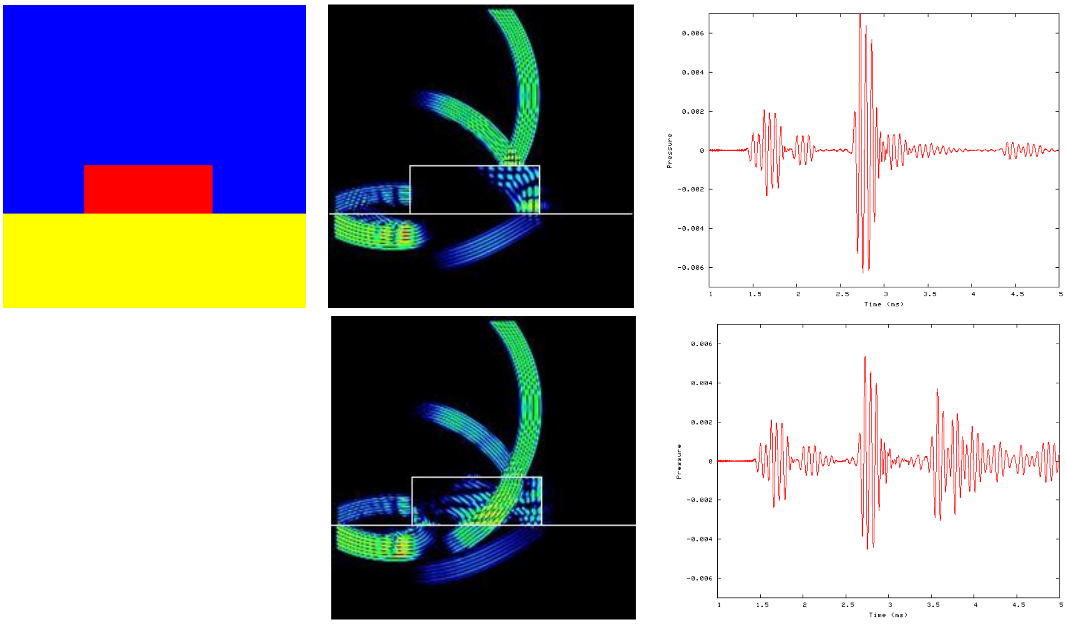

Figure 5. (a) Simulation scene of solid target on flat seabed (b) Acoustic field after 1.7ms and (c) received signal if acoustic only PSTD model is employed (d) Acoustic field after 1.7ms and (c) received signal if elastic wave FDTD model employed

4.2 APPLICATIONS OF FDTD MODELS

These models have been used to analyse a variety of problems. This has included studies to investigate scenarios and techniques under which it may be possible to detect buried targets including multi-static scattering and frequency dependence issues [20]. In addition there is significant interest in the design of novel waveforms for target detection and classification including the potential impact of bio-inspired chirp waveforms [21, 22]. The models have also been employed previously to determine the optimal frequency range for the detection of nets as part of the obstacle avoidance system for an AUV.

4.3 ADVANTAGES AND DISADVANTAGES

The FDTD based models have significant advantages in particular their ability to inherently model all aspects of the problem producing the output directly in the time domain. They can model rough interfaces between materials, inhomogeneities in the sediments and water column, arbitrary time-domain source signals can be introduced at any point and any number of sources and receivers can be positioned within the scene. The output provides a visualization of the acoustic field across the whole scene and provides an accurate representation of the time-series output signal.

The primary disadvantage of these techniques is their computational complexity. The grid sizes are dictated by the frequency of the acoustic source and the time discretisation is also related to the frequency, with an upper limit dictated by stability conditions. As the entire grid is updated at each time step, acceptable run times can only be obtained with the whole simulation in the physical memory of the computer. This limits the methods to modelling environments with ranges of only a few metres in only two dimensions. However, given current increases in processing speed and memory, these bounds are constantly increasing.

5 CONCLUSIONS

There are many different techniques for simulating the sonar process and producing realistic synthetic data. The approaches discussed here can provide complementary roles for the design, testing and visualisation of sonar systems: the FD approach providing accurate research benchmarking and the ray tracing and augmented reality providing faster operational style models.

There is an increasing scope for the application of models, with modeling increasingly underpinning both the design of sonars and the processing algorithms and indeed for unified approaches whereby the sonar and the subsequent processing algorithms are designed together, with one influencing the other.

The integration of different simulation techniques into a hybrid model has also been considered [23]. This would utilize a high resolution model, such as the FDTD technique, to model accurately the acoustic field in the region (and within) objects of interest and then use a lower resolution technique, such as ray theory, to calculate rapidly the field arriving in this region. This approach would combine the advantages of both techniques, however there are still significant issues to be addressed with the transfer of data from one method to the other as a result of the differing natures of each solution.

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7 REFERENCES

1. P.C. Etter. Underwater Acoustics Modelling and Simulation, Taylor & Francis 2003
2. J.M. Bell, L.M. Linnett, ‘Simulation and Analysis of Synthetic Sidescan Sonar Images’, IEE Proceedings - Radar, Sonar and Navigation, 144(4), pp. 219-226, Aug. 1997
3. K.B. Briggs, ‘Microtopographical Roughness of Shallow-Water Continental Shelves,’ IEEE J. Oceanic Eng., 14(4), pp. 360-367 (1989).
4. C.G. Fox and D.E. Hayes, ‘Quantitative Methods for Analyzing the Roughness of the Seafloor,’ Rev. Geophysics, 23(1), pp. 1-48 (1985).
5. APL-UW9407 High Frequency Ocean Environmental Acoustic Models Handbook, Technical Report, Applied Physics Lab, University of Washington
6. J. P. Riordan, D. Toal, ‘Performance Optimised Reverberation Modelling for Real-Time Synthesis of Sidescan Sonar Imagery’, IEEE J. Oceanic Engineering
7. G. Wendleboe, J. Bell, F. Jacobsen, ‘Localisation of Seabed domains ensonified by object reflected sound at very high frequencies’, Boundary influences in high frequency shallow water acoustics, Bath, September 2005
8. E. Coiras, Y. Petillot, D.M. Lane, ‘Multi-resolution 3-D Reconstruction from Side-Scan Sonar Images’, IEEE Trans. Image Processing, Vol. 16, No. 2, pp. 382-390, February 2007
9. PY. Mignotte, E. Coiras, H. Rohou, Y. Petillot, J. Bell and K. Lebart, ‘Adaptive fusion frame work based on augmented reality training ‘, IET Radar, Sonar and Nav, 2(2), 146-154, 2008
10. E. Coiras, PY. Mignotte, Y. Petillot, J. Bell and K. Lebart, ‘Supervised Target Detection and Classification By Training on Augmented Reality Data’, IET Proceeding - Radar, Sonar and Navigation, 1(1) , p. 83-90, February 2007
11. S. Reed, Y. Petillot and J. Bell, ‘An Unsupervised Approach to the Detection and Extraction of Mine Features in Sidescan Sonar’, IEEE J. Oceanic Engineering 28(1), 90-105, Jan 2003
12. E. Dura, J. Bell, D.M. Lane, ‘Reconstruction of Textured Seafloors from Side-Scan Sonar Images’, IEE Proceedings – Radar, Sonar and Navigation, 151(2), pp. 114-126, April 2004
13. D. Clark, I Tena-Ruiz, Y. Petillot and J.Bell, ‘Particle PHD Filter Mulitple Target Tracking in Sonar Images’, IEEE Trans. Aerospace & Electronic Systems, 43(1), 409-416, Jan 2007
14. S. Reed, I. Tena-Ruiz, Y. Petillot, D.M. Lane and J.M. Bell, ‘Concurrent Mapping and Localisation using Side-scan Sonar for Autonomous Navigation’, 13th Int. Symp. Unmanned Untethered Submersible Technology (UUST03), New Hampshire, August 2003
15. G.R. Elston, J.M. Bell, ‘Pseudospectral Time Domain Modeling of Non-Rayleigh Reverberation: Synthesis and Statistical Analysis of a Sidescan Sonar Image of Sand Ripples’, IEEE J. Oceanic Eng, 29(2), April 2004
16. B. Fornberg, A Practical Guide to Pseudospectal Methods. Cambridge University Press, 1996; pp. 36-47

17. J. Virieux, ‘SH-wave propagation in heterogeneous media’, Geophysics, 49(11), 1933-1942
18. M. Lianantonakis, ‘Sonar Simulation: Modelling the effect of shear from elastic objects and seabeds’, Project report for QinetiQ, March 2003
19. Q-H. Liu, ‘A three dimensional finite difference simulation of sonic logging’, J. Acoust. Soc. Am, 100(1), 72-79, 1996
20. J. Bell, M. Lianantonakis, ‘Analysis of Target Scattering using a Finite Difference Time Domain Model’, in Proceedings of the Institute of Acoustics Conference on Sonar Transducers and Numerical Modelling, Vol. 27, Pt. 1, March 2005.
21. Y. Pailhas, C. Capus and K. Brown, ‘The Multiview limitation of target classification by broadband echo analysis’, IEEE Oceans 2007, Aberdeen 2007
22. Y. Pailhas, C. Capus and K. Brown , ‘Classification of bottom-set targets from wideband echo responses to bioinspired sonar pulses’, Proc IOA 29(3), Bio-Acosutics 2007
23. S. Page, R. Brothers, K. Murphy, G. Elston and J.M. Bell, ‘A hybrid ray-trace/finite difference model for target strength evaluation’, 5th European Conference Underwater Acoustics, Lyon, July 2000, pp. 15-20