THE SIMULATION OF SIDE SCAN SONAR IMAGES USING RAY TRACING TECHNIQUES

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Abstract
Recent progress in computer graphics has produced techniques which create extremely realistic images by modelling the behaviour of light as it interacts with the objects in a scene. This paper presents some initial attempts at using the light model as a vehicle for the development of a sonar simulation system; the aim being to produce synthetic images which closely approximate real side scan sonar images. Using this approximation to the sonar process, the effects of several variables are explored. For example, beam shape and orientation, and basic sediment properties such as reflection coefficient and microstructure. Some analogies with light will be presented and the results of some simulations compared with real images will be given.

1. INTRODUCTION

1.1 Computer graphics
Ray tracing is a well known technique in computer graphics. Impressive and realistic images are built up by calculating the level and colour of light at each point as a result of the interactions of the surface with rays emanating from elsewhere in the scene. Snooker balls on a chess board show reflections of each other and the squares of the board, and reflections of those reflections and so on.

Ray tracing was originally used in computer graphics by Appel [1] and was introduced in its current form by Kay [2] and Whitted [3]. Each ray is traced backwards from the eye through a pixel in the viewing plane until it hits an object. If the surface is reflective or transparent, the trace continues recursively. This is illustrated in figure 1. The light intensity of a pixel is equal to the local contribution plus reflected contribution plus transmitted contribution.

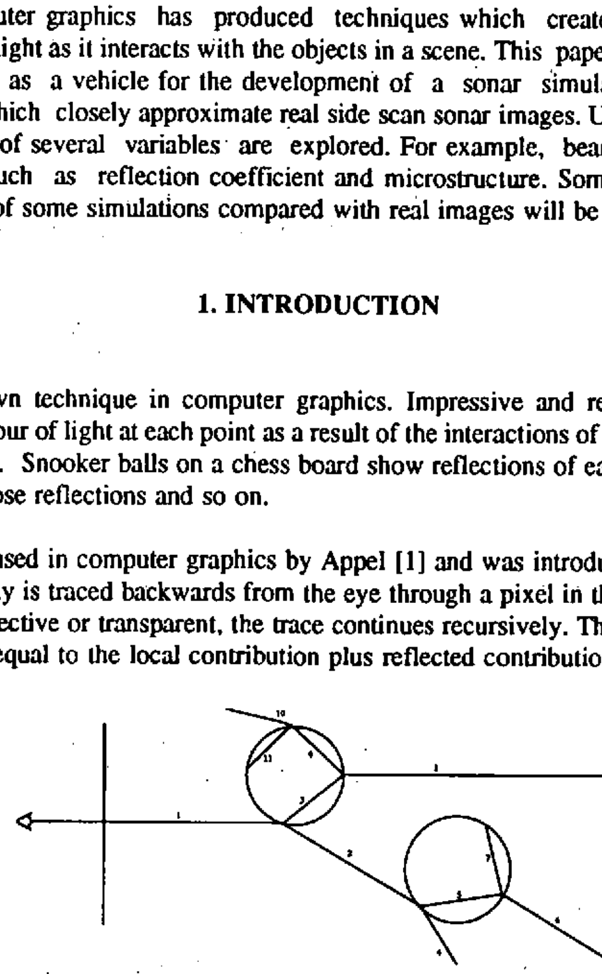


Figure 1. Recursive ray trace following ray of light through reflections and refractions

Examples of ray traced images frequently consist of spheres and other basic geometric primitives. Calculating ray intersections for simple scene descriptions is straight forward, but to do this for natural scenes such as the seabed is more complicated. Several fractal models have been developed which are capable of producing realistic images of different seabed types and these models will be described in a later section.

1.2 Underwater acoustics
In underwater acoustics, the term 'ray tracing' has become associated with the production of ray diagrams. Buckingham [4] gives a review of a number of ray trace codes currently in use, including GRASS (Germinating Ray-Acoustics Simulation System, from the Naval Research Laboratory, Washington DC), PLRAY (Ray Propagation Loss, from the Naval Air Development Centre, Warminster, Pennsylvania) and HARPO (Hamiltonian Acoustic Ray-tracing Program for the Ocean, from the National Oceanic and Atmospheric Administration, Colorado) which

is a three dimensional ocean acoustic ray tracing program. HARPO is further described in Georges et al [5]. The ray solution of the wave equation is a high frequency approximation, valid when wavelength is very much less than water depth and bottom and surface roughness. The models give a useful pictorial representation of the sound field in the channel.

'Ray tracing' also has an extensive literature in the fields of auditoria design, for example, Krokstad et al [6] and sound propagation in air, for example Hallberg et al [7].

2. SONAR SIMULATION

With the program described in this paper, the images do not show the paths of the rays themselves, but the trace which those rays would produce. The technique of ray tracing, in the computer graphics sense, is used to mimic a side scan sonar.

A side scan sonar displays the time it takes for a pulse to travel from the transducer to a target and return. With a pen plotter, a current proportional to the echo strength passes through an electrosensitive paper, so that stronger echoes make darker marks. As the ship moves forward, successive scan lines build up an image. The computer program simulates this process by generating one line of pixels at a time. The position of a pixel is related to time elapsed since the sound pulse was transmitted and the intensity of that pixel is proportional to the sound returned after that time.

The light model applies Lambert's law for scattering from matt surfaces. The rule assumes that a perfect diffuser scatters light equally in all directions, so that the amount of reflected light seen by a viewer does not depend on the viewer's position [8]. The intensity of diffuse reflected light,

$$I_d = I_i k_d \cos\theta \qquad 0 \le \theta \le \pi/2$$

where I_i is the intensity of the light source, k_d is the diffuse reflection coefficient and θ is the angle between the surface normal and a line from the surface point to the light source.
In vector notation, this is

$$I_d = I_i\, k_d\, (\mathbf{L}.\mathbf{N})$$

where **N** is the surface normal and **L** the direction vector from the light source to the point on the surface.

Many materials follow Lambert's law closely in scattering light and it is also a good approximation for backscattering of sound by rough sea bottoms [9].

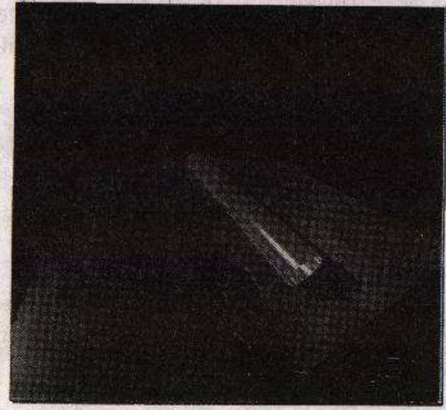
For smoother materials, a specular reflection of light or sound is seen around a reflection angle equal to the angle of incidence.The intensity of light returned is then diffuse plus specular component, according to the Phong model:

$$I = I_d + I_i\, k_s\, (\mathbf{R}.\mathbf{V})^n$$

where k_s is the specular reflection coefficient, **R** is the direction along which specular light is reflected and **V** is the viewing direction. A large value of n gives a small highlight area.

This simple model forms the basis of the simulation and produces images which show good agreement with real traces.

Figures 2 (a) and (b) show a short section of pipe on the seabed. Where the pipe lies on the seabed, the sonar shadow appears next to the light return from the pipe. Where there is a span or space beneath the pipe, the shadow moves away from the return. This is also shown on the actual image in figure 2(c).



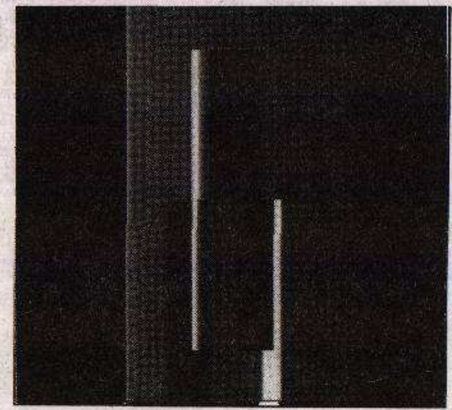


Figure 2. (a) Light image. (b) Simulated sonar image (transducer path on left hand side).

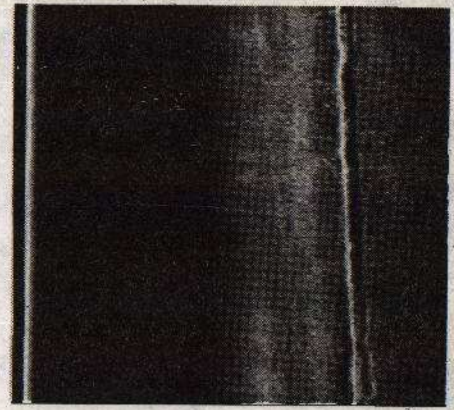


Figure 2 (c) Actual sonar image of seabed pipeline.

3. DIFFERENCES BETWEEN LIGHT AND SOUND AS ILLUMINATORS

The naive use of the light model for sonar simulation produces promising results, but there are a number of differences between the principles of light and acoustics which must be considered. The first of these is the difference in wavelength between the two illuminators.

In the original computer graphics techniques, light is taken as a continuous wave emanating from the source. In sonar applications, sound is usually emitted as pulses and must be modelled as such. These pulses produce a frequency spectrum centred around the main operating frequency but with sidebands produced by the time limited window. This time limiting affects the bandwidth and consequently this has an effect on the resolution of detail within the signal return.

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In the computer graphics models, the light is traversing through air to illuminate the object, and the medium is physically treated as a vacuum and neglected from the calculations.

The medium can not be neglected for sonar simulations as the seawater produces substantial refraction effects. This is due to the variation in the velocity of propagation of sound in seawater from place to place and particularly with depth, which is influenced by three major factors: depth, temperature and salinity. This can be illustrated using the standard expressions for sound velocity,

$$c = 1449 + 4.6t - 0.55\,t^2 + 0.0003\,t^3 + (1.39 - 0.012t)(s - 35) + d/61$$

where c = velocity in metres per second, t = temp in degrees celsius, d = depth in metres, s = salinity in parts per thousand.

It is the temperature of water which produces the most substantial of effects, but it is not always a predictable parameter as it is influenced by latitude, weather, season and time of day.

Using the basic laws of reflection and the refraction principles of Snell's Law, the classical two dimensional ray traces can be easily constructed, as shown in figure 3. These illustrate clearly the effect of even a small change in velocity of propagation and illustrate the bending of rays towards regions of minimum velocity, producing shadow zones.

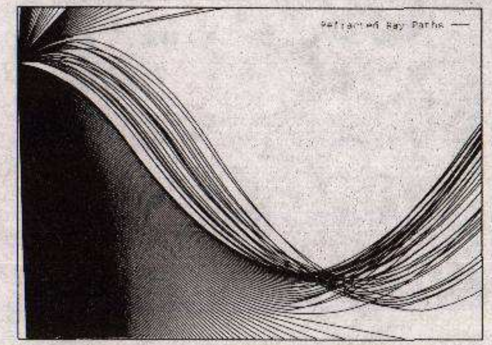

Figure 3. Ray traced diagram showing only refraction effects.

This distortion of the ray path must be accounted for during the creation of the sonar simulations as it will produce anomalies due to the shadow zones and the variation in path lengths. Once incorporated into the program it will permit simulation of effects such as ghosting or the production of caustics.

Although illustrating how complex an effect the medium will have on the sonar simulation, this is still a simplification as it considers only the variation in velocity with depth and not with distance. In practice there is also another group of effects which is quite different in that the variations within the medium cannot be specified in regard to space or time, i.e. reverberation and fluctuation. Random effects of this kind can be specified only in terms of statistical parameters and will further complicate the modelling process.

4. BEAM PATTERNS

A further difference between the light and sound illuminators is the beam pattern. The most simple light source is a point source, radiating equally in all directions. The ideal sound source is a perfect, knife edge beam, one pixel wide horizontally and uniform in all directions vertically. This beam was used to produce figure 2(b) and figure 4(a). Objects on the seabed always appear perfectly sharp and resolution does not deteriorate with distance from the transducer. The first approximation to a beam pattern is a fan beam, where the beam spreads out horizontally by a user definable angle. Resolution then deteriorates with distance, as shown in figure 4(b).

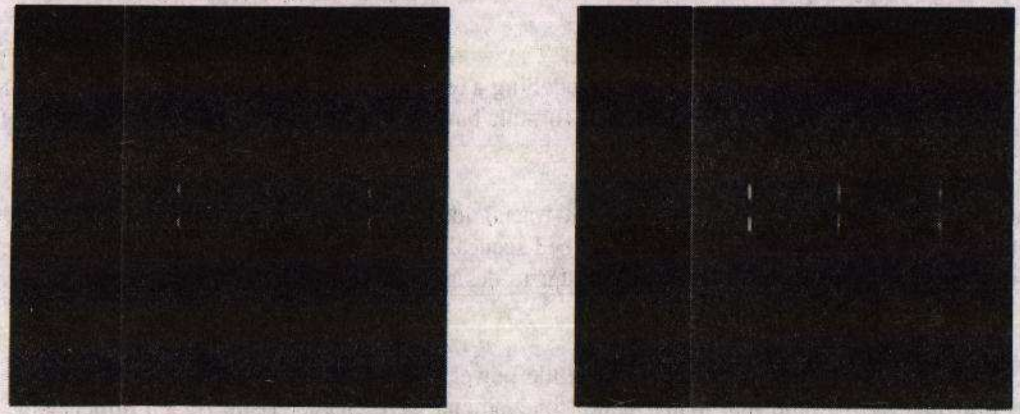

Figure 4. 3 pairs of objects on the seabed
(a) ideal sound source (b) fan beam sound source (angle 2.5 degrees)

5. SEABED MODELLING.

5.1 Material properties

The image, or intensity map, of the seafloor produced by a side scan sonar is a function of material properties and surface shape. A flat sea bottom with a pattern of materials of different reflection coefficients can give the same image as a single material bottom with appropriate relief, as shown in figure 5.

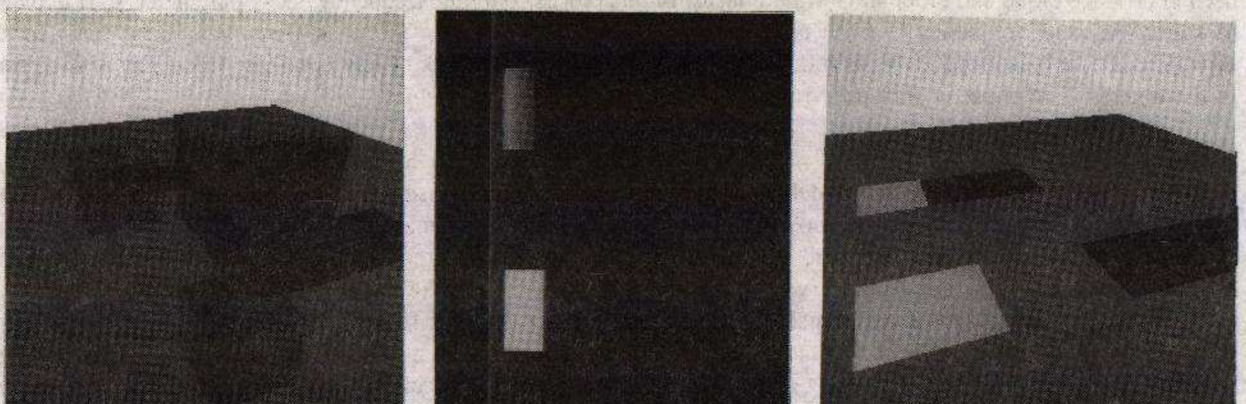

Figure 5 Light and sound images showing a sonar trace with two possible interpretations.

In seabed modelling, therefore, there are two main factors to consider - (i) the reflective properties of the seabed and the targets upon it, and (ii) the shape, or relief, of the seabed.

5.2 Fractals

The advent of fractals [10] and the impetus given to imagery by computer graphics has resulted in the creation of many realistic images. Some excellent examples of computer generated fractal images of natural scenes have appeared. These began with the work of Voss [11] and have appeared as illustrations in the work of Mandelbrot [10]. They are mainly of mountainous terrain and, by careful control of colour mapping, clouds. A realistic planet can be produced by using computer graphics techniques which enable a surface to be wrapped around a sphere.

Since then other authors have extended the work. The works of Lewis [12] and Mastin [13] are particularly impressive. Lewis used stochastic techniques for modelling a texture based on a given autocorrelation function, and Mastin et al. produced a sea model using an intricate formula based on the Pierson-Moskowicz spectrum [14]. Neither of these techniques was fractal based.

In the following section, several models based on fractal ideas are considered, some of which are capable of producing excellent representations of synthetic seabed scenes. In this work emphasis is solely on modelling in the frequency domain in two dimensions, which is similar to designing suitable 2D filters for filtering a random noise image.

The essence of modelling using fractal ideas is that the power spectral density obeys a $1/f$ relationship (where f = frequency). Burrough [15] found that many natural phenomena have characteristic fractal dimensions, e.g.clouds, craters, shorelines and wind-blown sand. In having this characteristic fractal dimension, they have associated power spectral densities in which the fractal dimension is related to the frequency decay exponent, β. To facilitate development of the models, the spectra of several natural seabed textures were examined. The models developed extend the ideas of a single fractal producing an isotropic image to those producing varying fractal dimensions in different directions, and also to the idea of multi-fractal images.

5.3. Some fractal models of texture.

Model 1.

This is the simplest model and is the one which directly models the fractal processes. This model is the one usually used to produce cloud and mountain terrain images. In this process only the frequency decay parameter, β, is allowed to vary. The peak frequency is fixed at zero (DC) and the roll off from the peak frequency is the same in all directions, i.e. it is isotropic. This is reflected in the fact that there is a lack of any dominant frequency or direction in the images. The phase is uniformly random in the range $-\pi$ to π.

Model 2.

The next stage in using the fractal modelling technique is to maintain the isotropic decrease of the frequency decay and to allow the peak frequency to move away from DC. Immediately many variations present themselves. The simplest is to move the DC component to a position within one of the frequency quadrants (duplicating it in the diagonally opposite quadrant, to preserve the symmetry relationships of the Fourier Transform) and observing the effect. The result is now an image which is very similar to some textures found naturally on the sea floor. Figure 6 shows the image produced from this model with a β value of 1.4 (giving a fractal dimension of 2.1). In this image the peak frequency in the *x*-direction (f_x) was 8 units and that in the *y*-direction (f_y) was 4 units. The image size is 256 * 256 and the range of pixel values is 0..255. This model then simply locates a peak frequency(F_{peak}) given by

$$F_{peak} = (f_x^2 + f_y^2)^{1/2}$$

where the direction(θ) of the texture is given by

$$\theta = tan^{-1}(f_y/f_x)$$

The frequencies away from the peak are evaluated as $1/(F^{\beta})$ where F is found from an expression similar to that for F_{peak} at the particular x and y frequencies.

Figures 6 Model 2 image, β = 1.4

If this model is extended to include more peak frequencies, more images of plausible textures emerge. For example, if the peak frequency of figure 6 is duplicated in another quadrant, now giving the same peak frequency in each of the four quadrants, a more structured texture appears. The idea of adding more peak frequencies may be extended, producing in effect multifractal textures. If a second peak frequency is added in the same quadrant to the one shown in figure 6, further realistic images of the seabed are produced.

Model 3.
This model is similar to model 2 except that the frequency decay is anisotropic. The amplitude of the frequency response is allowed to decay in a $1/f^{\beta}$ manner in a direction from the peak frequency to DC and in a similar manner at right angles to this. The value of β in each direction need not be the same. This model was developed to investigate the effect of anisotropy on the texture, and whether or not differing roll off rates in different directions affected the visual appearance of the texture. Mathematically the modelling equations are :-

$$F_{xy} = |f_x - f_{xpeak}|^{-\beta x} . |f_y - f_{ypeak}|^{-\beta y}$$

$$\text{where } |f_x - f_{xpeak}| = 1 \text{ if } |f_x - f_{xpeak}| \leq 1$$

$$\text{and } |f_y - f_{ypeak}| = 1 \text{ if } |f_y - f_{ypeak}| \leq 1$$

Here | | signifies absolute value, β_x and β_y are the roll offs in the x and y directions, f_{xpeak} and f_{ypeak} are the peak frequencies in these directions, and f_x, f_y are the frequencies at a point (x,y) in the frequency domain.

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6. CONCLUSION

The ray tracing program uses techniques from computer graphics to simulate side scan sonar images. In its simplest form, the model is capable of producing images which show good agreement with real examples. It is recognised, however, that many assumptions and approximations have been made and some of these have been discussed. As the program develops it will be used to model the effects of variables such as beam pattern and sediment properties. As ray tracing in computer graphics has helped the physicist to study interactions with light, so ray tracing with sound will help with the study of the sonar process in three dimensions.

7. REFERENCES

[1] A. Appel, *Some techniques for shading machine renderings of solids*, AFIPS Conference Proc. 32 pp37-45 1968

[2] D.S. Kay, *Transparency, refraction and ray tracing for computer synthesised images*, Masters Thesis, Cornell University, 1979

[3] T. Whitted, *An improved illumination model for shaded display*, Communications of the ACM 23 (6) 1980

[4] M.J. Buckingham, *Ocean-acoustic propagation models*, J Acoustique pp223-287 1992

[5] T.M. Georges,R.M. Jones, J.P. Riley, *Simulating ocean acoustic tomography measurements with Hamiltonian ray tracing*, IEEE Journal of Oceanic Engineering. 11 (1) pp58-71 1986

[6] A. Krokstad, S. Strom, S. Sorsdal, *Fifteen years experience with computerised ray tracing*, Applied acoustics, Vol 16 pp291-312 1983

[7] B. Hallberg, C. Larsson, S Israelsson, *Numerical ray tracing in the atmospheric surface layer*, J. Acoust. Soc. Am. 83 (6) pp2059-2068 1988

[8] A.H. Watt, *Fundamentals of three-dimensional computer graphics*, Addison-Wesley publishing company. 1990

[9] R.J. Urick, *Principles of underwater sound*, 3rd edition, McGraw-Hill Book Company. 1983

[10] B.B.Mandelbrot, *The Fractal Geometry of Nature*, W. H. Freeman, New York, 1983

[11] R.F.Voss, *Random Fractal Forgeries*, in Fundamental Algorithms For Computer Graphics, R.A.Earnshaw (ed.), Springer-Verlag, Berlin, 1985 pp805-835

[12] J.P.Lewis, *Generalised Stochastic Subdivision*, ACM Transactions on Graphics, Vol 6 No.3 pp167-190 July 1987

[13] G.A.Mastin, P.A.Watterberg, J.F.Mareda, *Fourier Synthesis of Ocean Scenes*, IEEE Computer Graphics and Applications, pp16-23 March 1987

[14] W.J.Pierson, L.Moskowicz, *A Proposed Spatial Form for Fully Developed Wind Seas Based on the Similarity Theory of S.A.Kilaigorodskii*, J. Geophysical Research, pp5181-5190 December 1964

[15] P.Burrough, Fakes, Facsimiles and Facts: Fractal Models of Geophysical Phenomena, in *Science and Uncertainty*, Proceedings of a Conference, London, March 1984, pp150-169, IBM UK Ltd., Science Reviews Ltd. 1985

[16] S.Lovejoy, *Area-Perimeter Relation For Rain and Cloud Areas*, Science, Vol.216, pp185-187 1982

[17] P.Burrough, *Fractal Dimension of Landscapes and Other Environmental Data*, Nature, Vol.294, pp240-242 1981