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Remote sensing in underwater archaeology: simulation of side scan sonar images using ray tracing techniques

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6.1. Introduction

Marine archaeologists have used remote sensing devices with varying degrees of success since at least 1966. The most obvious devices are sonar, side scan sonar, sub bottom profilers, and magnetometers and examples of their use are given.

A unique computer program has been developed to simulate side scan sonar images. The system applies ray tracing techniques from computer graphics to the problems of underwater acoustics. Simulated images show good agreement with real results and some examples are given below to illustrate some of the problems of interpreting side scan images when searching for and surveying archaeological remains under water.

6.2. The archaeological potential of the seabed

Recently, BP commissioned a study to evaluate the impact of test drilling and oil production in the Poole Bay area (Velegrakis *et al.* 1992). The proposed drilling project involved the construction of an artificial island from which boreholes would be sunk, linked to the land by two trenches. The north trench was planned as a shallow, 3km long service trench. The south trench would hold the oil pipeline and be 4m deep.

The study firstly considered the archaeological potential of the site. The water depth of much of the area affected is less than 5m and almost all is less than 10m. During the Late Devensian, sea level in the English Channel was around -118m OD (Ordnance Datum) and so Britain's shoreline was some 50km south of the present coast. By around 9,000 BP, sea level in the project area had risen to -25m OD, but the site was still dry land and could have contained settlements. By *c.* 5,500 BP, sea level may have advanced within the bay to around -5m OD. There is then archaeological and documentary evidence for maritime activity in the area from the Bronze Age, through the Iron Age, to Roman, Saxon and Medieval times, and on to the present day.

In short, the area could contain anything from submerged palaeochannels to modern shipwrecks. The study concluded "that the area is high in its archaeological potential, probably one of the highest along the southern coastline of England".

In a densely populated country such as Britain, though, this area is by no means unique in its archaeological potential. The conclusion could be echoed all around our coasts. With ever increasing demands on the seabed from industry, important sites could be dredged up for building aggregate without anyone even knowing that they exist.

In the case of Poole Bay, the project was abandoned and replaced by an innovative process whereby the drilling could take place on shore and be directed horizontally to the required spot in the bay.

6.3. Remote sensing

The Poole Bay study included an assessment of echo-sounder, side scan sonar, and sub-bottom profiler data which identified 77 targets needing further examination. As the project was abandoned, these targets were not identified.

A simple sonar, echo sounder, or fathometer will give the depth of water from the time taken for a pulse of sound to travel from the transducer to the sea floor and back again. As it is looking directly downwards, very narrow bands are covered as the ship tracks back and forth. By turning sonar on its side, larger areas can be covered each side of the ship's track. 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 electrosensitive paper, so that stronger echoes make darker marks. As the ship moves forward, successive scan lines build up an image (Fig. 6.1).

With a sub-bottom profiler, a beam of low frequency sound penetrates the sea bed and gives a section through the underlying material.

Redknap & Fleming (1985) describe the use of a suite of equipment including these devices, and a magnetometer to detect anomalies in the Earth's magnetic field caused by iron and steel objects. In 1983, the Marine Archaeological Survey (MAS) identified 98 significant contacts in just 7.5km^2 of sea bed in the North Goodwin Sands. The area consists of continually shifting sands which periodically expose and re-bury remains of early wrecks.

Loch Ness has been the subject of many investigations. Klein & Finkelstein (1976) describe the use of a combined side scan sonar/sub-bottom profiler system, which failed to find any large skeletons, and a side scan sonar used in stationary "watching" mode, with moving objects labelled "Nessiteras rhombopteryx". Morrison (1981) explains the "stone circles" found by side scan sonar on the bottom of Loch Ness and Holmes (1981; 1992) describes the search for and retrieval of the Wellington bomber now being conserved in Brooklands Museum, Surrey. Most recently, in 1992, Project Urquhart investigated the Loch with an im-

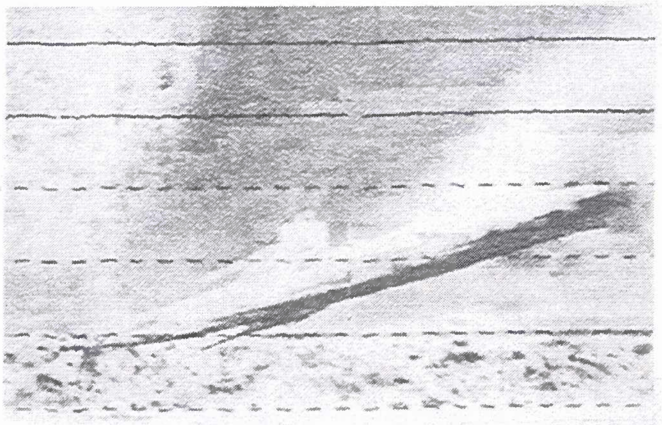


Figure 6.1: Side scan sonar image of the M2 submarine in Lyme Bay. The high return from the hull shows as the dark area. Details of the superstructure can be seen in the sonar shadow, or light area.

pressive array of equipment, including acoustic and visual systems.

The Nautical Archaeology Society guide (NAS 1992) gives a readable introduction to underwater work, including search and survey, and further examples of the use of remote sensing devices are given in Blake (1991; 1992).

6.4. Waves and rays

A beam of light or a pulse of sound may be thought of as a continuous wave, spreading out like ripples after a pebble has been thrown into a pond, or it may be thought of as a number of discrete "rays" (Fig. 6.2).

The following sections describe a computer program which generates simulated side scan sonar images by calculating the path of each ray of sound. The system applies the principles of ray tracing from computer graphics to the problems of underwater acoustics.

6.5. Ray tracing in 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 (1968) and was introduced in its current form by Kay (1979) and Whitted (1980). Kuchkada (1987) gives a practical guide to ray tracing and C code for a basic system. Each ray of light 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 Fig. 6.3. The light intensity of a pixel is equal to the local contribution plus reflected contribution plus transmitted contribution.

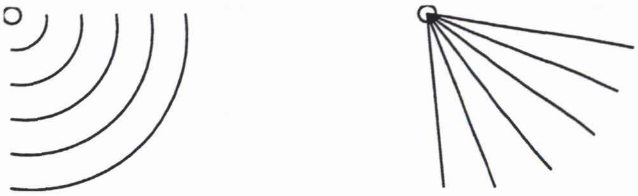


Figure 6.2: Wave and ray representations.

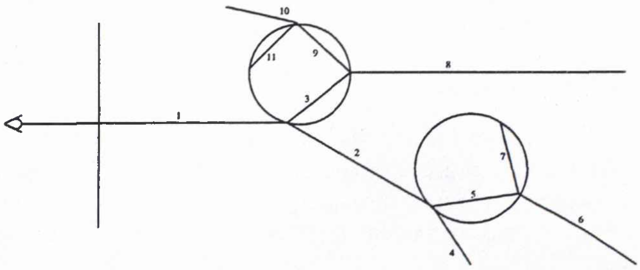


Figure 6.3: Recursive ray trace following ray of light through reflections and refractions

6.6. Sonar simulation

The computer program simulates the sonar process by replacing the light source and eye point by an imaginary sonar transducer. This is both transmitter and receiver. As a real transducer is towed through the water, so the simulated source also moves in space, generating one line of pixels at a time. A beam of rays is emitted and as each ray returns, its intensity is added to a pixel calculated from time elapsed since the sound pulse was transmitted.

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 (Watt 1990). The intensity of diffuse reflected light:

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

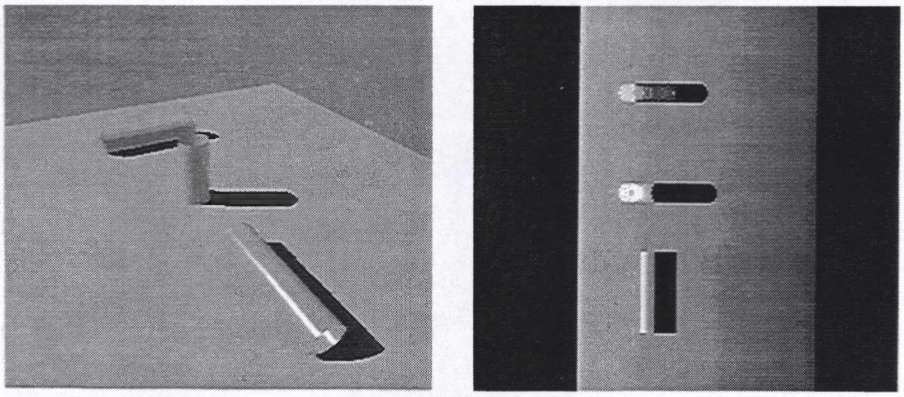
where I_i is the intensity of the light source, k_d is the diffuse reflection coefficient and θ is the angle between the surface normal and a line from the surface point to the light source.

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 (Urick 1983).

This simple model forms the basis of the simulation and produces images which show good agreement with real traces. The method is described further in Blake *et al.* (1993). Example images produced by the system are used in the following sections to illustrate some of the problems of interpreting side scan images when searching for and surveying archaeological remains underwater.

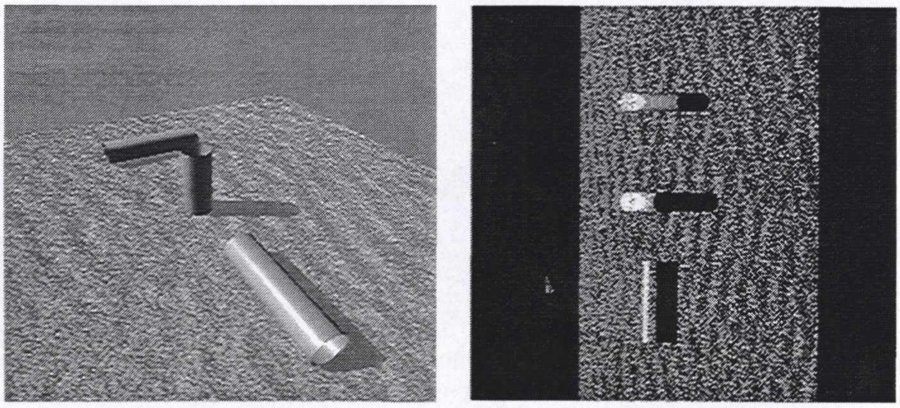
6.7. Interpretation of side scan images

Examples of side scan sonar images in the literature frequently show intact ships which are easily recognisable.



(a) (b)

Figure 6.4: Cylinder at different orientations (a) light image (b) simulated sonar.(High returns are light and low returns are dark — this is the opposite convention to that used in Fig. 6.1).



(a) (b)

Figure 6.5: Cylinders as shown in Figs. 6.4a and 6.4b, but with ripples.

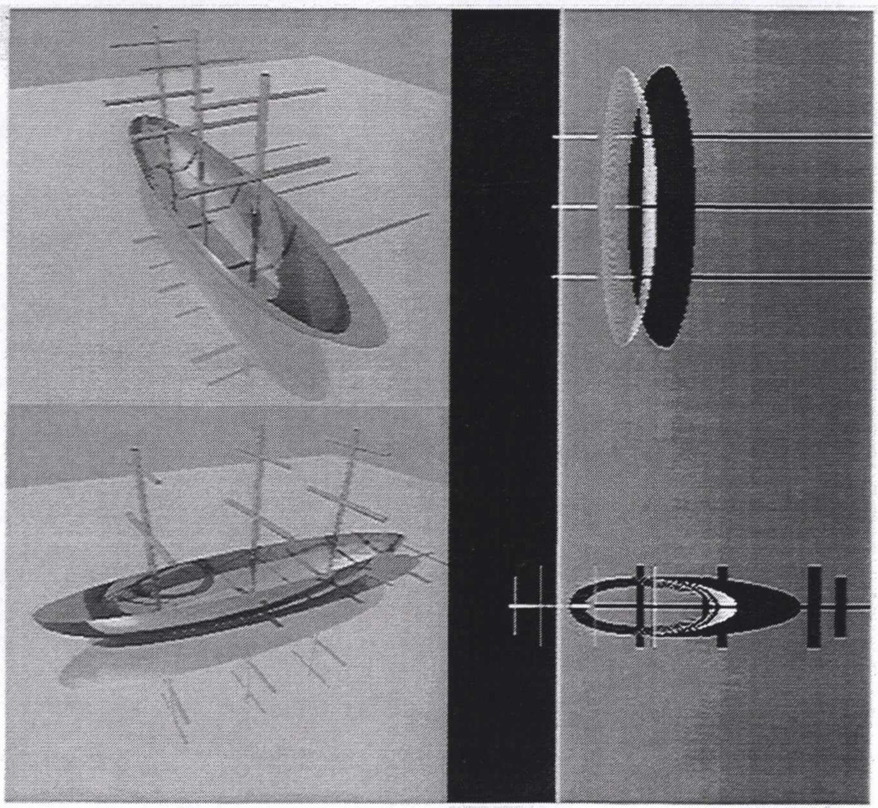


Figure 6.6: Simulated schooner at different orientations.

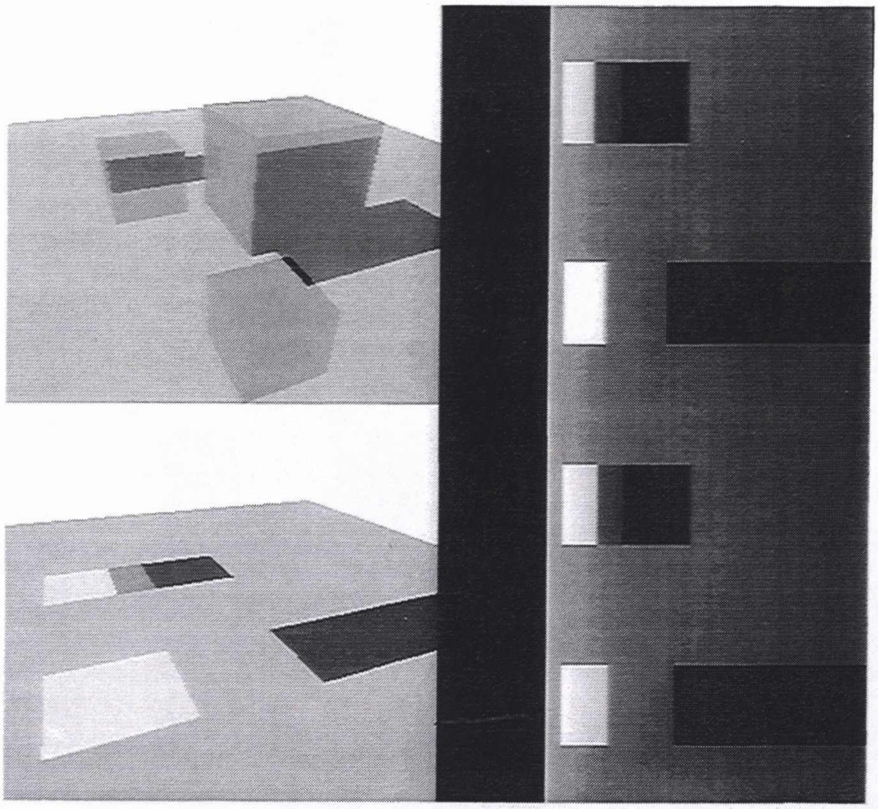


Figure 6.7: Areas of high and low reflectivity on a flat surface can mimic the high return and shadow produced by objects on the surface.

Fig. 6.1 in this paper is no exception. In well preserved wrecks such as the Hamilton and the Scourge (sunk in the War of 1812 in Lake Ontario) even the masts and superstructure are visible (Throckmorton 1987). In archaeological searches, the vessels are more likely to be broken up and partially buried, with artefacts scattered over a wide area.

An amphora mound on a flat sandy bottom will show up beautifully, but smaller objects can easily disappear against a background of sand ripples, pebbles, or coral.

The same object can appear differently on a side scan sonar trace, depending on the frequency of the sonar, the seabed sediment type and the direction in which the fish is towed over it. Figs. 6.4a and 6.4b show light and simulated sonar images of a cylindrical object (which might be a cannon or a seabed mine) at different orientations. In Fig. 6.4b and following illustrations, the sonar fish can be thought of as flying down the left hand side of the picture and although side scan sonar covers areas to either side of the ship, only one side of the trace is shown.

Figs 6.5a and 6.5b show the same scene as 6.4a and 6.4b but with a sand ripple effect superimposed upon it. The ripple effect is achieved by mapping a fractal image onto a flat surface by the technique of "bump mapping", as proposed by Blinn (1978).

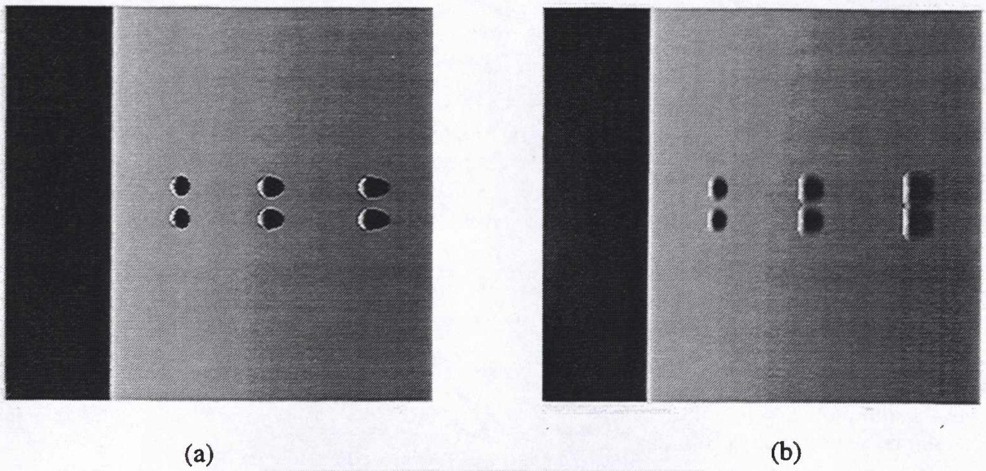
Fig. 6.6 shows how even an intact vessel can be more difficult to recognise if the sonar fish is towed across the bows.

The image, or intensity map, of the sea floor produced by a side scan sonar is a function of material properties and surface shape. Fig. 6.7 shows how a flat sea bottom with a pattern of different materials can give the same image as a single-material bottom with appropriate relief.

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. For example, for light travelling through air, the medium can be treated as a vacuum and ignored, but for sound travelling through sea water, the variation of speed of sound with temperature, pressure and salinity produces substantial refraction effects. The distortion of the ray paths follows Snell's Law and can lead to shadow zones — areas of seabed which are not covered. Buckingham (1992) discusses the behaviour of sound underwater in some detail and Stewart (1989) describes some of the anomalies that can be produced by the sensor.

The ideal beam of sound is a perfect, knife edge beam, one pixel wide horizontally and uniform in all directions vertically. With such a beam, objects on the seabed always appear perfectly sharp and resolution does not deteriorate with distance from the transducer, as shown in Fig. 6.8a. In reality, the beam is a complex shape defined by the design of the transducer, but as a first approximation, the beam may be modelled as a fan shape. Rays are also followed along paths to either side of the ideal knife edge but the intensities returned are still added to the current line of pixels. The fan view is condensed into one line of pixels. Resolution decreases with distance, as shown in Fig. 6.8b.

In the initial examples, sound rays were not followed beyond the first hit. Sound will reflect from the sea floor, the sea surface, layers of water of different properties, and any objects present. It is necessary to follow the rays along all these reflections (and refractions) and this further degrades the image. "Ghost images" occur as the same object appears firstly as a strong echo from its direct reflection



(a)

(b)

Figure 6.8: (a) ideal beam, (b) fan beam.

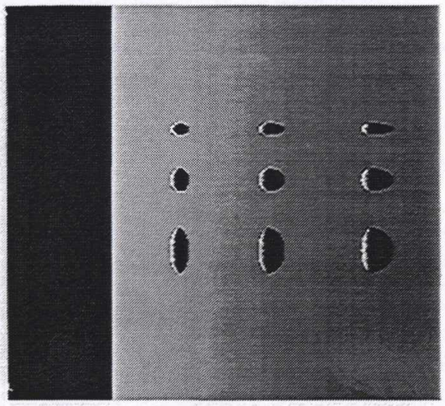


Figure 6.9: The effects of changing fish speed.

and then later as a weaker echo reflected via the sea surface or some other boundary.

As a further complication, the sonar fish may not always be towed straight, level and at a constant speed. If the fish loses altitude and dips towards the seabed, or if the ship turns or changes speed then the sonar image becomes distorted. Fig. 6.9 shows a simulated sonar image of nine identical spheres. Where the ship is travelling at double speed the spheres appear compressed, and where it is travelling at half speed, the spheres are elongated.

6.8. 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, and these illustrate some of the problems which face an archaeologist searching for sites underwater. With the program's ability to show both light and simulated sonar images of scenes, it could be a useful training tool for those learning sonar interpretation.

However, the main purpose of the research is to study side scan sonar image production. A great deal of research effort is spent on image processing. This involves taking a degraded image, and trying to reconstruct it using mathematical techniques without understanding the processes which degraded it in the first place. Applying techniques developed for enhancing photographs to side scan sonar images will often improve them, but this ignores the fact that they are created in a different way. By using this program as an approximation to the sonar process, the effects of some of the many variables which degrade sonar images can be explored.

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