Sounds interesting: Wavefronts, caustics, whales and reefs

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ABSTRACT

Underwater sound has many practical applications and some of these will be reviewed. The ocean forms a complicated waveguide for sound and there are a variety of methods of calculating the sound field. Nevertheless the theoretical description of underwater sound propagation still presents some challenges. Wavefront modelling has recently been developed to give efficient evaluation of the sound field including the field near the foci and caustics that are common in both deep water and shallow water with surface waves. Many applications of underwater acoustics are well established but others such as large scale oceanography and large scale fish monitoring are under development. Underwater sound is also of great interest in marine biology. Whale sounds are routinely recorded at Great Barrier Island and are probably due to a resident population. The larval stages of some marine species appear to use sound to find suitable reef habitat to continue their life cycle. Current research is investigating what features of the sound field can give the required orientation cues.

INTRODUCTION

The sea is transparent to sound in the same way that air is transparent to light. We see objects in air because light reflects off objects and into our eyes. Sound similarly reflects off objects in the sea and marine mammals such as dolphins and sperm whales are able to "see" using sound. Many sea creatures use sound to communicate, find prey and to navigate. Snapping shrimp even use intense sound to stun their prey.

Sound is now routinely used in many applications. Echo sounders use the travel times of pulses to determine water depth. Side scan sonar is used to measure distance to the bottom over a wide swath and to produce a detailed image of the bottom. Sound is used in fish finding and biomass surveys. Recent scientific applications of sound include large scale monitoring of ocean temperature and communication with autonomous underwater equipment.

UNDERWATER SOUND PROPAGATION

Deep water propagation

The speed of underwater sound increases with both temperature and pressure. Warm water at the surface and the pressure increase with depth combine to produce a minimum of sound speed at about 1 km depth in mid latitudes. This sound speed minimum leads to trapping of sound by refraction as waves curve towards regions of shorter wavelength.

Figure 1. shows a ray trace in a representative situation. A fan of rays of sound in 1 degree increments is emitted by the source at a depth of 1200 m. These rays curve up and down as they propagate horizontally. The depth scale is exaggerated and the ray angles at the source are between ±12 degrees from the horizontal.

At low frequencies the attenuation of sound is so low that these rays propagate for many thousands of kilometres and arrive separately. Their travel time can be monitored and any change in travel time results only from temperature changes along the ray path. By monitoring many ray paths with multiple sources and receivers it is possible to do large scale oceanography and to deduce large scale circulation.

In a ray diagram such as Fig. 1 intensity of sound is proportional to the density of the rays. There are high intensity regions or foci of sound at several distinct ranges. There are also boundaries between high intensity regions and low in-

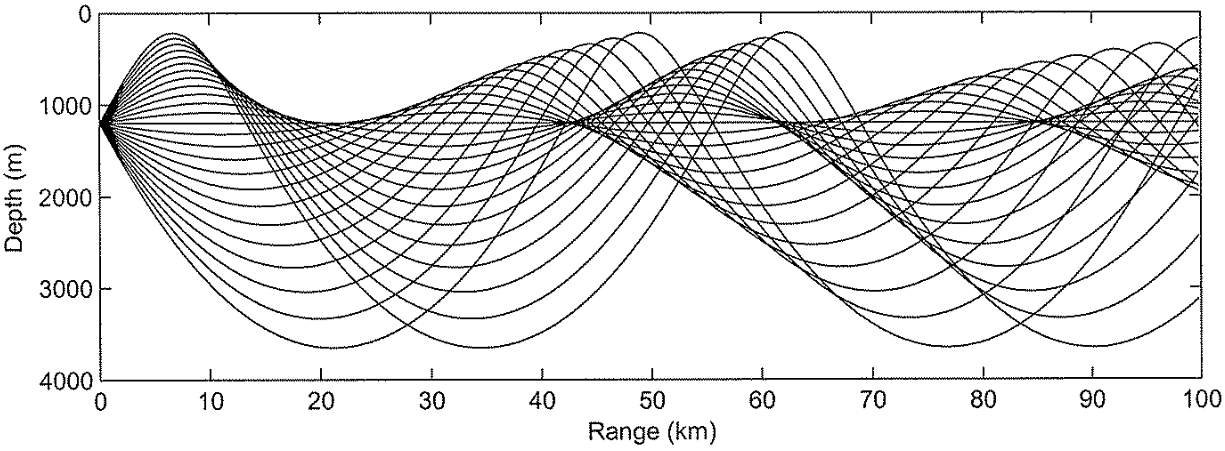

Figure 1 Ray paths in a representative sound speed profile. Intensity is proportional to density of rays. Foci occur where many rays cross. Caustics are the boundaries between high intensity and low intensity regions.

tensity regions. These boundaries are caustics. Simple ray geometry suggests infinite intensity on one side of a caustic and zero intensity on the other. A predicted zero intensity region is called an acoustic shadow zone. In fact, because sound is a wave motion the intensity is finite at a caustic and drops off steadily into the shadow zone.

Ray traces give a very intuitive physical picture of sound propagation. However they have not been used for detailed calculation of the sound field because up to now it has proved difficult to directly calculate the field near a caustic using a ray based method.

Acoustic field near caustics

A new method of determining the acoustic field in the vicinity of caustics has recently been developed (Tindle 2002, Tindle and Deane 2005)). The method is called wavefront modelling and results from a solution of the wave equation which is interpreted in terms of wavefronts formed by tracing a fan of rays all for the same time. The wavefront progresses at the local sound speed as time progresses. The wavefront in deep water develops folds each time the rays pass through a focus. An example is shown in Fig. 2. The left panel shows the wavefront as it passes a vertical string of hydrophones at a range of 80 km. The circles mark the depth and arrival time of a fan of rays traced from the source. The sharp reversals in the wavefront correspond to the caustics in Fig. 1. No rays from the source reach the shadow region beyond a caustic.

The right hand panel in Fig. 2 shows the signal expected at successive depths when the source emits a two cycle pulse at 75 Hz. The first pulse to arrive at 800 m depth is a replica of the source pulse. The resulting signal at each depth is the combination of the contributions from each section of the wavefront. There is strong interference of the pulses and the modelled signal agrees very closely with the reference solution which is also plotted as the thinner line.

An important feature of the modelled signals is that three of the pulses in Fig. 2 are in acoustic shadow zones. These shadow zone pulses are the single pulse at 200 m, the second pulse at 400 m and the second pulse at 1400 m. Each of these pulses is accurately found from the wavefront analysis which correctly predicts the amplitude, phase and arrival time of the pulses in the shadow zone. The wavefront model is fast and efficient and the successful modelling of the shadow zone pulses demonstrates its accuracy.

Shallow water propagation

The wavefront method is also applicable in shallow water where the surface waves are a significant fraction of the water depth. The underside of a wave crest acts like a curved reflector for sound. This leads to focussing and caustics which can be accurately and efficiently modelled. Other approaches are not useful in this situation and the wavefront model is a significant advance.

BIOLOGICAL APPLICATIONS

Whale monitoring

The New Zealand Navy has operated a three hydrophone array on the east coast of Great Barrier Island for many years. It was installed to monitor submarine and ship activity. Since 2004 it has been made available to the university to study marine mammal acoustics.

A very common whale sound is a low frequency grunt which is a downward sweeping tone from about 80 Hz to 40 Hz. Figure 3 shows the track of a whale making such low frequency grunts. The axes are in metres and the three hydrophones are indicated by the asterisks. The track covers a period of about 90 minutes and the grunts were made at the numbered positions. It is likely that the sounds were made by a Bryde's whale as these are common in the area.

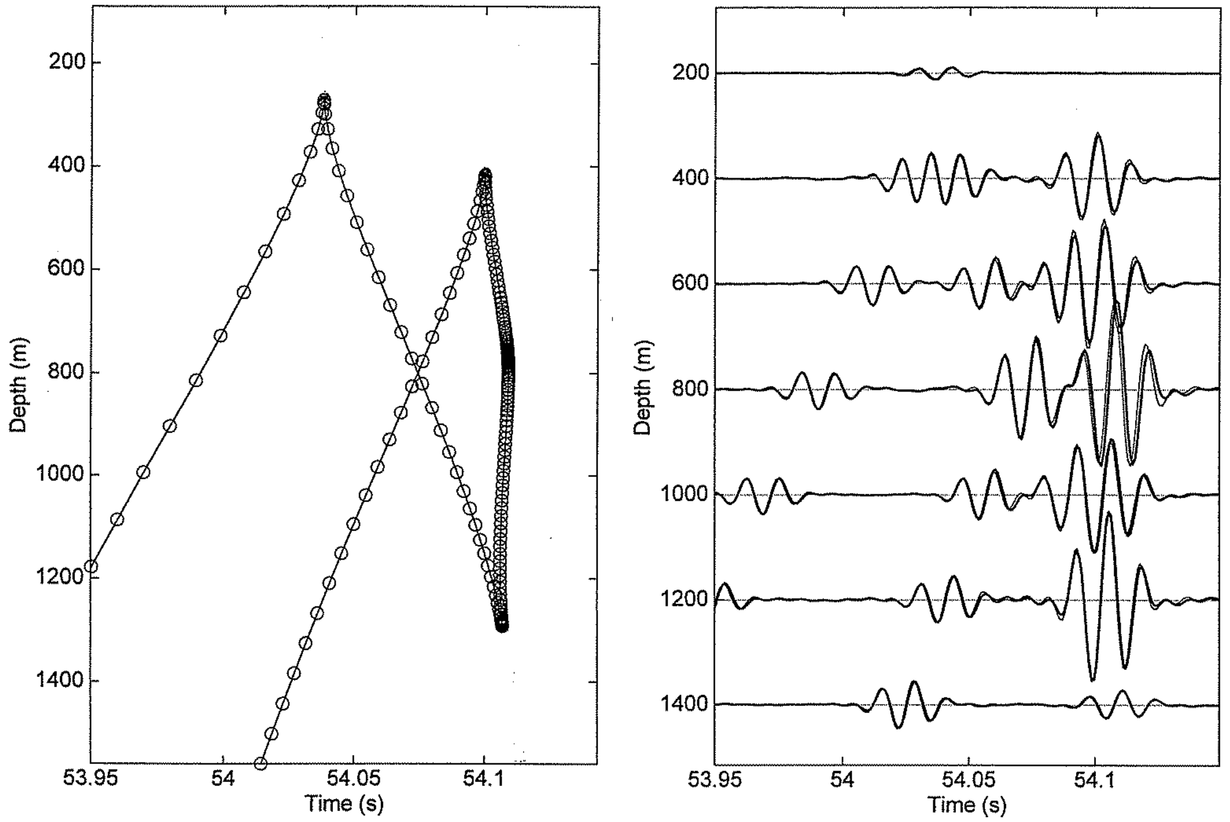

Figure 2. Waveforms near caustics. The left panel shows the wavefront. Circles represent individual rays. The sharp reversals are caustics and mark the boundary of shadow zones. The right panel shows the modelled waveforms at different depths and the reference solution (thin line). Three of the modelled pulses are in shadow regions.

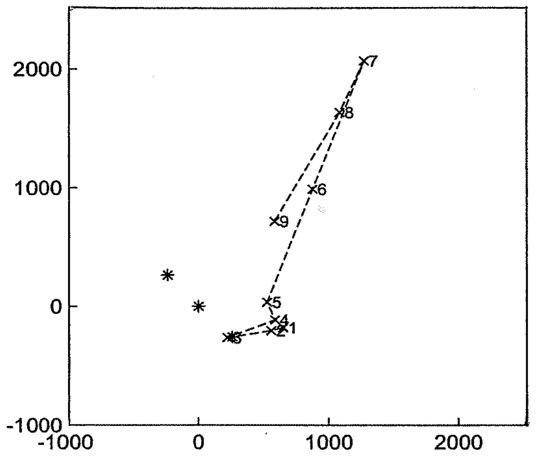

Figure 3. Track of a whale for 90 minutes. The axes are in meters and the asterisks show the hydrophone positions.

Several humpback whale calls were detected on 29 June 2005 but whether it was one whale or more than one is not known.

Reef sounds

A reef or rocky coastline provides many sources of underwater sound. Wave action, breaking waves and bubble oscillations produce wide band noise. Snapping shrimp are present in shallow water everywhere and produce intense short pulses of sound. The shrimps close a special claw quickly enough to make a cavitation bubble. The collapse of this cavitation bubble produces a sound intense enough to stun the shrimps' prey. Shrimp are very active around sunset and there are so many of them that the background noise is a constant hiss like the sound of fat in a frying pan.

Sea urchins provide another source of sound. They feed on algae on rocks by scraping the rock surface with their mouthparts. The urchin shell acts like a resonator and produces a sound in the 500-2000 Hz range. When many urchins are feeding there is a broad peak in the underwater sound frequency spectrum.

Several types of marine creature have a life cycle with a larval stage which drifts in the open ocean. When the larvae are big enough they actively swim towards the shore and settle on reefs or rocky coastline. They seem to be able to sense the direction of the shore. They also seem able to distinguish reef habitat from sandy beaches which would be unsuitable for settling. This raises questions as to whether the larvae use reef sound to navigate and if so what features of the sound field are they using? Current research is trying to answer these intriguing questions.

REFERENCES

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