Listening to the ocean: insights into marine animals and the ocean environment

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ABSTRACT

Active acoustics, which makes use of the echo of a transmitted signal, has long been used to obtain information about the ocean. Passive acoustics, listening to ocean sounds, has been less widely used, but this is changing, with significant recent developments. This paper discusses some of these developments, their potential and the challenges. Sound propagates through the ocean with far less absorption loss than in the atmosphere, so that sources in the ocean are audible at much greater distances than might be expected from our terrestrial experience. This allows passive acoustics to be effective over large areas and distances, in some cases up to hundreds of kilometres. Signals from individual sources can provide information about the source, its behaviour, location and environment. Breaking waves across the open ocean produce broad band noise that is very well correlated with wind speed, so acoustic receivers can be used for long term measurements of wind speed at sea. Rain on the sea surface also produces broad band noise that is related to rainfall rate. The dominant sources of noise for both breaking waves and rain are the bubbles formed as air is entrained, either as the wave breaks or as the rain droplet penetrates the surface. Marine animals make extensive use of sound in an environment where vision is very limited. Passive acoustics provides information about their behaviour by tracking animals using their sounds and by understanding the function of their signals. Their sounds provide cues for estimating their abundance and distributions, in many cases on scales that would not be possible by other means.

INTRODUCTION

Ever since it was discovered that sound propagates through water with far less absorption attenuation than in air, and thus penetrates much further, techniques to explore the ocean acoustically have been developed. Unlike the atmosphere, the ocean is a poor transmitter of electromagnetic radiation because of high absorption losses. Light penetrates only short distances. Shallow tropical reefs with their extraordinary display of coloured fish and invertebrates are exceptional rather than typical environments. One of the earliest applications of acoustics was the echosounder, which sends pulses of sound towards the sea floor and measures the time for the echo to come back to the source and uses this to estimate the water depth. An echo sounder is a form of active sonar: it transmits signals and uses the echoes to obtain the information about the ocean environment. Dolphins have active sonar which is usually referred to as echolocation in the biological context.

We use sonars for many purposes including mapping and imaging of the sea floor (side scan and multibeam), locating fish, imaging the structure of the rock strata beneath the sea floor (e.g. seismic air guns), as well as searching for submarines and mines in naval defence.

The ocean, however, is by no means an ideal medium for the use of sound. Propagation is almost never in straight lines but is subject to complicated refraction. Reflections from boundaries result in multiple arrivals and significant interference between arrivals. Reflection from and transmission into the bottom causes wide variation in sound levels transmitted in shallow water. Horizontally varying sound speeds, as encountered in fronts such as boundaries of eddies, also cause significant variation in transmitted signals. Scattering from the sea surface and from marine animals adds to the confusion. For many years, these factors were simply seen as problems to be dealt with as best as we could. Eventually it was realised that every perturbation of a sound signal by the environmental features added useful information to the signal, information that could be used to determine the characteristics of these environmental features.

Passive acoustics or simply listening to sounds from sources in the ocean has also seen widespread application. The menace of submarines to shipping in the first half of the 20th century led to substantial efforts to detect them and passive acoustics seemed an obvious tool. Submarines made noise and sound travelled so well through the ocean that passive acoustics should allow detection of submarines at greater distances than other methods. Indeed that was the case, but success was variable and not as straight forward as theory would suggest. Submarines are not the only sources of noise in the ocean. Marine animals make extensive use of sound for much the same reasons that we used sound in the ocean, though with greater sophistication and effect than we can achieve. Breaking waves and rain on the sea surface make noise. The result is a myriad of natural sources of sound, resulting in a high and variable background noise which limits the detection of sources of interest. These other sources of noise have long been seen as limitations in the effectiveness of our use of sound and thus problems to be dealt with, just as with the variability in propagation was seen to be a problem to be dealt with in active sonar.

More recently, there has been considerable interest in the potential to exploit passive acoustics to obtain information about the ocean environment and the animals that live there. Just listening to the ocean is turning out to be effective and can provide information that may be very difficult to determine by other means. Passive acoustics is more benign than active sonar since there is little disturbance of the ocean and not the concern about the effects of high levels of noise on the marine animals as with active sonar.

A less obvious value of using passive acoustics to provide information about the ocean is that it gives some insight into the information that marine animals might obtain by listening, something that might be a significant component of their behaviour, and important to their development and survival.

This paper discusses the potential of just listening to the ocean and what we can learn about the ocean by this means, with examples, particularly of work in Australian waters. .

SOURCES OF SOUND IN THE OCEAN

Many of the sources of sound in the ocean result from movement of interfaces between a gas (often air) and water. This is an efficient way of generating sound since the source level depends on the difference between ρc^2 either side of the interface (Cato, 1991), and this difference is very large for gas and water. Perhaps the best known such source is the air bubble in water which can oscillate in a number of modes. When the oscillation is radial, so that the volume changes, it radiates as a monopole source.

Many sources of sound in the ocean are effectively oscillating gas bubbles, and thus radiate very efficiently. These include the noise from breaking waves and the air entrained by rain drops as they pass through the surface. A major component of the noise from vessels results from the cavitation bubbles formed by the motion of the propeller. Fish use the swim bladder, a gas filled sac, to generate sound.

SENSING OF PROCESSES AT THE SEA SURFACE

Sensing of wind speed

We are familiar with the noise of breaking waves in the surf zone, but breaking waves occur across the surface of the ocean and are major sources of noise. Interestingly, the noise correlates much better with wind speed than with any measure of the wave height, so is known as wind-dependent noise. The wave height at sea depends not just on the wind speed, but also the fetch of the wind (distance over which it is blowing) and time that the wind has been blowing. When the wind starts to blow over a calm sea, the waves will grow over many hours before equilibrium conditions are reached. Rules of thumb relating sea state and wave height to wind speed apply only to these equilibrium conditions. In an experiment in deep water, Perrone (1969) found that when wave height and wind speed were correlated, the peak of the correlation occurred when the wave height lagged the wind speed by 6 h, as might be expected from the time it takes for waves to develop. He also found that when the noise was correlated with wind speed and wave height, the noise showed little lag with the wind speed, but the wave height lagged the noise by 6 h. This was a clear demonstration that the noise depends more directly on wind speed than on wave characteristics.

The source of noise in breaking waves, at least at frequencies above about 100 Hz, is the oscillation of air bubbles that are formed as the water falling over the face of a wave entrains air (Banner and Cato, 1988). The air is compressed by the weight of the water and the resulting excess pressure causes it to rebound and expand until the pressure falls below that of the surrounding water, so that it then contracts. This results in a damped oscillation, generating sound. Although each bubble has its own resonant frequency (which depends inversely on the radius), myriads of bubbles in a breaking wave provide such a range of bubbles sizes, and thus resonant frequencies, that the overall noise of a breaking wave is broad band. The sound generated has been shown experimentally to match the general measurements of wind-dependent noise (Medwin and Beaky, 1989).

Figure 1 shows how the noise of waves breaking at the sea surface correlates with wind speed, measured at a site in Spencer Gulf, South Australia. Wind speed was measured using an anemometer on a buoy close to the acoustic recording systems so that it is a reliable measure of the actual wind speed where the waves were entraining air and the sound was generated. It is apparent that such a relationship can be inverted to provide an effective measure of wind speed in the ocean.

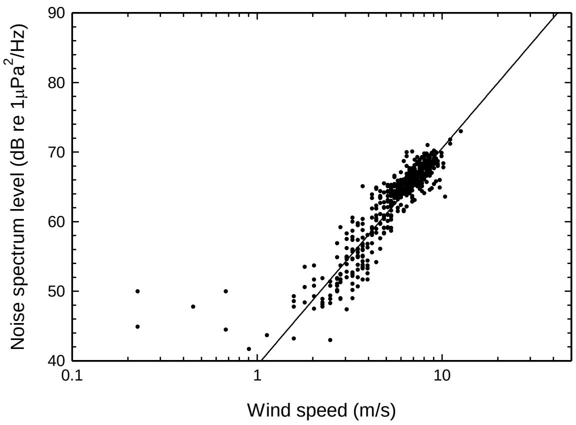

Figure 1. Underwater noise as a function of wind speed measured in Spencer Gulf, South Australia. The level is the average over the 1/3 octave band centred on 1 kHz.

Such a measurement of wind speed inherently includes a spatial average of wind speed over some area of the sea surface. The sources are monopoles very close to the sea surface, which is an almost perfect reflector of sound but with a phase reversal. Each bubble source and its out of phase surface image will thus radiate in a manner similar to a dipole with maximum radiation downwards. This limits the area of the sea surface that contributes significantly to the noise received at a hydrophone at depth. In the absence of bottom reflections, 90% of the sound energy reaching the hydrophone comes from a circular area of radius about three times the receiver depth (Cato and Tavener, 1977). If bottom reflections contribute a significant amount to the noise, the area of contributing sources will be larger. Hence the receiver depth can be used to select the area of sources contributing the noise, and thus the extent of the spatial averaging. The near surface atmospheric structure is advected past a stationary observer, so that this spatial average approaches a temporal average (Cato et al., 1994).

Hence a noise recorder moored in the ocean can provide long term measurements of wind speed averaged over selected spatial scales. Such a recorder may be significantly simpler to support logistically than a moored anemometer.

An important application of measuring wind-dependent noise under extreme conditions has been addressed by Wilson and Makris (2006). They assessed the feasibility of estimating the destructive force in hurricanes or cyclones from acoustic recordings as the hurricane passes near a hydrophone. The destructive force of hurricanes and cyclones is well known and methods of estimating this in disaster planning to minimise destruction and loss of life have been established. The destructive force depends on the maximum wind speed but most methods of measuring this have substantial errors. The only method with the accuracy needed involves flying specialised aircraft through the hurricane itself. The cost of these aircraft, both to purchase and operate is substantial and currently they are used only by the United States. Wilson and Makris (2006) show that the underwater noise recorded from hurricanes has the potential to provide estimates of wind speed with accuracy approaching those of the aircraft measurements. They discuss methods of deploying sufficient sensors in advance so that the hurricane passes close (within 5 km is adequate) of one. The cost would be much less than the purchase and operation of the aircraft.

The creation of bubbles by air entrainment and their bursting at the sea surface play an important role in the transfer of gases across the air sea interface. Of particular interest, of course, is the transfer of carbon dioxide. Wind-dependent noise provides a means of sensing aspects of this process.

Sensing of rain

Rain fall on the sea surface generates high underwater sound levels over a broad frequency band. At frequencies above a few kilohertz, the noise of a heavy rain storm tends to exceed the highest levels observed for wind-dependent noise. Some of the noise results from the sounds of the impacts of rain drops on the sea surface, but more comes from oscillation of the bubbles formed from the air entrained as the drop passes through the surface (Medwin et al., 1992). As with wind-dependent noise, these bubbles and their out of phase surface reflection generate sound similar to dipole sources with maximum radiation downwards. Hence rain noise can be used to measure rain fall over an area of the sea surface determined by the depth of the receiver and the local propagation conditions. Not all drops entrain air – it depends on the size of the drop, its impact velocity and the angle at which it hits the surface.

Nystuen (2001) describes instruments to measure rain fall rate and drop size from underwater acoustic measurements.

SENSING MARINE ANIMAL MOVEMENTS, BEHAVIOUR AND ABUNDANCE

Marine animals make extensive use of sound in an environment where sound penetrates much better than light. The shallow clear tropical water environment of the Great Barrier Reef, with its wide diversity of colourful animals, is an exception rather than a typical marine habitat. Most marine animals live where light is limited and vision is useful only over very short distances. They tend to rely on sound for sensing their environment, the presence of prey and predators as well as for communication.

Marine animals produce a wide variety of sounds with high source levels and these can be used to detect their presence and movements. Their vocalisations play an important part in their behaviour, so need to be included in any behavioural studies.

One of the best known sources of biological noise is the snapping shrimp, which has a disproportionally large claw used to generate sound. Although the noise of snapping shrimps has been known for more than a century (Goode, 1878), it is only recently that the actual mechanism of sound production has been determined. The very rapid motion of the large claw produces a cavitation bubble that collapses rapidly, producing a high level, sharp click with a very broad frequency range (Versluis, 2000). There are many species of snapping shrimp and they abound in shallow temperate and tropical waters, producing a sustained background noise.

Many species of fish generate sound by muscular excitation of the swim bladder, which is a gas filled sac used by the fish to control its buoyancy (Tavolga, 1964). The acoustic impedance of flesh is similar to that of water, so acoustically, the swim balder provides an efficient source of sound in the manner of a gas bubble in water. Fish sounds generated using the swim bladder vary from tone bursts to drumming or knocking sounds.

Whales are divided into two suborders: baleen whales, the filter feeders, such as the blue and humpback whales, and toothed whales, such as sperm whales, killer whales and dolphins. The two suborders produce distinctively different sounds (see Richardson et al., 1995, for lists of sounds produced). The baleen whales produce a range of sounds at frequencies generally in the audio frequency range, from as low as 20 Hz for blue and fin whales, to harmonics of humpback whale sounds which extend to beyond 20 kHz. Toothed whales, on the other hand, tend to be higher in frequency with broad band clicks used for echolocation (active sonar) extending to frequencies in excess of 150 kHz in some dolphins.

Many baleen whale sounds cover a relatively small frequency band, or show a range of harmonics, suggesting that some resonance process is involved, though the mechanism of sound production has not been established. Baleen whales have a large laryngeal sac or diverticulum (tens of centimetres long) that could function as a gas filled sac resonator (Quayle, C.J, 1991; Reidenberg and Laitman, 2007) and contribute significantly to the sound production by these whales. Calculations of the range of frequencies and source levels that could be achieved by oscillation of air cavities in a blue whale are consistent with those observed (Jones et al., 2003). Mechanisms of sound generation in toothed whales involves use of air sacs in their heads. Given the similarity of the acoustic impedances of flesh and water, these use of gas cavities approach the concept of the gas bubble source and provide an efficient source of sound.

Tracking marine animal migrations and locating aggregations and distributions

Whale sounds may be detectable for tens, or at times, hundreds of kilometres. Source levels are very high. For example, measurements of sperm whale clicks show source levels up to 223 dB re 1 µPa at 1 m (Møhl et al., 2000). Baleen whale sounds have lower rms source levels but are much longer in duration so that the energy transmitted may be comparable or greater. For example, blue whale source levels are as high as 188 dB re 1µPa at 1 m (Cummings and Thompson, 1971) with durations of around 20 s compared to the sperm whale sounds of order milliseconds. Ambient noise in the ocean is typically around 100 dB re 1 µPa over the audio frequency band, so the high source levels of whales allow them to be detected at substantial distances.

Baleen whales have been tracked over large distances (track lengths of more than 11,000 km) over the northern Pacific Ocean using the US Navy Sound Surveillance System (SOSUS) arrays (Watkins et al., 2004). Although most acoustic tracking would not have the capability and sophistication of the SOSUS arrays, this does illustrate the potential.

An example of the use of passive acoustics to study whale movements is given by the work in the Perth Canyon, where pygmy blue whales regularly come to feed and humpback whales pass through on migration (McCauley et al., 2001, 2004). Moored acoustic recorders (acoustic loggers) were used to detect the presence of whale sounds as a way of determining the seasonal dependence of the presence of particular species. These can provide long term (order one year) recordings. Deployments of the loggers in other areas around Australia, particularly along the west coast have provided patterns of the migrations of the pygmy blue whales. Some of the acoustic work in the Perth Canyon included aerial and vessel based visual surveys which helped interpret the results of the acoustic surveys. In general, however, moored acoustic surveys can provide much greater coverage both geographically and temporally than aerial surveys or visual surveys from ships.

An example of where acoustics can be particularly effective is provided by two surveys of beaked whales in an area of the Coral Sea where joint U.S. Australian naval exercises are conducted. Beaked whales have been overrepresented in whale strandings coincident with naval exercises on a few occasions in the northern hemisphere. Consequently, part of the environmental management for the exercises was to determine the presence and distribution of beaked whales in the area. There are several species of beaked whales but these are the least well known of all whales because they live in deep water and are so elusive. They are relatively small toothed whales, most being smaller than killer whales, and are rarely seen at sea, hence they are almost impossible to survey visually. The sounds they produce are, however, distinctive, sufficiently so to distinguish them from the sounds of other toothed whales. Johnson et al. (2004) were able to put acoustic tags (DTAGs) on some beaked whales in two areas (the Mediterranean Sea and the ocean near the Canary Islands) and recorded their sounds. They found that when the whales dived below several hundred metres, they produced an almost continuous sequence of echolocation clicks.

Two combined acoustic and visual surveys were conducted in the Coral Sea in 2008 and 2009 each covering the area which extended 171 km east west and 111 km north south (Cato et al., 2010). Acoustic recordings were made using a small towed array and two drifting loggers which were deployed and recovered every few days. Both systems had the frequency response to record the beaked whale sounds which cover the range from about 25 kHz to 80 kHz. Many more acoustic detections of beaked whales were made than sightings, and in many more locations.

Fish produce sounds for a variety of reasons. In particular, when large aggregations of fish are calling, high level choruses are produced (McCauley and Cato, 2000). Some of these choruses are related to spawning so provide a means of detecting spawning aggregations for management of populations. For example, Parsons et al. (2009) report the passive acoustic tracking of spawning mulloway in turbid waters in the Swan River, Perth.

Estimating abundance of marine animal populations

Marine animals spend most of their time submerged so are difficult to count visually, except in shallow water areas were vision is good. Surveying for whales, for example, relies on the need for whales to surface to breathe, but the proportion of time they spend at the surface is small. Visual surveying is effective for species that migrate near the coast but is far more limited for populations that are well offshore. Visual surveying by vessel can cover only a small area of an ocean. Since whales are likely to be detectable acoustically for much greater distances than they can be seen, acoustics provides a way of covering much larger oceanic areas.

Both visual and acoustic surveying have limitations and combinations of both are likely to be the most useful. There will be conditions in which visual surveying is more effective and others, such as in the open ocean, where acoustic surveying will be more effective. The potential and challenges of acoustic methods of estimating marine animal abundance were discussed at a previous conference (Cato et al., 2006). Estimation of abundance involves taking the detected cues of the presence of the animals (in this case sound detections) and transforming these into estimates of the number of individuals in the population. Animals are detected only when they vocalise, and not all individuals vocalise at any time. The proportion vocalising depends on the species and the behaviour among other things. The vocalisation behaviour needs to be well known for the species being surveyed. The detectability of the sounds depends on the transmission loss and the background ambient noise, both of which show substantial variation.

Unlike the pygmy blue whale that feeds in the Perth Canyon, the ‘true’ blue whale keeps to deep water well offshore. The two are subspecies of blue whale and produce generally similar sounds. The ‘true’ blue whale is the largest animal ever to exist but their numbers were severely reduced during whaling and they are now considered to be endangered. Of all whale species, these are of the most concern in our region of the world. Visual surveys in the open ocean are limited because of the very small part of the ocean that can be sampled in any reasonable time. Consequently, current estimates of blue whale populations are unreliable. Because their sounds are so distinctive and carry to great distances, efforts are being made to develop acoustic surveying techniques to improve the estimates of their abundance.

Behavioural studies of marine animals

Since marine animals make extensive use of sound, acoustic monitoring plays an important part in any behavioural studies. Vocalisations are an important component of their behaviour. The movements of vocalising animals can be tracked while they are submerged and hence not visible. This can provide important information about the way they interact with other animals.

Passive acoustics has been used extensively in the Humpback Whale Acoustic Research Collaboration (HARC), a series of experiments observing the behaviour of humpback whales as they migrate southwards along the southern Queensland coast. An array of three to five hydrophones moored about 2 km from shore radioed back acoustic data to a shore station, allowing almost real time tracking of vocalising whales (Noad et al., 2004). At the same time visual tracking with theodolites was conducted from a near shore hill. These two observation methods provided intensive observations of behaviour and how the whales react to each other’s vocalisations as a means of understanding their acoustic communication. Some of the knowledge gained about whale acoustic communication has been reported by Dunlop (2008, 2010).

USING SOURCES OF OPPORTUNITY TO IMAGE OBJECTS IN THE OCEAN

Active sonar generates a signal and uses the reflections of that signal from objects to image those objects. If the source and receiver are spatially separated, it is referred to as bistatic. Sources of opportunity may be used instead of the sonar source for this purpose so that a passive sonar can do the imaging without having to generate a signal. The source would generally be spatially separated from the receiver as in bistatic active sonar.

Imaging with ambient noise: "Acoustic Daylight"

A novel concept known as "acoustic daylight" was introduced by Buckingham (1992) and uses the reflection of ambient noise from objects as a method of image the objects. The name comes from the way the sources are dispersed rather than localised, somewhat like the way light is dispersed in daylight on a cloudy day. Beamforming with a planar array of receivers can be mapped to pixels to produce a two dimensional image to provide a picture of objects in the ocean. In practice, the effect works better when sources are less dispersed spatially. For example, snapping shrimps which are predominantly on the sea floor have proved to be an effective source. Work on acoustic daylight in Australia has been reported by Readhead (2001).

Using sounds of singing whales to detect non vocalising whales

Detecting whales with passive acoustics has important potential but there are also limitations. One is that not all whales in a population are vocalising at any time, so that only a proportion of the whales can be detected by listening. Humpback whales are particularly vocal, and are known for their long and complicated but stereotyped song that is detectable for at least tens of kilometres. However, it is only the mature males that sing. Typically, about 13% of humpback whales migrating southwards along the east and west coasts of Australia are singing at any time (Cato et al., 2001). The high source levels of the sounds, however, allow then to be used to as the source in a bistatic sonar to image the non singing whales.

In a theoretical study, Makris and Cato (1994) showed that it should be possible to detect non singing whales from the reflections of the sounds of singers up to distances of several kilometres using a 128 element towed array.

SENSING OTHER PHENOMENOM

Underwater acoustic waves from underwater volcanoes and earthquakes can provide information about their location to supplement that from crustal borne waves.

Rifting and breaking of ice shelves and icebergs produce high noise levels which can be used to locate the source. Gavrilov and Li (2008) have shown how such events in the Antarctic can be located from sound recordings in the Indian Ocean thousands of kilometres away.

CONCLUSIONS

The ocean is sometimes referred to as the last frontier. It covers about 70% of the earth's surface and much of it extends to depths of several kilometres. Australia's ocean territory covers a larger area than the entire Australian continent. The ocean is poorly explored compared to the terrestrial world, partly because so much of it is so difficult to probe or to sample. Since electromagnetic radiation penetrates only short distances through water, acoustic waves are our main means of sensing information at significant distances in the ocean.

There are many sources of sound in the ocean and these can provide information about the sources and what generates the sound by passive acoustic listening. These include processes such as wind speed and rain fall over the ocean as well as the behaviour, movements and abundance of the marine animals.

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