Chapter 15

Passive acoustics as a key to the study of marine animals

DOUGLAS H. CATO
University of Sydney, Australia

MICHAEL J. NOAD
University of Queensland, Australia

ROBERT D. McCAULEY
Curtin University, Australia

Summary

The vastness of the oceans makes it difficult to study marine animals because they are so often out of sight, except in a few specialized environments such as the clear shallow waters of tropical reefs. Because sound travels so much further in the sea than light or other forms of electromagnetic waves, it is natural to turn to acoustics for finding and studying marine animals. Active sonar is used for this purpose but the sounds that the animals produce themselves may also be exploited because so many have high source levels and are detectable at great distances. These vocalizations can be quite spectacular, and are intriguing in terms of the biological function they perform. This chapter describes some methods used and recent research in the use of fish and marine mammal sounds to study behavior, distributions, and movements, as well as acoustical methods of estimating population sizes and rates of increase in numbers. Even a single hydrophone can provide useful information, while multiple hydrophones can provide detailed information about movements and behavior.

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15.1 Introduction

Life began in the sea where it has developed to a level of diversity unparalleled on land. Yet we do not often see marine animals in the wild because of the poor penetration of light through water and it is difficult to study them in their natural environment. Acoustics provides the means of monitoring animals at much greater distances than visual observations allow. Marine animals have evolved an extensive range of capabilities to exploit underwater sound, particularly through their vocalizations, such as communication signals and breeding (courtship) displays, and in some species such as dolphins, echolocation (active sonar) and signals for individual recognition. Their sounds tend to have high source levels so are detectable at substantial distances. Quite simple listening systems are effective to distances of tens to hundreds of meters for fish and invertebrates and tens of kilometers for whales. In addition, vocalization is such an important component of marine animal behavior that passive acoustics is essential in behavioral studies.

15.2 Sounds of the marine animals

Animal sounds vary from a few microseconds duration at frequencies up to hundreds of kilohertz (dolphin clicks: Au, 1993; shrimp snaps: Everest *et al.*, 1948; Cato and Bell, 1992) to 15 to 45 s duration at frequencies as low as 20 Hz (blue whales: Cummings and Thompson, 1971; McCauley *et al.*, 2000). The sounds of most animals, however, are within the audio frequency range and durations lie between 0.1 to 5 s (Tavolga, 1964, 1967; Richardson *et al.*, 1995).

Invertebrates produce sounds that are usually short, impulsive, and broadband, such as clicks or series of clicks (Tavolga, 1964). The best known is the snapping shrimp which abounds in shallow warm water where it provides a continual background from about 1 kHz to more than 300 kHz. Other invertebrate sounds are made by scraping or impact of hard parts, usually clicks or series of clicks.

Fish produce a wide range of sounds (Tavolga, 1964). Some are short, impulsive, and broadband, click-like sounds. Many fish, however, use the swimbladder, a gas filled sac, to enhance sound production. Because the flesh of fish has an acoustic impedance similar to water, the swimbladder is acoustically similar to an air bubble in water (Section 6.4), which is a very efficient source of sound. Many species of fish drum on the swimbladder with attached muscles, producing drumming and knocking sounds of varying rates. Frequencies are usually in the range 50 Hz to a few kilohertz (Tavolga, 1964, 1967). Some species contract the attached muscles at a rate close to the resonant frequency of the bladder, producing harmonic sounds with fundamentals usually in the range 10 Hz to 300 Hz. Source levels (mean square pressure levels) of fish sounds vary widely from 110 to 160 dB re 1 μPa at 1 m, although most are in the range 130 to 150 dB re 1 μPa at 1 m (Cato, 1980; Myrberg *et al.*, 1986; D'Spain *et al.*, 1997; McCauley, 2001).

Marine mammal sounds generally fall into categories according to the classification: baleen whales (mysticetes), toothed whales (odontocetes), and seals. Baleen whales produce a wide range of sounds, from the long, low-frequency tonal signals (15–100 Hz) of the blue whales, to the variety of ever-changing sounds of the humpback song, in the range 50 Hz–10 kHz (Richardson *et al.*, 1995). Odontocete sounds include whistles and impulsive clicks. Much is known about the way dolphins use clicks for echolocation (Au, 1993; Section 5.5.2). Whales produce the most intense sounds of all marine animals, with most source levels (mean square pressure levels) at one meter from 165–185 dB re 1 μPa (Richardson *et al.*, 1995).

15.3 Use of passive acoustics to determine direction and location

One hydrophone can indicate the presence of the animal and something of its behavior, although detection ranges vary substantially with variations in propagation loss and the ambient noise against which the signal must be detected. Two hydrophones provide substantially greater capability. Figure 15.1 shows two hydrophones on the x axis at positions $H_1(0, 0)$ and $H_2(s, 0)$ receiving sound from a source at $Q(x, y)$. Since the source is closer to hydrophone H_1, the signal from the source will

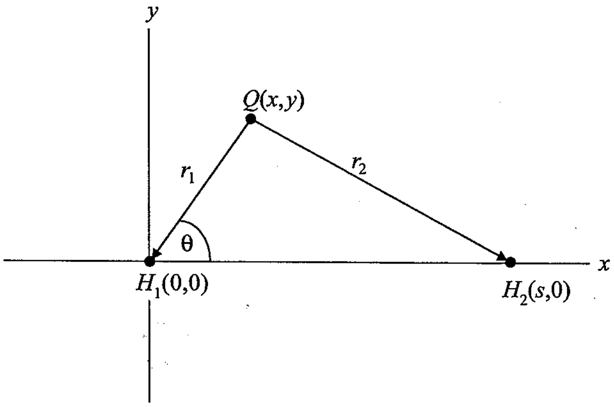

Fig. 15.1. Sound from a source at position $Q(x, y)$ is received by hydrophones at H_1 and H_2, Cato *et al.*, 1998.

arrive at H_1 before it arrives at H_2, and the received pressure will be higher at H_1 than at H_2. In a homogeneous, isotropic medium (constant speed of sound, no boundaries), the difference in the arrival times of the signals to the two hydrophones and the ratio of received pressures are enough information to determine the position of the source, though with an ambiguity (see Section 15.3.3). In the real ocean, travel time differences are affected by variations in the sound speed and interference from multiple propagation paths such as the reflections from the sea surface and the bottom. Received pressures vary substantially with variations in the propagation.

It turns out that the difference in arrival times is, however, quite robust and is little affected by sound speed variations, mainly because the paths to the two hydrophones experience similar variations. The ratio of received pressures is far more affected by environmental conditions, and is of more limited use, though it can be useful when the source distance is comparable to or less than the hydrophone separation.

15.3.1 Determination of the source direction and location using arrival time differences for distant sources

Figure 3.18, shows a wave front arriving at a line array of hydrophones where the distance of the source is much greater than the size of the array, so that the received signal is effectively a plane wave, see (3.57). The angle ϕ, the direction or bearing of the source from the array depends on τ, the arrival time difference between hydrophones, and the speed of sound c. Since $\sin\phi$ is proportional to τ, the accuracy of estimating ϕ decreases as ϕ increases and is highest broadside to the array (perpendicular to the array) and least at endfire (along the array) (see Section 3.9.5).

A second array located in another position would provide a second bearing and the source location could be determined by the intersection of the bearings. There is an uncertainty or ambiguity in determining the direction and position of the source. In Fig. 15.1, the signals from a source at position $Q'(x, -y)$ below the line through the hydrophones, would produce the same times of arrival as those from the source at Q, so we cannot determine if the source is at Q or Q'. Using two hydrophone arrays does not necessarily resolve this ambiguity. It depends on the source position and the relative orientation of the arrays, as in the example of Fig. 15.2. There is an ambiguity in both direction and location using the two arrays with similar orientation (the pairs H_1, H_2 and H_3, H_4), but not if either of these were used with the pair H_5, H_6 which has a different orientation. Sometimes external factors can resolve ambiguities.

Three hydrophones are enough to localize a source since this provides three pairs. In practice, extra hydrophones can provide more array

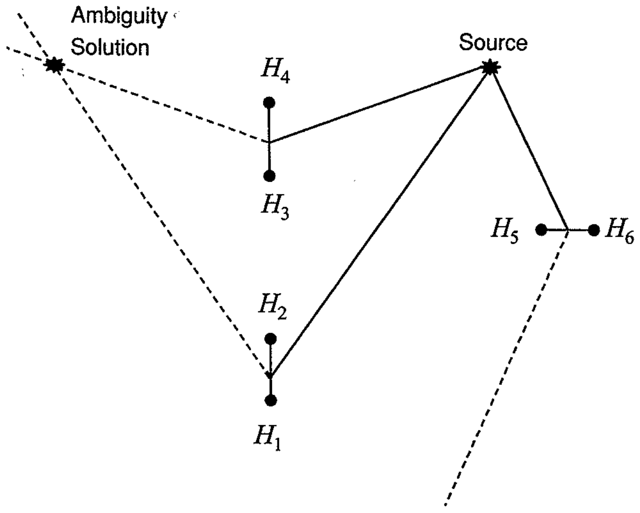

Fig. 15.2. The position of the source is determined by the intersection of the bearings from hydrophone pairs. There is an ambiguity using hydrophones pairs H_1, H_2 and H_3, H_4, but not if either of these is used with hydrophone pair H_5, H_6. This assumes that the distance of Q is much greater than the separation of hydrophones in any pair, so that the received wave front is close to plane.

orientations and greater accuracy, since it increases the chance that some arrays will have the source nearer broadside where accuracy is highest (six hydrophones provide 15 pairs in Fig. 15.2).

15.3.2 Determination of source location by arrival time differences for any source distance

In many cases, especially in the study of marine animal behavior, we are interested in sources that are much closer relative to the hydrophone separation, so that the plane wave front assumption is no longer valid. This section gives a more general solution for any source distance.

In Fig. 15.1, the time for sound to travel from the source at $Q(x, y)$ to the hydrophones at H_1 and H_2 is r_1/c and r_2/c respectively. The difference in the times of arrival τ is then given by

$$c_0\tau + r_1 = r_2 \qquad (15.1)$$

where c_0 is the speed of sound which for this purpose can be assumed constant. Squaring both sides and substituting $r_1^2 = x^2 + y^2$ and $r_2^2 = (s - x)^2 + y^2$ gives

$$2c_0\tau\sqrt{x^2 + y^2} = s(s - 2x) - c_0^2\tau^2 \qquad (15.2)$$

Squaring both sides again and collecting terms in x and y leads to

$$4x^2\left(c_0^2\tau^2 - s^2\right) - 4sx\left(c_0^2\tau^2 - s^2\right) + y^2\left(4c_0^2\tau^2\right) = \left(c_0^2\tau^2 - s^2\right)^2$$

Dividing by $(c_0^2\tau^2 - s^2)$, then by $c_0^2\tau^2$, gives

$$\frac{4x^2 - 4sx + s^2}{c_0^2\tau^2} + \frac{4y^2}{c_0^2\tau^2 - s^2} = 1$$

which can be written as

$$\frac{\hat{x}^2}{a^2} - \frac{y^2}{b^2} = 1 \qquad (15.3)$$

where $a^2 = c_0^2\tau^2/4$, $b^2 = (s^2 - c_0^2\tau^2)/4$, and $\hat{x} = x - s/2$. Equation (15.3) is the equation of a hyperbola which is symmetrical about the x axis and has asymptotes crossing the x axis at $x = \hat{x}$, the point midway between the hydrophones. Thus for a particular arrival time difference, the source can lie anywhere on the hyperbola given by (15.3). The asymptotes are the lines of bearings for the plane wave case for distant sources. A second pair of hydrophones would give a second hyperbola for the particular source, so that the source position is given by the intersection of the two hyperbolas. An example with three hydrophones is shown in Fig. 15.3 for a source at position Q. The hyperbolas intersect at two points, giving an ambiguity in the determination of the source position, as in the case of distant sources discussed above. Three hydrophones are sufficient to localize, but more well placed hydrophones increase the accuracy and reduce the likelihood of ambiguity.

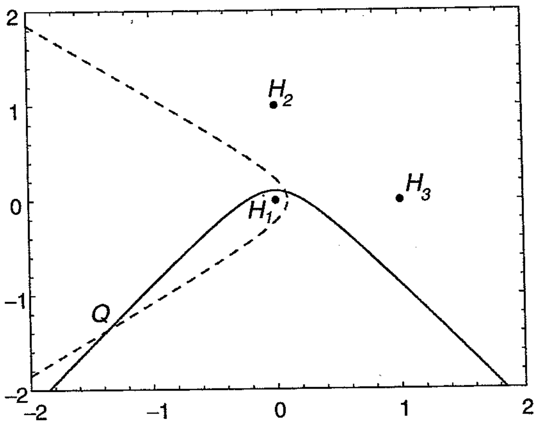

Fig. 15.3. The arrival time difference between hydrophones H_1 and H_2 of sound from a source at Q indicates that the source is somewhere on the hyperbola shown by the solid line. The time difference between hydrophones H_1 and H_3 indicates that the source is on the hyperbola indicated by the dashed line. The source position is thus given by the intersection of the two hyperbolas, but there is an ambiguity since there are two points of intersection.

Arrays of many hydrophones are often used in ocean acoustics because the capability to detect signals in noise increases as the number of hydrophones increases. In many marine animal applications, however, the signal levels are so high relative to the noise that the substantially greater cost and complexity of multi-hydrophone systems are not justified. Simple systems that have been used to monitor marine animals include those reported by Cummings *et al.* (1964), Watkins and Schevill (1972), Clarke (1980), Cummings and Holliday (1985), Freitag and Tyack (1993).

We have tacitly assumed that the source and hydrophones of Fig. 15.3 are in the horizontal plane, and treated this as a two dimensional problem. Rotating the plane containing the source and a pair of hydrophones about the line through the hydrophones does not change the result, so that the possible source position determined from two hydrophones is actually on the surface swept out by rotation of the hyperbola. The location of the source in three dimensions using two pairs of hydrophones is on the line forming the intersection of the surfaces swept out by rotation of the two hyperbolas. Often the geometry of the measurements is such that a two dimensional solution is adequate, for example, in shallow water for distances significantly greater than the water depth.

Measurement of time of arrival difference

Arrival time differences are usually very small, and accurate localization requires measurement accuracy of milliseconds or less. Signals from the hydrophones in an array must be recorded on the same multi-channel device (tape recorder or computer) or time synchronized to minimize the errors. The most effective method of measuring τ is by cross correlation of the signals from hydrophone pairs. The cross correlation as a function of time delay τ' is

$$R(\tau') = \frac{1}{NT} \int_{-T/2}^{T/2} f_1(t) f_2(t + \tau') dt \qquad (15.4)$$

where $f_1(t)$ and $f_2(t)$ are the signals received at the two hydrophones and N is a normalizing function equal to the product of the rms values of $f_1(t)$ and $f_2(t)$ so that $R(\tau')$ lies between -1 and $+1$.

When $\tau = \tau'$, the cross correlation is maximum since the two received signals are in phase. Sinusoidal signals, however, are in phase for all values of τ' that are multiples of the sinusoidal period, so τ cannot be determined reliably for very narrow band signals. For transient signals common from marine animals, the period of integration T is usually chosen to enclose the duration of the signal as received on the two hydrophones. Software known as ISHMAEL (Mellinger, 2002) is available to perform cross correlations between pairs of hydrophones, calculate the hyperbolas, and determine the position of the source from three or more hydrophone pairs.

15.3.3 Determination of location using two hydrophones, by differences in arrival times and received levels

Using differences in arrival times and received levels, only two hydrophones are required for localization (with ambiguity), and the distance of the source can be determined without knowing the hydrophone separation. This method is more limited, however, because differences in received levels are much more variable than time differences, so errors tend to be larger. Acceptable accuracy requires the source to be significantly closer to one hydrophone than to the other and knowledge of the propagation conditions. The logistics are simpler and so it can be used where it is impractical to deploy multiple hydrophones with the high positioning precision required for localization using arrival time differences alone. For example, in estimation of the abundance of vocalizing animals during ship transits, the spatial density can be estimated by deploying sonobuoys at intervals and determining the distance to each source. Only a rough idea of the positions of the sonobuoys is needed.

In Fig. 15.1, let $k = r_2/r_1$ and $r_2 > r_1$. Let the received intensity at H_1 and H_2 from the source at $Q(x, y)$ be I_1 and I_2 respectively. We assume that propagation loss is proportional to ar^n, where a and n are constants, so that the received intensity at H_1 is

$$I_1 = I_0 / \left(ar_1^n\right) \tag{15.5}$$

where I_0 is the source strength (intensity at unit distance). The difference in received level DL at the two hydrophones is

$$DL = 10\log_{10}(I_1/I_2) = 10n\log_{10}(r_2/r_1) = 10n\log_{10} k \tag{15.6}$$

When $a = 1$ and $n = 2$, propagation loss is according to spherical spreading. This would be applicable for example, for relatively short distances less than the water depth for vocalizations that are sufficiently broad band that the interference effects like Lloyd's Mirror (Section 1.5.6) are not significant. These circumstances are often the case in studying vocalizing fish. Fitting (15.5) to propagation loss as a function of distance is likely to be suitable for a wider range of conditions, again for sounds that are not very narrow band.

Substituting $r_2 = r_1 k$ in (15.1) gives

$$r_1 = c_0\tau/(k - 1) \tag{15.7}$$

This simple expression for the distance of the source from the closer hydrophone is useful so long as the source is significantly closer to one hydrophone than the other ($k \gg 1$). This can be seen by noting that

$$\partial r_1/\partial \tau = c_0/(k-1) = r_1/\tau \quad \rightarrow \infty \quad \text{as} \quad \tau \rightarrow 0$$

and $$\partial r_1/\partial k = -c_0\tau/(k-1)^2 = -r_1/(k-1) \quad \rightarrow -\infty \quad \text{as} \quad k \rightarrow 1$$

so that r_1 changes very rapidly as $\tau \rightarrow 0$ or $k \rightarrow 1$ and small errors in either τ or k would result in large errors in the estimate of r_1. The significance and magnitude of these errors, and ways of reducing them, are discussed by Cato (1998).

Evaluation of (15.7) does not require knowledge of the positions of the hydrophones or their separation. The accuracy of the result, however, will tend to improve as the hydrophone separation increases.

Determination of the source position

If the positions of the hydrophones are known, the position of the source can be estimated, with the usual ambiguity that arises when arrival time differences are used. From Fig. 15.1,

$$k^2 = \frac{r_2^2}{r_1^2} = \frac{(s-x)^2 + y^2}{x^2 + y^2} \qquad (15.8)$$

and

$$\cos\theta = x/r_1 \qquad (15.9)$$

where θ is the angle between the line H_1Q and the x axis (Fig. 15.1). Substituting $y^2 = r_1^2 - x^2$ into (15.8) and rearranging leads to

$$x = s/2 - r_1^2(k^2-1)/(2s) \qquad (15.10)$$

Using the expression for r_1 from (15.7) with (15.9) and (15.10) gives

$$\cos\theta = \frac{s(k-1)}{2c_0\tau} - \frac{c_0\tau\ (k+1)}{2s} \qquad (15.11)$$

Equations (15.7) and (15.11) provide the distance of the source from hydrophone H_1, and the angle of the source direction relative to the line through the hydrophones at the closer hydrophone, respectively. There is the usual ambiguity. Rotation of the plane containing Q, H_1, and H_2 about the x axis (Fig. 15.1) does not change the above results. Thus $Q(x, y, z)$ lies on the circumference of this circle, centered at $(x,\ 0,\ 0)$ with radius $\sqrt{y^2 + z^2}$. If the differences in depths of the source and the hydrophones are much less than their separations, the angle θ is approximately the azimuthal bearing of the source relative to the line through the hydrophones. It is not possible, however, to determine if θ in Fig. 15.1 is positive or negative (since $\cos\theta = \cos -\theta$) so that the source can be either side of the line through the hydrophones.

Manipulation of (15.10) gives

$$(k^2-1)x^2+(k^2-1)y^2-s^2+2sx=0$$

which leads to

$$(x-x_0)^2+y^2-\rho^2=0 \tag{15.12}$$

where

$$x_0=-s/(k^2-1) \qquad \rho=sk/(k^2-1) \tag{15.13}$$

Equation (15.12) is a circle with radius ρ, and center at $(x_0, 0)$. It is the locus of the point $Q(x, y)$ for fixed values of k and s, and thus DL. The circle lies in the plane containing the points. Since rotation of this plane containing Q, H_1, and H_2 about the x axis does not change the above result, the three dimensional locus of the source position, $Q(x, y, z)$, is the surface of the sphere swept out by rotation of the circle about the line H_1 and H_2. Thus from the difference in received level we determine that the source lies on the surface of a sphere of radius ρ centered at the point $(x_0,\ 0,\ 0)$ so that the position of the source is on the intersection of this sphere and the surface swept out by rotation of the hyperbola determined from the arrival time difference.

In the plane containing the source and the two hydrophones, the source must lie on the circle determined from difference in received levels and the hyperbola determined by the difference in the arrival times, its position being one of the two points of intersection of the circle and the hyperbola. Fig. 15.4 shows the circles for various values of DL (for square law propagation) and the hyperbolas for various values of τ.

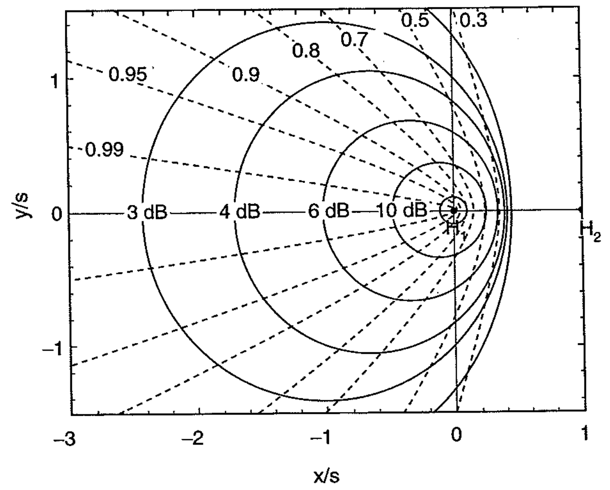

Fig. 15.4. Localization of a source as the intersection of the circle determined from the difference in levels and the hyperbola determined from the difference in the times of arrival between the two hydrophones at H_1 and H_2, separated by distance s. There are two points of intersection due to the ambiguity, Cato *et al.*, (1998).

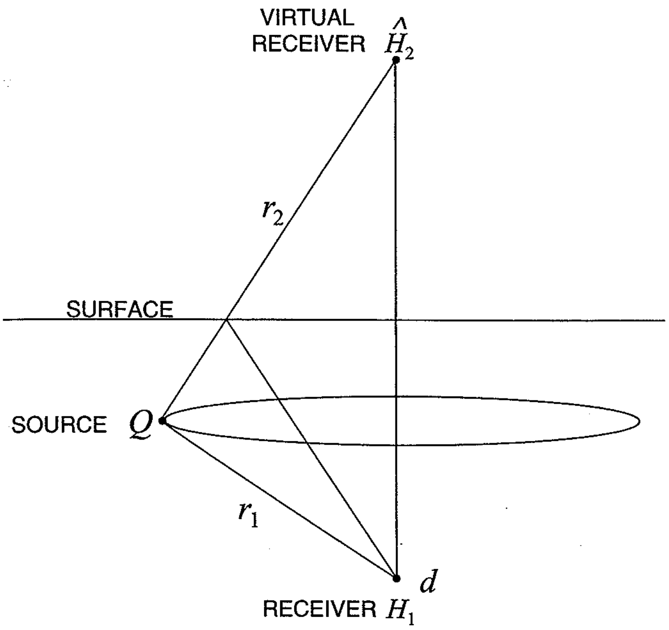

Fig. 15.5. Localization in the vertical plane using one hydrophone and a virtual hydrophone provided by the surface image of reflected sound from the source (Cato *et al.*, 1998).

Use of difference in level requires accurate measurement of the received levels so that the hydrophones need to be properly calibrated. The effectiveness depends on how well the propagation loss is known (see Cato (1998) for further discussion of the significance of these factors and the errors involved).

Use of the surface reflection to provide an additional virtual hydrophone

When the source to receiver distance is less than the water depth, the surface reflected path provides a surface image which may be used as a virtual hydrophone if the direct, surface reflected and bottom reflected arrivals are separated (Fig. 15.5). Two horizontally separated hydrophones and their surface images provide effectively four hydrophones and the arrival time differences to pairs can be used to localize a source.

Vertical localization is possible with one hydrophone, using the arrival time difference and the difference in received levels by the direct and surface paths. Reflection from the sea surface occurs with negligible loss for rms wave heights much less than an acoustic wave length (Section 9.2), a situation that occurs with many biological sounds in all but very rough weather. Hence (15.10) and (15.11) can be used with the geometry of Fig. 15.5 replacing that of Fig. 15.1. If the depth of the hydrophone is known, the source can be localized vertically to the horizontal circle shown in Fig. 15.5.

15.4 Application to tracking migrating humpback whales

Humpback whales are medium-sized mysticete whales found in all the oceans of the world. During summer, humpbacks feed in high latitude areas, but in autumn, start long migrations to tropical breeding grounds where they calve and mate over winter and spring. During the breeding season, male humpback whales produce long complex vocalizations known as "songs" because of their repetitive structure (Payne and McVay, 1971). Each song consists of several "themes," each theme being a string of similar repeated "phrases." Each phrase is a sequence of sounds or "units."

An individual male may sing continuously for several hours, producing a variety of sounds such as groans, moans, grunts, roars, trills, yaps, violin-like sounds, bellows, and squeaks. Most energy is in the frequency range 50–2500 Hz and source levels range from 175–188 dB re 1 μPa at 1 m (Richardson *et al.*, 1995). This continuous stream of high level sounds makes singers excellent subjects for passive acoustic tracking for ranges up to tens of kilometers. Frankel *et al.* (1995) used three moored buoys each with bottom-mounted hydrophones to track singing whales off Hawaii. Noad and Cato (2002) and Noad (2002) used a similar set up to track singing whales off Peregian Beach on the east coast of Australia. Both used the arrival time differences on pairs of hydrophones (Section 15.3.2). The acoustic tracking, in conjunction with simultaneous land-based visual tracking of singers and non-singers using a theodolite, allowed studies of behavior in relation to singing, calibration of acoustic counts against visual counts of whales for survey purposes, and estimation of swimming speeds of singers.

15.4.1 Example of tracking a singing humpback whale

This section describes the results of tracking a singer using arrival time differences on three hydrophone pairs, as in Section 15.3.2. Three hydrophone buoys were moored approximately 750 m apart and parallel to the coast in 20 m water depth off the east coast of Australia. Humpback whales pass close to this coast during the annual migrations between the Antarctic feeding grounds and the breeding grounds within the Great Barrier Reef. The hydrophone on each buoy was firmly fixed to a mooring which ensured it did not move while the buoy was free to swing around the mooring with the wind and currents. Each buoy transmitted the signals from the hydrophones by radio to a nearby shore station, where they were recorded on tape. For analysis, samples of the signals were captured by a stereo soundcard in a desktop computer from each of the three pairs of buoy hydrophones.

An example of a humpback whale sound recorded on one pair of hydrophones is shown in Fig. 15.6 as spectrograms and wave forms. The different arrival times of the sound at the two hydrophones are evident. The cross-correlation function of the signals at the two hydrophones, calculated using a routine written in MATLAB (Mathworks Inc.), is also shown as a function of the sample number. MATLAB calculates the cross correlation by shifting one sample record relative to the other in steps equal to the sample interval, starting with the last sample of the first record aligned with the first sample of the second record, and ending with the first sample of first record aligned with the last of the second record. Thus correlation of two records of 4000 samples each produces a result that is 8000 samples long, the two records being aligned at sample number 4000.

Cross correlation was performed for each buoy-pair to estimate the arrival time differences between the hydrophones, and the MATLAB routine then calculated the hyperbolas for the three pairs, and the intersections of the hyperbolas were found iteratively. In practice, the three hyperbolas usually intersected at three points rather than one and the position of the whale was taken as the geometric center of the triangle formed by the intersecting points. Ambiguity was usually not a problem in this experiment as most whales passed seaward of the hydrophones which were close to the coast, so the ambiguity usually resulted in a solution inshore – impossible for a swimming whale! On the other hand, having the three hydrophones parallel to the coast meant that for much of the time, the whales were broadside to the arrays where the localization had the greatest accuracy.

The track of one singer over 7 h, determined by this method is shown in Fig. 15.7. Also shown is the track of the same whale determined from the theodolite fixes from Emu Mt. The theodolite gives the bearing of the whale from the horizontal angle measured from a reference bearing, and the range is calculated from the vertical angle to the whale from the horizon. The visual positions were taken when the whale surfaced whereas the acoustic positions were taken when submerged (the received sound amplitude decreases as the source approaches the surface making it difficult to detect acoustically). Hence acoustic and visual positions do not coincide though they are expected to follow similar tracks, as in Fig. 15.7. Singers surface on average about once every 10 min, but are detectable from their sounds every few seconds, so acoustics provides many more opportunities for localization.

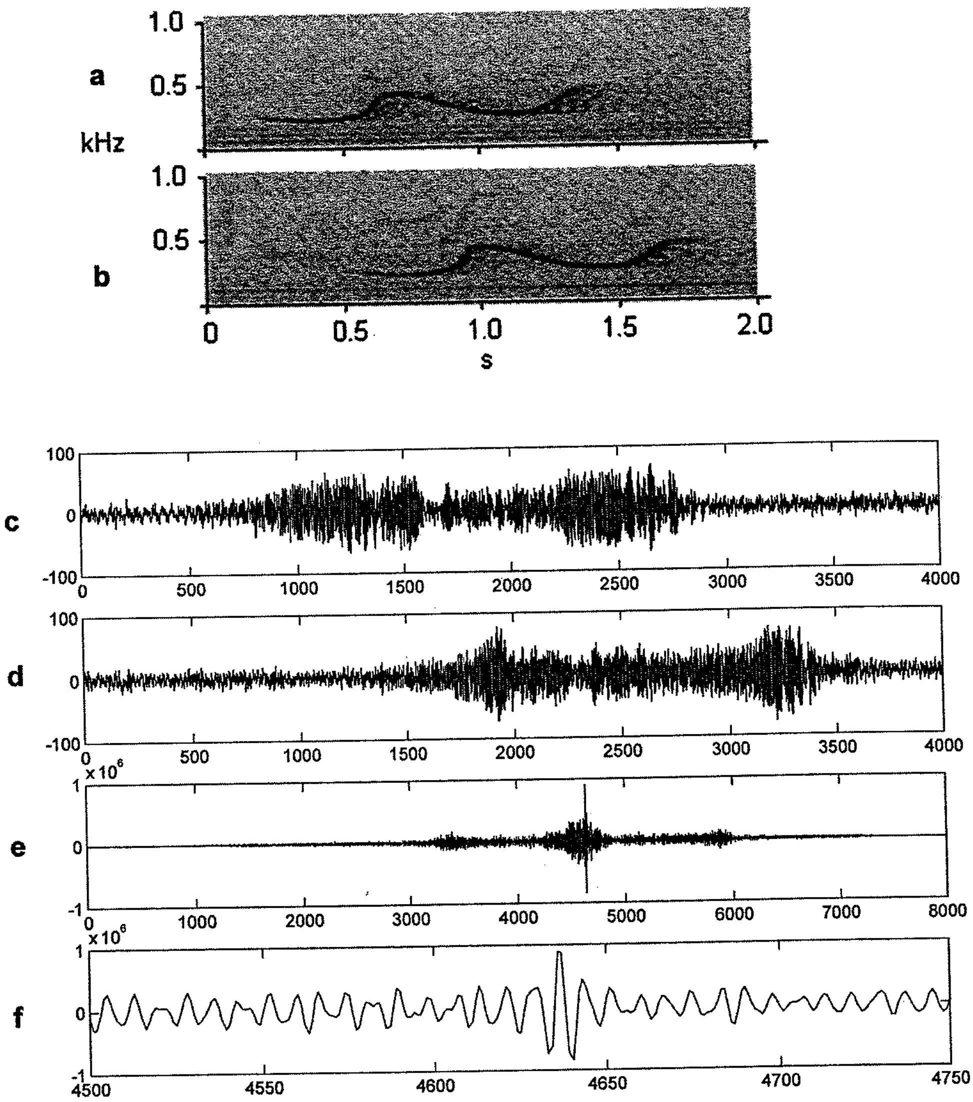

Fig. 15.6. A "modulated bellow" sound from a humpback whale off Peregian Beach. (*a*) and (*b*): spectrograms on hydrophones B and C (8 kHz sampling rate, 512 point FFT). (*c*) and (*d*): waveforms corresponding to (*a*) and (*b*). (*e*): full cross-correlation function, (*f*): expanded view of the cross-correlation function around the peak. For (*c*) – (*f*), the signals were down-sampled to 2 kHz, 8 bit (each sound signal 2 s in duration) to reduce computation time. The maximum cross-correlation value occurs at sample value 4636, which is 636 samples from the mid-point. The signal therefore arrived at hydrophone B 318 ms before hydrophone C.

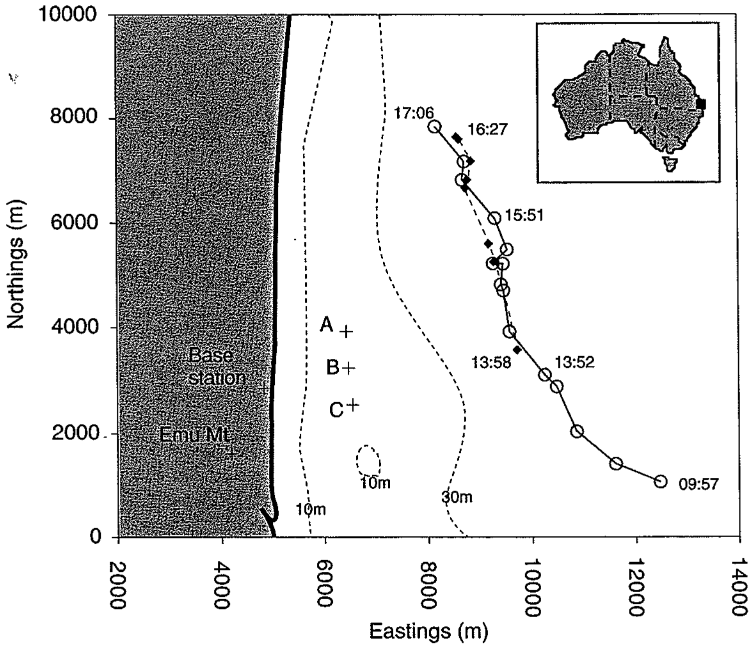

Fig. 15.7. Acoustical and visual tracks of a singing humpback whale during part of its northward migration along the east coast of Australia. Acoustical positions are circles while visual positions are diamonds. Acoustic data were received by hydrophones at A, B, and C and transmitted to the base station by radio, while the visual data were collected using a theodolite on Emu Mt. (73 m).

Accurate localization by arrival time differences requires accurate determination of the hydrophone positions and calibration of the system. For sources at distances significantly greater than the hydrophone separation, the asymptotes of the hyperbolas intersect at very small angles, so that small errors in bearing cause proportionally larger errors in estimate of distance. At Peregian, the position of each hydrophone was accurately measured using two theodolites on the beach, with a diver holding a surveyor's staff and prism vertically above the hydrophone. The accuracy of localization was checked by comparing visual and acoustics locations of a source, such as the boat or imploding light bulbs, with the position determined by GPS. The array at Peregian, with hydrophones spaced approximately 750 m apart, suffered mean range errors increasing from approximately 5% of range at 2 km to 10% at 10 km and 18% at 20 km.

15.5 Application of methods using a single hydrophone to movements of fish and whales

15.5.1 Application to fish

Many species of fish are vocal and their sounds are responsible for a substantial part of the ambient noise of the ocean. Fish use vocalizations for a number of purposes (Tavolga, 1964, 1967) providing many opportunities for acoustic localization. The following describes the results of

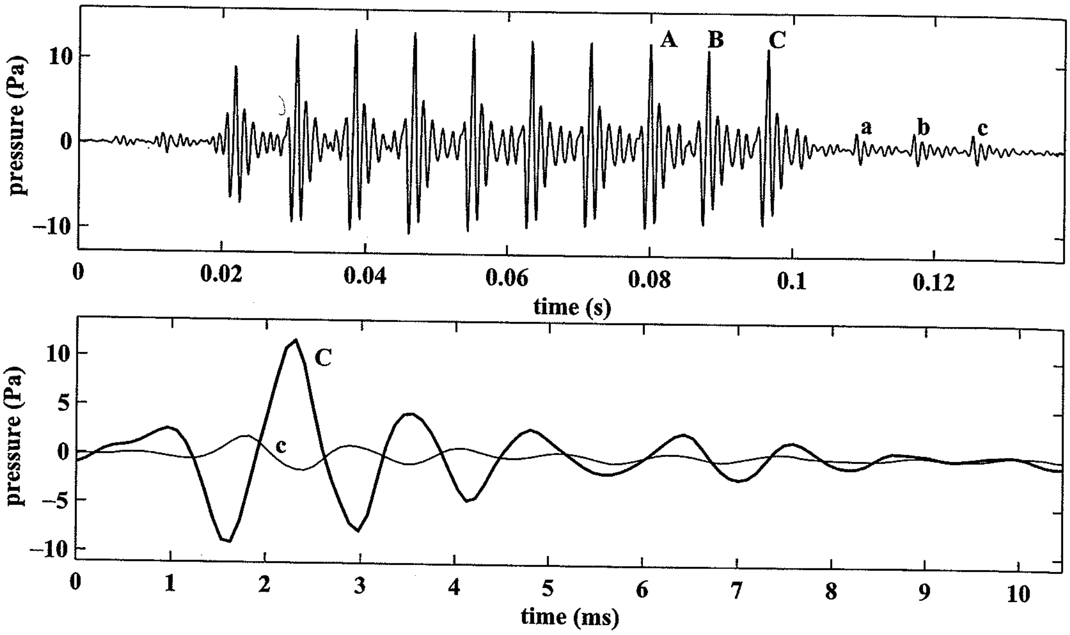

Fig. 15.8. Top: Waveform of the call at a bottomed receiver from a fish *Terapon theraps*. Surface reflections (a, b, c) of the last three direct pulses (A, B, C) are evident. Bottom: The last pulse of the wave form by direct path (C) and surface reflected path (c) with peaks aligned.

localization using one hydrophone and the virtual hydrophone formed by the surface image (Section 15.3.3), i.e., using the differences in arrival times and received levels between the direct and surface reflected paths.

Many recordings have been made of fish sources in Australian waters using single hydrophones located on the sea floor (McCauley and Cato, 2000). An example of a call of the species *Terapon theraps*, a very vocal fish known locally as flagtail trumpeter, is shown in Fig. 15.8. It was recorded in 28 m of water in the Gulf of Carpentaria, on the northern coast of Australia. The pulsed nature of fish calls is clearly evident on this plot. Each pulse represents a single "tug" of the swimbladder, in this fish, by specialized muscles attached to the anterior, dorsal, swimbladder end. The muscles rapidly expand the swimbladder, which is then allowed to oscillate, producing the damped decay seen for each pulse. The pulse rate in this instance was 121 Hz. Three trailing pulses can be seen following the primary pulses, considered to be surface reflections, as highlighted by the lettering of Fig. 15.8. On the lower plot of Fig. 15.8 the direct and appropriate surface reflection are overlaid.

With short impulsive sounds like those of Fig. 15.8, it is more appropriate to measure the integral of the pressure squared over the pulse

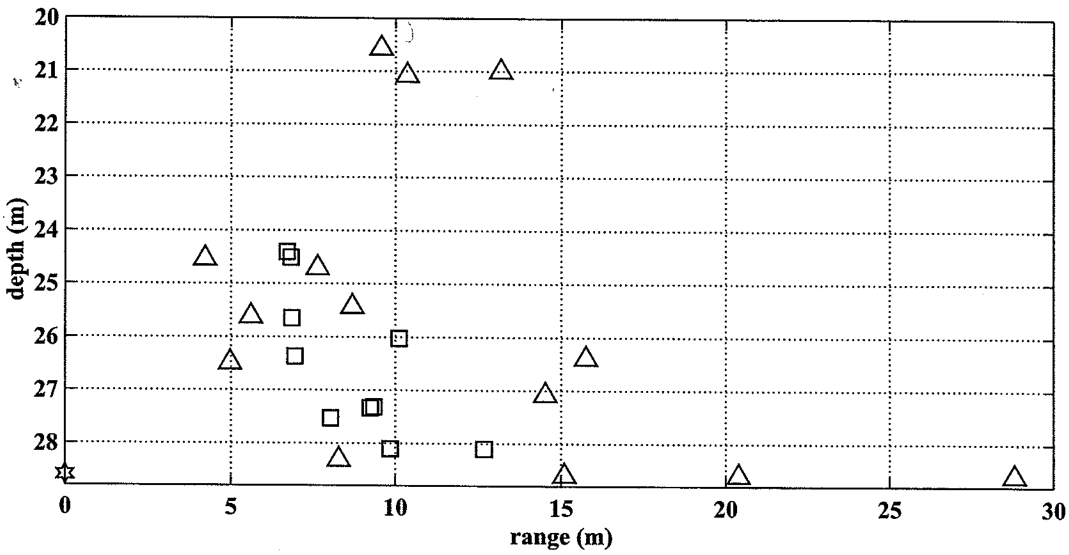

Fig. 15.9. Calculated locations of a calling fish *Terapon theraps* from a single bottomed hydrophone (indicated by the star at zero range). Two call types are differentiated by the different symbols (square and triangle).

duration (which is proportional to the energy flow through unit area) rather than the mean squared pressure, to determine the difference in level between the direct and surface reflected paths. The location of several fishes from this recording set, calculated using this technique is shown on Fig. 15.9 for two types of calls (different symbols) from *Terapon theraps*. It can be seen that calling was concentrated near to the bottom. Using these estimations of range and assuming spherical spreading, the source levels of the 24 calls were calculated to vary from 147–151 dB re 1 μPa (rms) at 1 m. Note that horizontal direction is not determined by this method.

15.5.2 Application to whales

A second example is presented for impulse signals made by blue whales recorded from a bottomed receiver in 450 m water depth off the Western Australian coast. An example of a series of pulses, with most energy between 20–40 Hz, can be seen on the top panel of Fig. 15.10. Since the hydrophone was on the bottom, all arrivals except the direct arrival reached the receiver via a surface reflection. For several pulses within this sequence it was possible to discriminate the first five arrivals and to make use of each reflected path as a virtual hydrophone. The time differences between the direct arrival and each of the first four reflected arrivals were used to determine the hyperbolas for each virtual hydrophone with the real hydrophone. The positions of a point on the direct pulse and

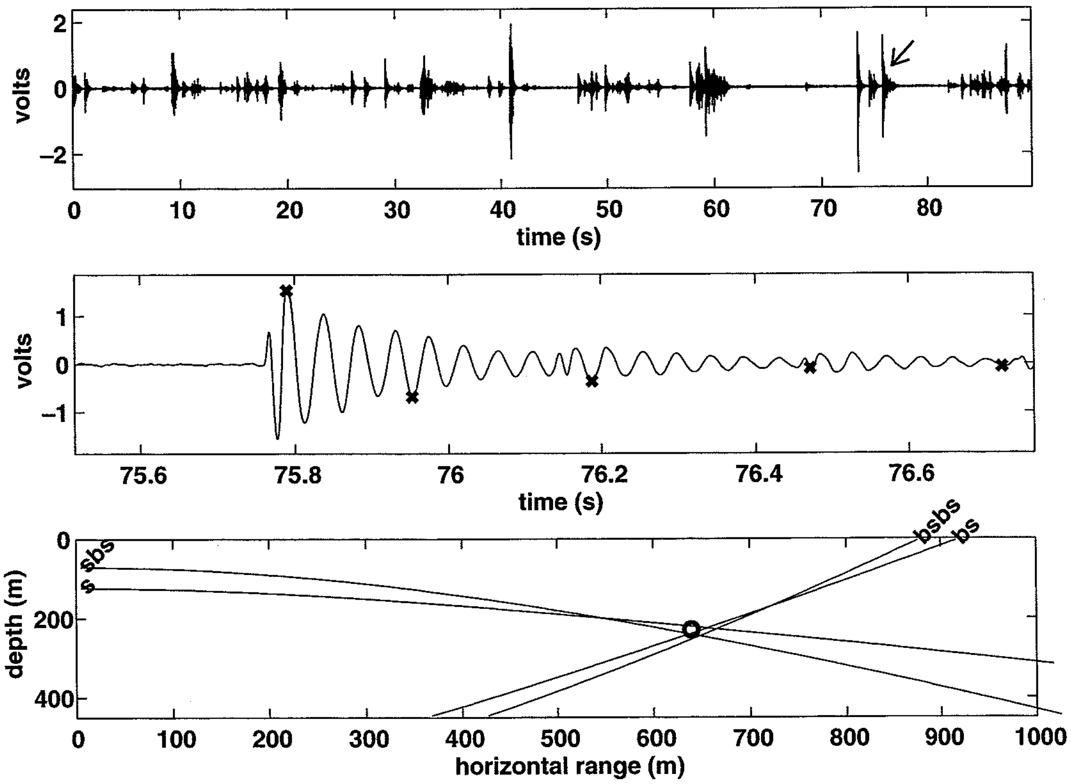

Fig. 15.10. (Top) Time series of several impulsive signals produced by blue whales off the Western Australian coast. (Center) Expanded waveform of the pulse highlighted by the arrow in the top panel. The crosses refer to the same part of the waveform for the following paths: (left to right) the direct, surface reflected, bottom–surface reflected, surface–bottom–surface reflected and the bottom–surface–bottom–surface reflected. (Bottom) The hyperbola of possible solutions for each of the arrival times relative to the direct arrival, with the estimated source position shown by the circle.

the same point on each of the first four reflected pulses are shown by the crosses in the middle panel of Fig. 15.10. The intersections of these hyperbolas then provide an estimate of the source location, as shown in the bottom panel of Fig. 15.10, at a range of 640 m and a depth of 240 m. There were a number of different sources evident in the full recording, with the source of the signal immediately preceding that shown by the arrow estimated to be at 1780 m range and 332 m depth and the pulse at 41 s at 970 m range and 212 m depth. It has been established that the study area from where these recordings were taken is a feeding area for whales and that during daylight, their food source is compacted into layers between 200–400 m depth, correlating with the source location of the impulse signals.

This technique relies on accurate discrimination between the various reflected paths. For long signals or very shallow sources (high in the water column) this discrimination may not be possible, thus the technique is limited to impulse signals which are preferably deep in the water column (hence having a reasonable time delay between their direct and surface arrival). The technique of using one hydrophone, and with virtual hydrophones provided by reflected paths, determines an estimate of range and depth of the source in the vertical plane, but not the direction or bearing of the source.

15.6 The future

More sophisticated techniques of acoustical oceanography are already being used to study behavior and movements of marine animals. Acoustical oceanography may also reveal how the animals themselves use acoustics to learn about their environment and their fellow animals. Environmental conditions cause sound signals to undergo a number of changes that add information about the environment and about the location and movement of the source. Acoustical oceanography is the study of this information and what it can tell us about the sources and their environment. Do marine animals also exploit this information? Probably they do, and probably they do it better than we do. Animals evolve to exploit any information they can sense that is useful to them. Through countless generations of trial and error, evolution would have favored the survival of those individuals that, by accident, turned out to have enhanced response to the acoustical information that gave them an advantage in finding food or mates. Their response is instinctive. Our study of acoustical oceanography can, however, show what is possible in the way that animals might exploit acoustical information in their environment. It will also provide the tools to test this experimentally.