

Sonar characteristics of the harbour porpoise (*Phocoena phocoena*): source levels and spectrum

A. D. Goodson and C. R. Sturtivant



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The international problem of incidental capture and consequent drowning of small cetaceans in passive fishing gear necessitates research to identify techniques which will minimize such interactions. Harbour porpoise (*Phocoena phocoena*) interactions with bottom-set gear are of considerable concern both in North America and in Europe. However, these animals are difficult to study and their apparent inability to avoid gillnets requires explanation. Few data on this animal's echolocation capabilities exist. Source levels (SL) and spectra have been determined for two young animals rescued from strandings. In the absence of direct acoustic measurement, the minimum sonar beam widths have been estimated using physical acoustic parameters with dimensions determined from autopsied animals. Individual harbour porpoises foraging in the Cromarty Firth in Scotland have been tracked at the surface with electronic theodolites and video, whilst their underwater acoustic emissions were monitored using an innovative acoustic detection system. The preliminary data suggest that these animals search for prey using a narrowbeam, narrowband, high-frequency sonar with a detection range, for single fish of an ingestible size, up to 30 m. These sonar characteristics appear to favour foraging close to either the sea surface or the bottom. The implications of this finding are discussed in the context of bottom-set gillnets.

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A. D. Goodson, and C. R. Sturtivant: Signal Processing Research Group, Bioacoustics and Sonar, Electronic and Electrical Engineering Department, Loughborough University of Technology, Loughborough LE11 3TU, England. Correspondence to Goodson [tel: +44 1509 222846, fax: +44 1509 222854].

Introduction

The apparent vulnerability of the harbour porpoise, *Phocoena phocoena* (L.), to entrapment in bottom-set gillnets is a matter of considerable concern in the commercial fisheries of the North-eastern seaboard of the USA and Canada (Read, 1994) and it appears that this problem is mirrored in several of the ground-net fisheries of the North Sea, Southern Baltic, and Northern European continental shelf (Kinze, 1994; Lowry and Teilmann, 1994). Since many of these bottom-set gillnet captures occur at depth and at night, and since the stomach contents of trapped porpoises usually indicate very recent feeding, it may be presumed that the animals are alert and foraging for food at the time of death. Under these conditions their primary sense is believed to be acoustic. Very limited literature on the echolocation signal characteristics of this animal exists (Sturtivant *et al.*, 1994), but harbour porpoises are known to employ narrowband, high-frequency sonar signals, in

contrast to the higher source level (SL) wideband pulses employed by many dolphins.

As with most other cetacean by-catch problems, the causes of entanglement are unclear and the behaviour of these animals close to fishing nets remains unknown. As part of a programme involving the development of both passive and active acoustic net markers, intended to make the mesh areas of a gillnet detectable to a small cetacean's sonar, tests have been carried out using juvenile harbour porpoises rescued after stranding and in human care at Harderwijk in Holland.

These animals' peak SLs were carefully measured in a series of tank tests at three different ranges with calibrated hydrophones. Whilst this reverberant environment may not have encouraged these juvenile animals to emit their maximum SL, the on-axis peak levels recorded were around 150 dB (re 1 μ Pa at 1 m) and exhibited a consistent narrowband power spectrum with most energy concentrated between 140 kHz and 160 kHz. The characteristics of this phocoenid's sonar are therefore

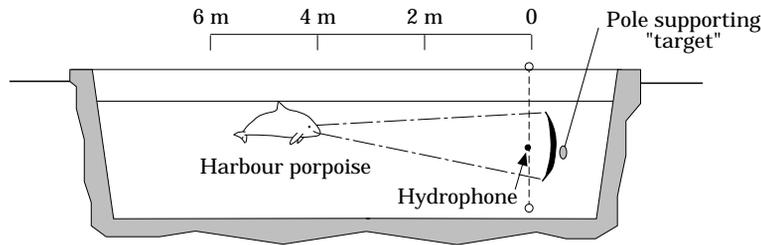


Figure 1. Porpoise, supported at a pre-set range, while recording echolocation sound pressure levels. Pool size 8.6 m × 6.3 m (not drawn to scale), water depth 1.3 m.

different from those of the bottlenose dolphin (*Tursiops truncatus*), which has much louder broadband signals (Au, 1980).

The direct measurement of the -3 dB beam width is difficult, and has still to be assessed. However, data from harbour porpoise autopsies have been used to estimate minimum beam angles from measurements of the projecting acoustic aperture.

Preliminary data from a short study of harbour porpoises foraging close to an inactive oil-rig in the Cromarty Firth, Scotland, suggest that rather higher SLs may be achieved in low reverberation open water conditions than in trials with captive animals. This same study confirmed that the sonar beam width in azimuth is very narrow and that very little detectable energy radiates outside the main lobe.

Harderwijk study animals

Until recently, very few harbour porpoise were available for close study. In 1993–94, two young harbour porpoises were rescued after stranding on the Dutch and German coasts and successfully rehabilitated at the Zeedierenpark Harderwijk in the Netherlands. On arrival in a poor state of health, their estimated ages were 5 weeks and 8 months, respectively. After their recovery, both animals were available for tests early in 1994 and have provided an opportunity to examine this species' sonar emissions, and measure their SLs and spectrum characteristics in controlled conditions (Goodson *et al.*, 1995). The age of the porpoises at the time the trials occurred was 8 months and 20 months, at which stage both were fully weaned and eating whole fish.

The animals were maintained in a specialist rehabilitation centre and tested individually in a concrete pool 8.6 m long by 6.3 m wide (Fig. 1). The pool depth of 1.4 m permitted a research assistant to stand in the water and position the animal at a preselected range from the hydrophones. The animals were accustomed to handling, having been both tube- and bottle-fed during rehabilitation, and they appeared calm throughout the measurements. The animals were positioned such that the tip of the rostrum was a measured distance away from the receiving hydrophones. After a number of

breaths, the porpoise was lowered some 30 cm below the water surface, and its attention attracted by side-to-side movements of a plastic target behind and at the same depth as the hydrophones. This had the effect of stimulating the porpoise to produce steady echolocation click trains directed towards the easily visible but acoustically weak target.

Sound pressure levels (SPL) were measured at 2, 4, and 6 m ranges with two 12 mm ball hydrophones (International Sonar HS120). These hydrophones were omni-directional at the frequencies of interest and were carefully re-calibrated after the tests. The porpoises' behaviour and orientation were recorded with two Hi-8 video cameras, one positioned above and one on the side of the pool. The sequence of pulses emitted as the animal attempted to follow the target rose to a peak SPL as the beam centre passed across the hydrophone, and this maximum value was measured during analysis on an oscilloscope. Maximum SPL values were determined from 3 (or 4) tests made at each of the three ranges and corrected for hydrophone sensitivity at 150 kHz (-210 dB re 1 V μPa^{-1}) and system gain ($+60$ dB). The SLs referred to 1 m were calculated from the SPL and the transmission loss (TL), i.e. losses due to the path length (R) between the porpoise and the hydrophone. These losses include absorption ($\alpha \approx 0.05$ dB m^{-1} at 150 kHz) and spherical spreading loss ($20 \log R$).

$\text{SL} = \text{SPL} - \text{TL}$ (Spreading Loss + Absorption)

Since porpoise waveforms are transient, the peak-to-peak maximum excursion of the waveform was measured and the equivalent rms value calculated, assuming a continuous wave signal of the same maximum value. This approach is in common usage and makes simple intensity comparisons possible. It may be argued that when the waveform is known the actual energy flux can be calculated, which is more informative when assessing target detectability. Peak-to-peak values, TS_{pp} , are also used in the literature, but as these differ by $+9$ dB from TS_{rms} values, some care must be taken when interpreting data from different sources.

The results from the two animals tested are shown in Figure 2. These values are believed to be accurate within 1 dB with respect to the calibrated hydrophone and it

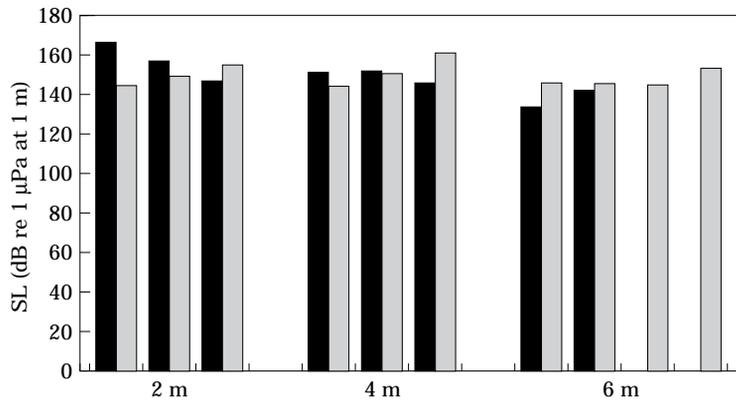


Figure 2. Source levels measured from juvenile harbour porpoises at three ranges: (■) 20 months old – SL maximum 166 dB, minimum 134 dB (average 149.5 dB) re 1 μ P at 1 m. (□) 8 months old – SL maximum 162 dB, minimum 144 dB (average 149.5 dB) re 1 μ P at 1 m.

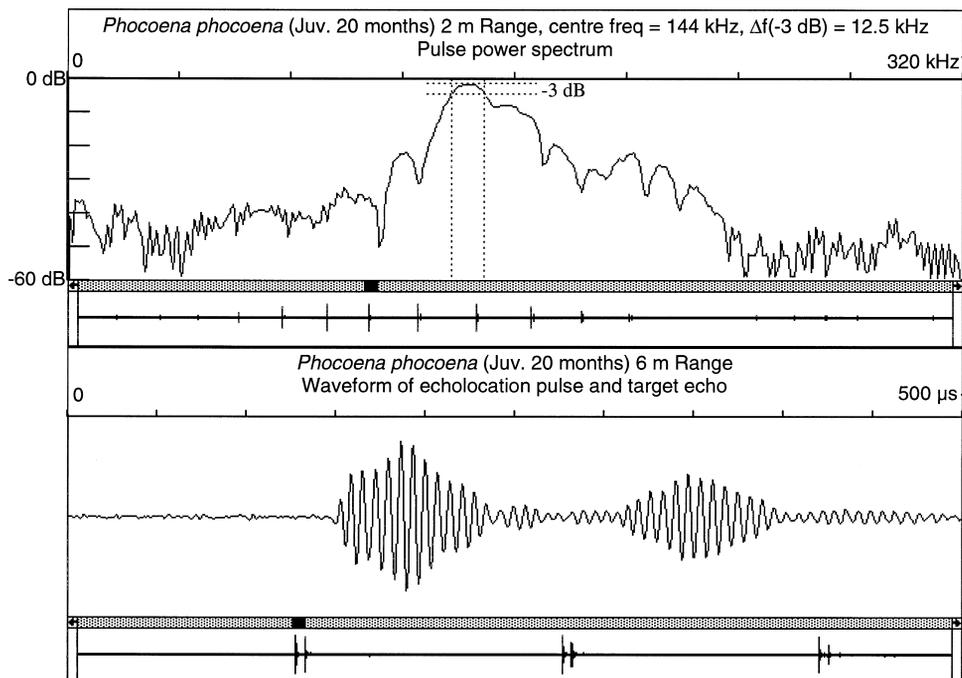


Figure 3. Typical power spectrum of a porpoise “click”, indicating that most of the energy is concentrated around 140 kHz. The lower window displays the amplitude waveform from a typical pulse followed by the reflected target echo.

seems that the animals have some control over the emitted SL. The power spectrum of the pulse and a spectrogram showing the direct path signal and the echo from the target are shown in Figure 3. The animal was using an inter-click repetition rate of approximately 30 ms to interrogate the target, which is considerably longer than the two-way travel time (2.67 ms at 2 m). This increased interval appears to be an adaptation to reverberations resulting from wall-to-wall reflections (Fig. 4), suggesting that the animal requires a SL to reverberation ratio greater than 50 dB.

The signals from these two animals were remarkably similar, with the average SL being 149.5 dB re 1 μ P at 1 m in both cases. The -3 dB signal bandwidths were 14 kHz for the younger animal and 12.5 kHz for the older, and the peak frequencies were 148 kHz and 144 kHz, respectively. This peak frequency is higher than has been reported for adult harbour porpoises (Møhl and Andersen, 1973). Hatakeyama and Soeda (1990) quote values of between 125 kHz and 140 kHz, although Kamminga and Wiersma (1981) also observed higher peak frequencies for a young harbour porpoise.

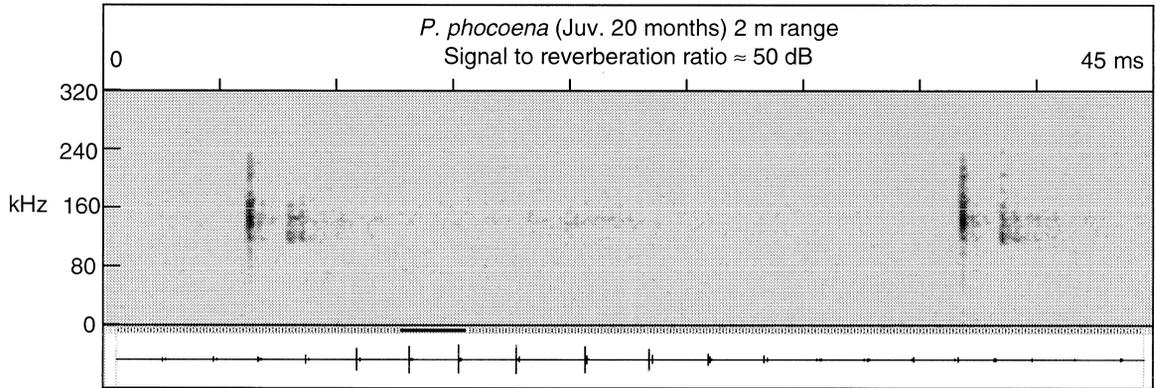


Figure 4. A time-frequency spectrogram showing two direct path pulses followed by decaying reverberation echoes from the pool walls. Residual reverberation had fallen to -50 dB (with respect to the source level) at the time of the next pulse.

This suggests that the frequency of the power peak in the spectrum may relate to body size and, if so, the peak frequency may be expected to fall somewhat as the animals approach maturity.

Anatomy

The echolocation sounds of the small odontocetes are emitted from the bulbous fore-part of the head through a fatty organ known as the melon. Whilst the exact mechanism generating the sound impulses remains to be demonstrated conclusively, most authors now agree that the sonar signals originate in (wetted) tissue at the dorsal bursae and do not propagate within the airway. Amundin (1991) demonstrated in an elegant experiment that when a porpoise was given a helium/oxygen mixture to breathe, the high frequency spectrum of these signals remained unchanged, and only the very-low-intensity, low-frequency artefacts of the pulse altered in pitch.

Aroyan *et al.* (1992) computed for the common dolphin (*Delphinus delphis*) the relative contributions to the sonar beam formation of the melon, air sacs, and skull bones. They concluded that the directivity was primarily determined by the air sacs acting as baffles with the melon providing the final beam shape, including shading and impedance matching to the water. The contribution of the melon is therefore important and this fatty lens is known to consist of a low sound velocity core surrounded by a graded index of higher velocity material (Norris and Harvey, 1974). Since for any transducer the maximum aperture of the projector defines the minimum angle that can be beam formed, the cross-section of the melon provides a baseline for estimating this parameter in both azimuth and elevation.

Harbour porpoise autopsy workshops held at the Sea Mammals Research Unit in Cambridge, to examine animals found dead on the UK coastline, provided an opportunity to examine similar-sized animals to those tested in The Netherlands. The fore-part of the head was

therefore dissected in a series of transverse slices in order to determine the maximum cross-section of this organ (Fig. 5). The maximum melon dimensions (Fig. 6) obtained in this way were used to estimate the minimum beam width in both azimuth and elevation (Goodson and Klinowska, 1990). The maximum melon dimensions were 62 mm (H) \times 37 mm (V). These values suggest that if λ is taken as ≈ 9.8 mm then the minimum sonar beam width in azimuth will be $\approx 9^\circ$ and in elevation $\approx 15^\circ$.

As the fatty tissues measured were relaxed when examined and as both skin and muscle tensions would be greater in life, these cross-section dimensions may increase slightly, possibly providing the animal with some control of acoustic focus to minimize near-field effects. However, from the limited mobility of this tissue it seems unlikely that the minimum beam width can be less than 8° horizontally and 14° vertically. It may be argued that the animal will strive to project a signal with high directivity to improve its detection range and that these minimum angles will be approached. However, the direct measurement of the acoustic beam width in the far field remains an objective.

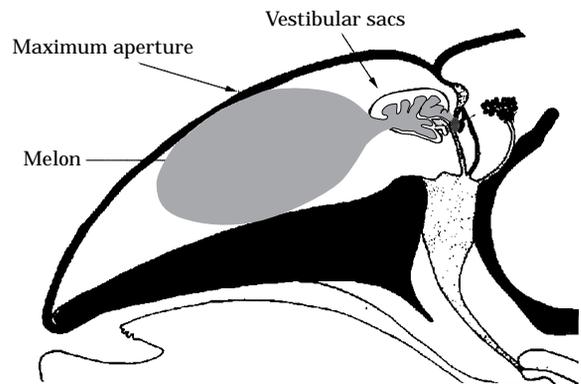


Figure 5. Diagram of forepart of harbour porpoise head showing melon and vestibular sac with section line.

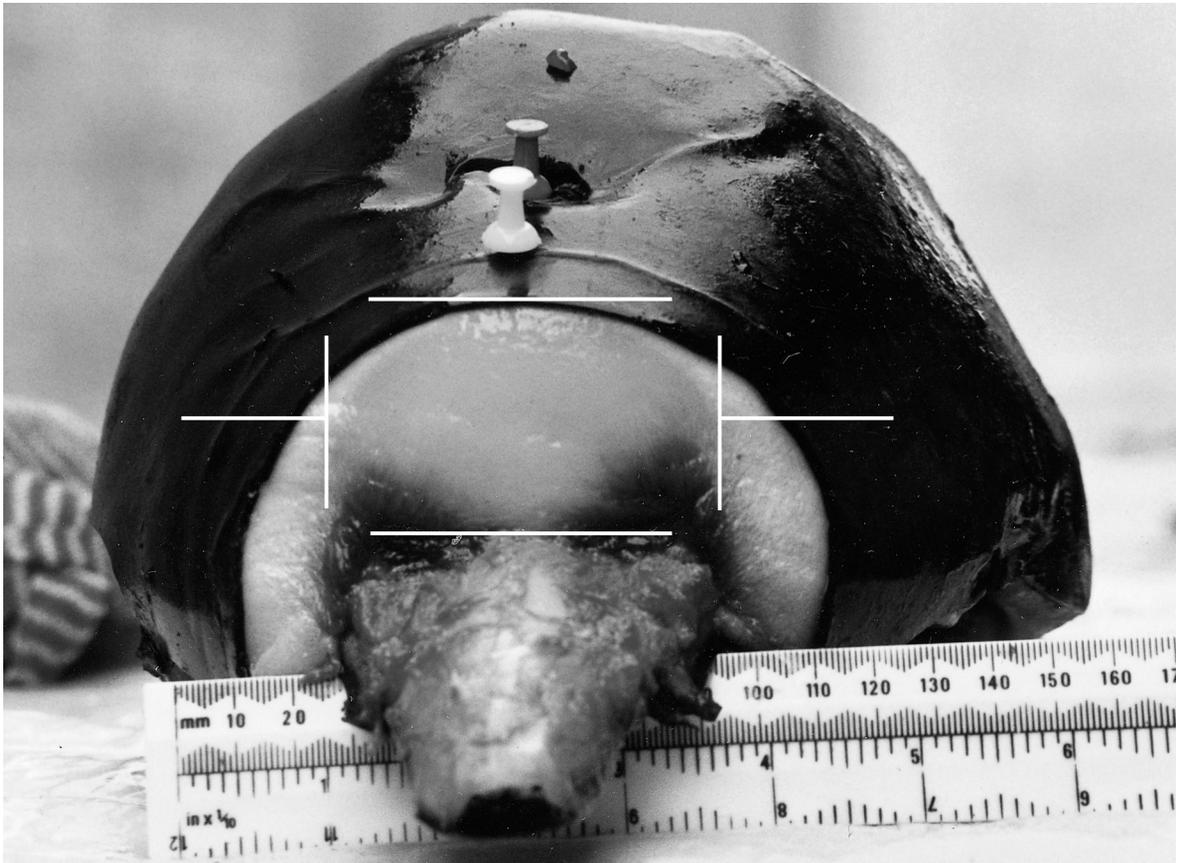


Figure 6. Harbour porpoise melon sectioned at the point of maximum cross-section.

It should be noted that the maximum sound velocity in dolphin lipid tissue corrected for body temperature is believed to be 1435 m s^{-1} , and the minimum at the core 1246 m s^{-1} (Norris and Harvey, 1974; Au, 1993). Au also suggests that the lipid's negative velocity/temperature coefficient results in an increasing sound velocity at the skin surface to a value which closely matches that of the sea water.

Examining foraging behaviour

Harbour porpoises are difficult to follow at sea. Dive duration may be several minutes, and time spent at the surface to breathe is appreciably shorter than for most dolphins. These characteristics, combined with the difficulty in predicting the porpoises' resurfacing position, render them difficult animals to track successfully. In the Cromarty Firth in Scotland a number of inactive oil-rigs are moored in the deepwater channel. In late summer and early autumn harbour porpoises frequent this area and pass close to these rigs, so the possibility of using a semi-submersible oil-rig as an elevated survey base was explored.

A position some 35 m above the sea surface was established on one corner of the oil-rig "John Shaw". Electronic theodolites were employed to track the animals and to establish the stability of the platform. Even in these sheltered waters in calm conditions the semi-submersible rig moved slightly with the swell arriving from the entrance to the Firth, and the significance of this was assessed (Mayo *et al.*, 1995). A dual video camera monitoring technique was used to derive angular corrections to compensate for errors induced by the rig's movement.

A novel hydrophone monitoring system was employed, since the signals to be observed were known to be ultrasonic and confined to the region of 100–160 kHz. High-speed instrumentation recorders traditionally used for such high-frequency work consume large quantities of tape, and are uneconomic for long periods of monitoring. A technique was therefore employed using an R-DAT digital recorder (Sony TCD-D7), where media costs are significantly less. This portable machine records two channels of 16 bit resolution data sampling at 48 kHz and has a flat response up to 22 kHz with a 90 dB signal-to-noise capability.

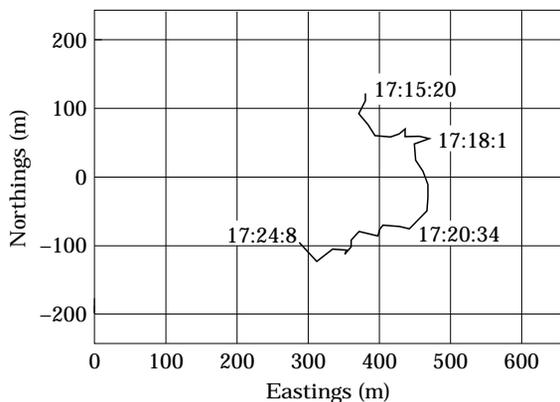


Figure 7. Track of foraging porpoise. Observation point (origin) at 57°41.2'N, 4°4.5'W.

The hydrophone signals were preprocessed into two bands: the lower from 2 kHz to 22 kHz, and the upper from 100 kHz to 160 kHz. The upper frequency band was passed through a precision rectifier and filtered to extract the envelope of the sonar clicks, which was converted by this process to an audible and recordable signal. This signal processing was carried out at sea level and a 100 m screened quad cable then carried the two processed signals (balanced) to the working platform 35 m above. The signals were monitored on an oscilloscope, fed to the two R-DAT recording channels, and relayed to loudspeakers near the observers.

In practice, the technique worked well, although falling water from the rig generated a significant masking noise on the low frequency channel which reduced its usefulness. Some 700 surfacings were plotted in sea-state zero conditions and the individual tracks computed from each surfacing position. The porpoise track could then be compared with echolocation clicks recorded on the R-DAT, and in these near perfect conditions the clicks could be detected from a porpoise pointing directly at the hydrophones out to a maximum range of 350 m. In most of the click sequences observed, the

signal intensities faded very sharply and reappeared strongly in an almost regular pattern, producing the effect of a series of very short click bursts. This evidence strongly suggests that the porpoise was scanning a small sector ahead of its path by body or head movements. Figure 7 shows a typical track of an animal searching a volume of water for fish believed to be close to the surface.

Figure 8 demonstrates the detection of a series of clicks detected as the porpoise at 300 m range headed directly towards the hydrophone in sea-state zero conditions. The regular click rate evident in this recording (36 ms inter-click period) suggests from the two-way travel time that the maximum range searched ahead of the porpoise was less than 27 m. Since at the instant of each transmission the receiver is desensitized, it is safe to assume that echoes arriving from small food targets at greater ranges than this will be lost. The detection range of a porpoise may be estimated using the sonar equation. Assuming a -41 dB TS fish (approximating the largest ingestible size as determined from stomach contents), a maximum SL of 170 dB (Akamatsu *et al.*, 1994), and assuming that the hearing threshold of the harbour porpoise at 140 kHz is 68 dB re $1 \mu\text{Pa}$ (Andersen, 1970), it would appear that the maximum detection range for such single fish targets will be around 30 m.

Conclusions

The SLs measured from the two juvenile porpoises were higher than the limited literature had suggested, and perhaps indicated that the target used to stimulate echolocation was easily visible but a very poor acoustic reflector. The highest SL observed was 166 dB re $1 \mu\text{Pa}$ at 1 m, which is considerably less than the 220 dB re $1 \mu\text{Pa}$ at 1 m observed for the bottlenose dolphin in open water, derived from Au (1980, 1993), who quoted a maximum peak-to-peak SL_{pp} of 229 dB. The peak frequency in the porpoise's echolocation signal spectrum

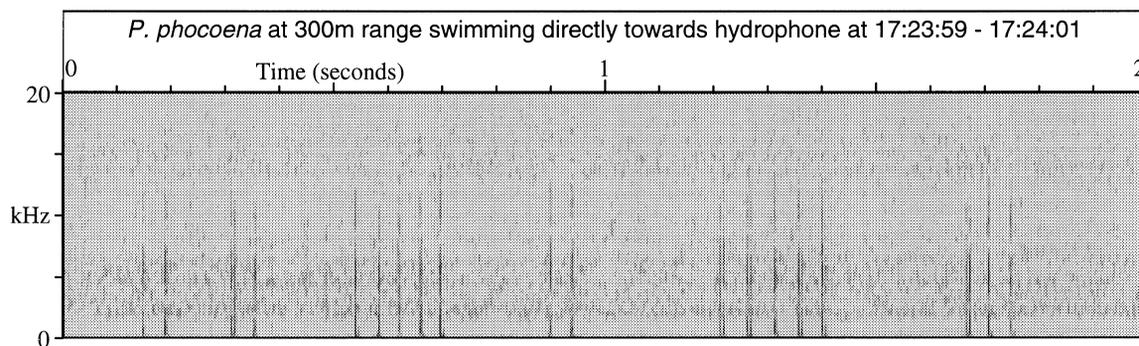


Figure 8. Time-frequency spectrogram showing envelope-detected porpoise clicks at 300 m range. In this display, the frequency axis represents the pulse bandwidth reduced to base band.

was 147 kHz with a -3 dB bandwidth of 13 kHz. It is unfortunate that SLs could not be estimated from the field measurements using the click detector circuit as the processed amplitudes were recorded using an uncalibrated R-DAT recorder. Adding an injected signal could allow calibrated recordings to be made.

The low-power, narrowband nature of the harbour porpoise signals suggests a sonar system that has evolved as a relatively short-range foraging sense. The narrowband nature of these signals also indicates that target echoes contain less spectral colouration to aid classification, a factor worth consideration when designing reflecting devices for net enhancement that must not appear "food-like". The relationship between click rates, defining maximum detection ranges, and the sonar beam width in the vertical plane may be a factor determining whether the choice of gillnet headline height above the seabed affects the by-catch. Float lines provide a good acoustic target, and Hatakeyama and Soeda (1990) reported that, in a test with a surface-set gillnet configuration, harbour porpoises reacted to the headline component at about 9 m range, whereas the mono-filament mesh zone was not detected at ranges greater than 2 m. In a bottom-set configuration, the headline is clearly more detectable. However, the echoes from the headline may not be observed at all if the animal is actively chasing prey with its sonar repetition rate locked to the fish. In addition, if the animal is hunting for fish on the seabed the headline may not be ensonified at all.

The anatomy of the porpoise melon suggests a minimum beam width of 9° in azimuth by 15° in elevation, although measurement with an array of hydrophones will be required in order to verify this. Risk of entanglement may therefore be greatest during slack water when the gillnet height may approach its maximum and when noise cues from the gear will be at a minimum. Bottom-set gillnet geometry alters radically in a short time scale when the tide changes, and this increases the problems of perception for the porpoise. From their intensive observations of a solitary bottlenose dolphin, Bloom *et al.* (1995) believe that these animals navigate within a memory mapped environment, and that the limited cone of perception afforded by their narrow "look-ahead" sonar may explain their inability to avoid large, diffuse structures.

Although detecting the presence of the animal by its vocalizations at a range of 350 m is significantly better than might be predicted from the juvenile captive SL data, the directional nature and lack of detectable energy outside the narrow sonar beam make these animals extremely difficult to track underwater. It seems likely that, even at very close range, they will remain difficult to detect unless pointing directly at the receiving hydrophone. New tracking techniques, such as sparse hydrophone arrays, which are being developed to localize the underwater position of vocalizing animals,

require all the hydrophones to be ensonified by the same acoustic emission. Such techniques appear to be more difficult to apply to the harbour porpoise than to other small cetaceans.

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