J. CETACEAN RES. MANAGE. 2(1):1–9

Experimental testing of acoustic alarms (pingers) to reduce bycatch of harbour porpoise, *Phocoena phocoena*, in the state of Washington

PATRICK J. GEARIN*, MERRILL E. GOSHO*, JEFFREY L. LAAKE*, LAWRENCE COOKE+, ROBERT L. DELONG* AND KIRT M. HUGHES*

Contact e-mail: pat.gearin@noaa.gov

ABSTRACT

Field tests were conducted on the effectiveness of acoustic alarms (pingers) in reducing the incidental catch of harbour porpoise (*Phocoena phocoena*) in a salmon gillnet fishery in northern Washington in July and August of 1995-1997. The alarms produced a broadband signal with peaks at 3 and 20kHz, with mean source levels between 121.7-124.7dB re 1μPa @ 1m. For 1995 and 1996 combined, 47 harbour porpoise were taken in control nets and only two were taken in alarmed nets. The alarms significantly reduced the bycatch of harbour porpoise for both seasons (1995: $\chi^2 = 5.28$, df = 1, $p = 0.02$; 1996: $\chi^2 = 11.2$, df = 1, $p = 0.001$). In 1997, all nets were alarmed and 12 porpoise were taken; however, the expected catch without alarms would have been 79. There were no significant differences in catch rates of chinook salmon (*Oncorhynchus tshawytscha*) ($\chi^2 = 0.31$. df = 1, $p = 0.58$), or sturgeon (*Acipenser* sp.) ($\chi^2 = 1.44$, df = 1, $p = 0.23$) in control or alarmed nets. There were also no significant differences in the bycatch of harbour seals (*Phoca vitulina*) ($\chi^2 = 0.09$, df = 1, $p = 0.76$) or depredation of salmon by seals in nets with and without alarms ($\chi^2 = 0.07$, df = 1, $p = 0.79$). The results of these studies indicate that acoustic alarms significantly reduce the probability of harbour porpoise entanglement in bottom-set gillnets in the fishery without reducing the catch of target fish species.

KEYWORDS: HARBOUR PORPOISE; BYCATCH; PACIFIC OCEAN; EXPERIMENTAL; ACOUSTICS

INTRODUCTION

Harbour porpoise (*Phocoena phocoena*) are susceptible to incidental mortality in gillnet fisheries throughout their range (e.g. Gaskin, 1984; Read and Gaskin, 1988; Gearin *et al.*, 1994; Kastelein *et al.*, 1995). In the Gulf of Maine, Bay of Fundy, and the North, Celtic and Baltic Seas, incidental catches of harbour porpoise may exceed sustainable levels and potentially threaten local stocks (e.g. see Donovan and Bjørge, 1995).

Numerous workshops, symposia and meetings have been conducted to address harbour porpoise bycatch and the broader issue of cetacean mortality in gillnets (Frady *et al.*, 1994; IWC, 1994; 2000; Reeves *et al.*, 1996). One of the primary objectives of these efforts has been to identify methods to reduce or mitigate gillnet mortality. Mitigation efforts using acoustic deterrents were developed primarily by Jon Lien and colleagues, from Memorial University in Newfoundland, who used sound making devices to reduce entanglements of humpback whales (*Megaptera novaeanglia*) in fish traps in Newfoundland (Lien *et al.*, 1992). Lien later developed a device he called a 'pinger', a simple homemade alarm using a piezo buzzer or truck back-up alarm as the sound source. Two preliminary trials of the devices were conducted in the New England sinknet fishery during the autumn of 1992 and 1993 (Lien and Hood, 1994). The results of the trials were statistically inconclusive, but the method showed some promise for reducing the bycatch of harbour porpoises. A review of the data and methodology by a NMFS (US National Marine Fisheries Service) scientific review panel in June 1994 concluded that further work was warranted, but that future experiments would require a more rigid design and a significant increase in sampling effort.

A large-scale experiment was conducted during the autumn of 1994 in the Gulf of Maine using a study design which conformed with the recommendations of the NMFS review panel. The results demonstrated conclusively for the first time that acoustic alarms reduced the bycatch of harbour porpoise in sink gillnet fisheries (Kraus *et al.*, 1995; 1997). However, Kraus *et al.* (1995) indicated that they did not know why the alarms were effective and, in particular, whether they functioned by alerting harbour porpoises to the nets or by scaring them away from a specific area. It is also not known whether habituation to the devices will occur over time, or whether the devices will function in another type of fishery for other species. Catches of Atlantic herring (*Clupea harengus*), a primary prey of the harbour porpoise, were lower in alarmed nets suggesting that alarms may function in part by scaring harbour porpoise prey away from nets (Kraus *et al.*, 1997).

Experiments using acoustic alarms were conducted in the Northern Washington Marine Set-net Fishery from 1995 to 1997. Observer programmes in the fishery since 1988 indicated that most harbour porpoises were taken during July and August (Gearin *et al.*, 1993; 1994). Most (99%) of the harbour porpoise observed or reported taken in the fishery from 1988 to 1997 ($n = 205$) were caught in the Spike Rock area, a small bay on the Pacific coast (Fig. 1). Catch rates at Spike Rock are among the highest reported in the world ranging from 0.10-0.70 porpoises taken per net day (Gearin *et al.*, 1994). Our goal was to determine if alarms would reduce the harbour porpoise bycatch in this fishery, and to learn more about how the alarms function. In addition, studies on observations of harbour porpoises in relation to alarmed nets were conducted and field measurements of alarms at the fishing grounds where the studies were conducted were obtained.

---

* *National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way, Seattle, Washington 98115, USA.*

+ *Makah Tribal Fisheries Management Division, PO Box 115, Neah Bay, WA 98357, USA.*

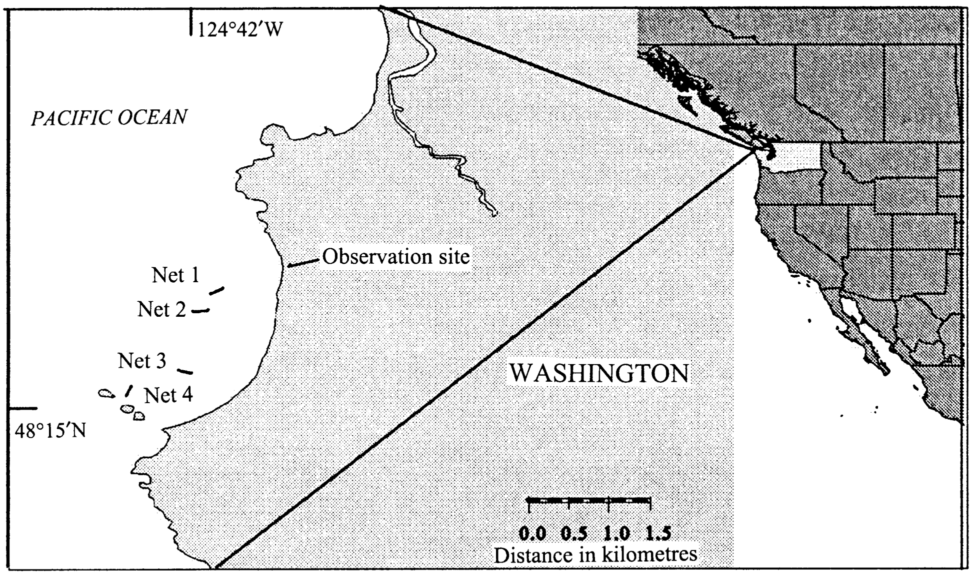

Fig. 1. Map of the Spike Rock fishing grounds on the outer Washington coast and location of set-nets, 1995-1997.

MATERIALS AND METHODS

Description of the fishery

The Northern Washington Marine Set-net Fishery is conducted by the Makah Indian Tribe and operates along the coast of Washington state in the Pacific Ocean and in the western Strait of Juan de Fuca (Fig. 1). The fishery is open from 1 May to 15 September each year and targets chinook salmon (*Oncorhynchus tshawytscha*) and sturgeon (*Acipenser* sp.) with peak landings during July and August. The fishing experiments were conducted in the Spike Rock fishing grounds, a small area relative to the overall fishing grounds utilised by the Makah Tribe. The Spike Rock area is 1km wide by 2km long and is a shallow sloping bay with a flat, sandy bottom. The area fished ranges from 11-30m in depth. Vessels used in the fishery are small: 5-8m in length and use gillnets with a maximum length of 100 fathoms (183m). The nets are composed of mono- or polyfilament nylon ranging from 19-22cm stretched mesh from 35-90 meshes deep. The nets are set on the bottom, anchored in position, and are checked on average every 24 hours. Fishing effort was defined in net days (ND), where 1ND equals a 100 fathom net set for 24 hours (Polacheck, 1989). A more detailed description of the fishery is provided in Gearin *et al.* (1994).

Design of alarms

The alarms used were slightly modified designs of Jon Lien's as described by Fullilove (1994). The alarm unit consisted of a piezo buzzer which operated on four 9 volt batteries, ABS pipe, screw caps, end caps and adapters. The central housing tube was cut from 5cm diameter ABS to lengths of 15-18cm. Rubber sealant and silicon was used instead of O-rings to seal the screw caps. The devices did not have a salt water switch and remained constantly active. Because the nets stayed in one location for long periods of time and remained in the water except for the brief period when they were checked, it was not necessary to save battery life by installing a salt water switch. Due to the short duration of the experiments, the four batteries installed were adequate to power the alarms for 6-8 weeks. Our alarms were simpler and probably less expensive than the Lien model, costing about US $20.00 to produce.

Field testing alarms

The attenuation and sound source levels of three alarms were tested before the 1995 experiment began to determine optimal spacing patterns and required distances between nets (Bain, unpubl. data). A spherical spreading formula was used to calculate optimum spacing given varying sea states and background ambient noise. The formula used was:

$$SPL_R = SPL_1 - 20 \log (R)$$

where SPL_R is sound level measured at range (R) and SPL_1 is sound level measured at 1m (Urick, 1983). The alarms produced a broadband signal at intervals of 4s centred at 3kHz with a second peak near 20kHz (Fig. 2). Minimum source levels were 90dB at 30cm (in air) according to manufacturers specifications.

Acousticians from Hubbs Sea World Research Institute were contracted to conduct field measurements of the ambient noise parameters and alarm attenuation at the Spike Rock study site in 1996 (Bowles *et al.*, 1997). Transmission loss and ambient noise levels in the area were measured using a broadband calibrated recording system including an *ITC 6050C* hydrophone and a *Nagra IV-SJ* recorder. The transmission loss was estimated using a shallow water loss model (spherical [20 logR] spreading out to bottom depth and approximately cylindrical spreading [10 logR] thereafter). The shallow water model was used to estimate the detection range of alarms at the two frequency peaks.

During the course of the field measurements, it became clear that the peak frequency of the alarms varied by unit depending on battery condition. Given that, calibration measurements were not made on all individual units in the field. Instead, the net was treated as a whole as the sound source for pinger attenuation measurements. As background noise appeared to have a large effect on the empirical data, the transmission loss was also modelled using decline in signal-to-noise ratio (SNR) of the alarms, or the difference between tonal level and ambient noise level in the appropriate bands ($SNR > 0dB$). SNR was obtained by subtracting ambient levels at 3kHz and 20kHz from the spectrum levels of the pings at each measuring station. SNR close to the net was 11-23dB at 3kHz and 12-24dB at 20kHz. Successive measurements of SNR were less variable than successive measurements of peak level. Therefore, SNR was also used to estimate attenuation rate using the equation

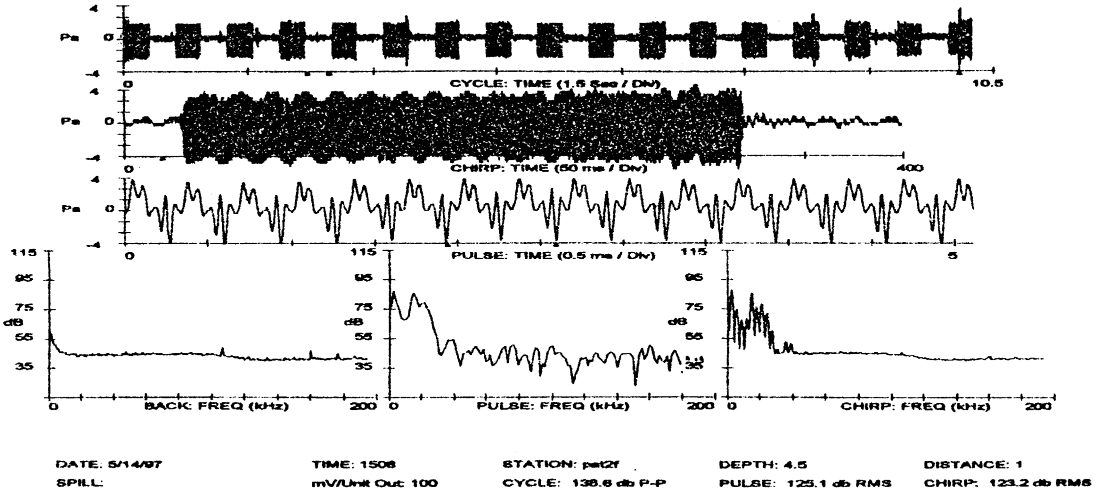

Fig. 2. Sound and pulse characteristics of an acoustic alarm (pinger) used in the experimental set-net studies during 1995-1997.

$SNRR = SNRO-Xlog10(R)$. A simple logarithmic decay model was used to fit the data; $dBR = dBO-Xlog10(R)$, where dBR = level at R, dBO = estimated source level, and X = best-fit slope. Further detail is provided in Bowles *et al.* (1997).

Field testing alarms on salmonids

Field tests were also conducted on the alarm's effect on salmonids before the experiment began. In June 1994, three alarms were tested in the fish viewing window at the Hiram M. Chittenden Locks in Seattle, Washington, USA. The chamber held between 80-100 adult sockeye salmon (*O. nerka*) during the trials. The fish were clearly visible through the viewing window, allowing a general description of any reactions by the fish to the alarms. Each alarm was lowered into the chamber in inactive mode for a 5min trial and then the trial was repeated in active mode. Two complete trials (on/off) were conducted for each of the three alarms for a total of six trials. Two parameters were measured; closest approach to alarm and time of closest approach to alarm. The measurements were made in bins of increments of 10cm for distance and increments of 10s for time. The results of the trials provide a qualitative assessment of the reactions of the fish to the alarms. The tests however should be repeatable by other researchers to determine if similar results are obtained.

Alarm function and failure rate

Alarms were checked each day during net retrieval and faulty alarms were replaced. Alarms which were either of apparent low amplitude or which were completely inaudible were replaced by functioning alarms during that day's net retrieval. Some alarms fell off the net and were lost when the nylon tie wraps broke or loosened. The lost alarms were replaced each day.

Experimental design and net configuration

The experiments were conducted in the Spike Rock fishing grounds in depths ranging from 8-18m. One tribal gillnet vessel was used during the fishing experiments which were conducted from 27 July to 28 August 1995, 7 July to 9 August 1996 and from 30 June to 16 August 1997. Four tribal nets were constructed to be used in the experiments, in order to control for net size, mesh size and condition (Table 1). The nets were 19.5cm stretched mesh and 183m long. In 1995-96, two nets were composed of three-strand green nylon and were 50 meshes deep and two were three-strand white nylon and 80 meshes deep. The 50 mesh nets fished approximately 7.5m deep and the 80 mesh nets fished 12m deep. In 1997 the nets were re-hung with new 19.5cm stretched mesh green colour web and each was 183m long and 50 mesh deep. The nets were checked once each day, weather permitting, and typically soaked for 24 hours. Each net was set and aligned so as not to overlap the other (Fig. 1). Minimum distance between nets was 300m in order to reduce the chance of sound overlap between nets. Alarms were rotated between different nets in an attempt to balance alarmed and control fishing effort through the season. The rotation schedule however could not be strictly adhered to as a result of inclement weather which prevented checking the nets on several occasions or large swell conditions which prevented changing alarms. Two nets were set on the south side of the bay and two in the centre of the bay acting as identical paired sets (Fig. 1). Nets were set in only four positions during each season and were not moved until pulled out of the water at the end of the season. Nets were set in approximately the same locations during each of the three fishing seasons. Each net acted as a control (without alarms) and as an experimental net when alarms were in place, except during 1997 when all nets were alarmed. The alarms were placed on the cork line of the nets using nylon tie wraps. When in position, the alarms were horizontal, parallel to the cork line. When fishing, the alarms were 4-7m below the surface. Each net was fitted with 11 alarms, spaced at intervals of 16.6m. When the nets were checked, observers recorded data on harbour porpoise bycatch, salmon and sturgeon catch and bycatch of other fish and marine mammals.

Table 1

Data for nets used in the experimental fishery 1995-1997.

Net #	Colour	Length (m)	Net depth (mesh)	Water depth (m)	Latitude/Longitude
1995 & 1996					
1	white	183	80	17	48°16.20' N; 124°41.40' W
2	white	183	80	16	48°16.03' N; 124°41.57' W
3	green	183	50	12	48°15.42' N; 124°41.72' W
4	green	183	50	11	48°15.23' N; 124°42.30' W
1997					
1A	green	183	50	17	48°16.19' N; 124°41.50' W
2A	green	183	50	16	48°15.91' N; 124°41.60' W
3A	green	183	50	12	48°15.40' N; 124°41.86' W
4A	green	183	50	11	48°15.17' N; 124°42.36' W

Statistical analysis

Fishing effort

Before the field trials began, a power analysis was conducted to determine the fishing effort required to detect a significant reduction in harbour porpoise entanglement rates given rates similar to previous years. Using entanglement rates of either 0.15 or 0.30 porpoise per ND, and a type I error rate of $\alpha = 0.10$, to detect a 50% reduction in entanglement rate, would require between 100 to 140ND of fishing effort.

Harbour porpoise bycatch

A statistical approach similar to Kraus *et al.* (1995) with some minor differences was used to analyse the porpoise catch data. Entanglements of multiple harbour porpoises in the same net within the same ND were likely to be dependent (e.g. mother and calf pairs), so the assumption of a Poisson distribution was not warranted. There were too few sets with entanglements to test the distribution of the number of porpoises entangled. Therefore, the probability that one or more porpoises were entangled in a single ND was determined. Thus, the outcome for each ND was either a 0 or 1 (an entanglement). The probability of an entanglement in an alarmed net is P_{active} and in a control net is P_{control}. All nets were checked at approximately 24 hour intervals, so it was not necessary to adjust for soak time following Kraus *et al.* (1995). A 2 × 2 contingency table with the χ^2 corrected for continuity (Snedecor and Cochran, 1973, p.215) was used to test whether $P_{\text{active}} = P_{\text{control}}$. The odds ratio $O = [P_{\text{control}}/(1-P_{\text{control}})]/[P_{\text{active}}/(1-P_{\text{active}})]$ and its confidence interval (Fleiss, 1973) was also calculated for comparison with the results of Kraus *et al.* (1995). The relative age and reproductive maturity of porpoises taken during the fisheries was estimated using data from Gearin *et al.* (1994). Females greater than 155cm total length and males greater than 140cm were considered to be reproductively mature.

Harbour seal bycatch

Catches of harbour seals (*Phoca vitulina*) were compared between alarmed and control fishing effort. The CPUE values were determined and compared using a chi-square analysis similar to that used for harbour porpoise.

Fish catches

Catches of chinook salmon and sturgeon were compared using the same techniques as for harbour seals and harbour porpoises except that an odds ratio was not calculated. A chi-square analysis was also used to evaluate whether significant differences existed in numbers of salmon damaged by pinnipeds in alarmed versus control nets.

Observational studies

Shore-based observations were made from a 47m high cliff above the Spike Rock fishing grounds to observe the behaviour and distribution of porpoises around the experimental nets in 1996. A three member observer team recorded porpoise sightings in relation to Net 1 and calculated the positions of sightings and distances from the net. The observer team was unaware of whether Net 1 was a control or alarmed net. Theodolite bearings to the buoys marking each end of Net 1 were recorded at low and high tides each day, providing a record of net locations relative to porpoise sightings. Searching for porpoises was conducted through 7 × 50 reticle binoculars, which have a 5.44° optical field of view with 14 reticle marks which measure vertical angle from the horizon. An internal magnetic compass provided 360° horizontal bearings. More detail on the methodology is provided in Laake *et al.* (1998).

RESULTS

Field testing alarms

Field measurements in the salt water environment of Puget Sound demonstrated that the three alarms tested each emitted sound source levels of between 121.7-124.7dB re 1μPa @ 1m (Fig. 2). The optimal spacing of alarms on the nets was determined to be 20m, which would allow porpoises to hear the alarms in sea states up to Beaufort 4. The alarms were spaced, however, at closer intervals (16.6m) to allow for attenuation of diagonal distances between the cork and lead lines.

The field measurements conducted on site at the Spike Rock fishing grounds (Bowles *et al.*, 1997) were similar to but slightly different than the Puget Sound measurements (Bain, unpubl. data). The alarms tested had broadband source levels of 123dB re 1μPa and peak tonals at 2.95 and 20.5kHz. They were nearly omnidirectional at low frequencies (< 2dB of directivity at 2.95kHz), but had some directivity at high frequencies (6dB at 20.5kHz) in the horizontal plane. Broadband ambient noise levels in the area ranged from 90-102dB re 1μPa. Most of the ambient noise energy was at the low frequency end of the spectrum, below 8kHz. In the band centred on the 2.95kHz tonal, levels ranged from 56 to 80dB. The inshore environment near Spike Rock was characterised by high energy wave action and the dominant sound sources at low frequencies were rocks rolling in the surge, surface noise and surf. At 20.5kHz, band-limited levels were more constant, varying from 50-60dB, with snapping shrimp (*Pandalus* sp.) being the dominant noise source. The sound source levels of an alarmed net as a whole at these frequencies were 113dB at 2.95kHz and 88.8dB at 20kHz. The estimated detection range of an alarmed net at 3kHz, given the typical range of ambient noise levels, would have been from 113m (80dB background level) to 2,196m (62dB background level). At 20kHz, the net would have been just detectable from 161m (62dB background level) to 1,615m (47dB background level). The SNR of the alarms reached 13-19dB close to the net (within 8-10m) at both frequencies and declined to 0dB at ranges of 400-600m. Based on the logarithmic decay model used to fit the data, the SNR declined to 0dB at a maximum range of 1,733m at 2.95kHz (67dB background level) and 1,033m at 20.5kHz (55dB background level). These estimates were consistent with reports of field observers who reported that alarms were difficult to detect at band-limited SNR < 4dB. Assuming that harbour porpoise required 4dB or more of SNR to detect the signals, the effective range of the alarmed nets would have been 293m at 2.95kHz and 113m at 20.5kHz under typical conditions of ambient noise levels between 57 to 70dB.

Field testing alarms on salmonids

During the three trials using inactive alarms, the fish exhibited an initial startle response to the devices and moved quickly (within 1s) away from the alarms to a distance of 1-2m. In all three trials, the fish appeared to resume their normal swimming activity within 10-15s and in each instance, several fish had approached the alarms less than 10cm away within 30s. The alarms were then activated and separately lowered into the chamber. Again, an initial startle response was noted, but the fish resumed normal swimming activity within 10-15s and showed no response to the alarms.

During each of the three trials with active alarms, multiple fish were swimming within 10cm of the alarms less than 30s after the introduction of the alarms to the chamber. During the full 5m trials for each alarm, the fish did not appear to demonstrate any reaction or change in behaviour to the device except for the initial startle response. The approach distances and time of approach between the inactive and active trials were essentially identical. Based on these observations, we concluded that the sound from the alarms was either inaudible to the fish, or that the fish were not disturbed by the sound.

Alarm function and failure rate

In 1995, during the first 24 hours of the fishing experiment, about half of the 44 alarms failed when checked the following day. The failure was determined to be caused by water leaking into the central housing through the upper end (screw) cap. Silicon sealant had been used to seal the upper end caps rather than the O-ring in Jon Lien's initial design. The problem was corrected by using a rubberised sealant on the threads of the upper end caps and also silicon sealant around the outer margins of both the upper and lower end caps. In 1996 and 1997, electrical tape was used to tape over the silicon sealant and a tight wrap of plumbers' tape was applied over the electrical tape. These modifications reduced the failure rate considerably for the remainder of the study. Daily failure rates were still higher than one would expect from a commercially produced alarm. In 1995, overall failure rates were about two alarms per day or 4.5%. In 1996-97 with the added feature of taping alarms, the rate dropped to about a quarter of the 1995 rate (1.12%). During the 1995-97 studies, about 10 alarms fell off the nets and were lost but were replaced during the next net retrieval. Alarm failures and alarm loss did not appear to affect porpoise entanglement since alarms were replaced each day and since overall loss and failure rates were relatively low. No instances of porpoises being entangled near a malfunctioning alarm or in an area where an alarm was lost were recorded

Statistical analysis

Fishing effort

The fishing effort for each of the seasons from 1995-97 is presented in Table 2. Each net was considered as an alarmed net when alarms were attached and as a control net when the alarms were removed. The 1995 experiment was conducted from 27 July to 28 August. A total of 103ND was fished including 52ND with control nets and 51ND with alarmed nets (Table 2). The 1996 experiment was conducted from 7 July to 9 August. A total of 121ND was fished which included 60ND with control nets and 61ND with alarmed nets. In 1997, alarms were placed on all the nets (except during the first two days). For 1997, 188ND were fished, which included 180ND with alarmed nets and 8ND with control nets, from 30 June-16 August. Observer coverage at Spike Rock was 100% for the three field seasons.

Table 2

Fishing effort in net days (ND) fished and harbour porpoise bycatch for 1995-97 (bycatch in brackets).

Year	Alarmed effort	Control effort	Total
1995	51 (1)	52 (19)	103 (20)
1996	61 (1)	60 (28)	121 (29)
1997	180 (12)	8 (0)	188 (12)
TOTAL	292 (14)	120 (47)	412 (61)

Harbour porpoise bycatch

The number of harbour porpoises incidentally caught during each year for alarmed and control effort is shown in Table 2. The distribution of fishing effort for each net when alarmed or not and porpoise catches for 1995 and 1996 are shown in Figs 3 and 4, respectively. In 1995, only one harbour porpoise was caught in an alarmed net and 19 were caught in control nets, over nine different ND (Fig. 3). Alarmed and control net CPUE were 0.019 and 0.365 per ND, respectively. The CPUE was 19 times greater in control nets than alarmed nets. This represents a 95% reduction in harbour porpoise bycatch. However, the porpoise catch was not uniformly distributed over time during the duration of the 1995 experiment; the majority of animals were taken in the first half of August and only one was taken in the second half of August (Fig. 3). All harbour porpoises were caught on seven days between 30 July and 18 August. Twelve harbour porpoises were taken on one day during the fishery, in three different nets, including seven in one net. The probability of an entanglement in an alarmed net ($P_{\text{active}} = 0.019$) was significantly lower than the probability of an entanglement in a control net ($P_{\text{control}} = 0.173$) ($\chi^2 = 5.28$, df = 1, $p = 0.02$). The odds ratio was 10.5 (95% CI 1.78-61.4) which implies that the odds are 10.5 times greater that a porpoise entanglement occurred in a control net than an alarmed net.

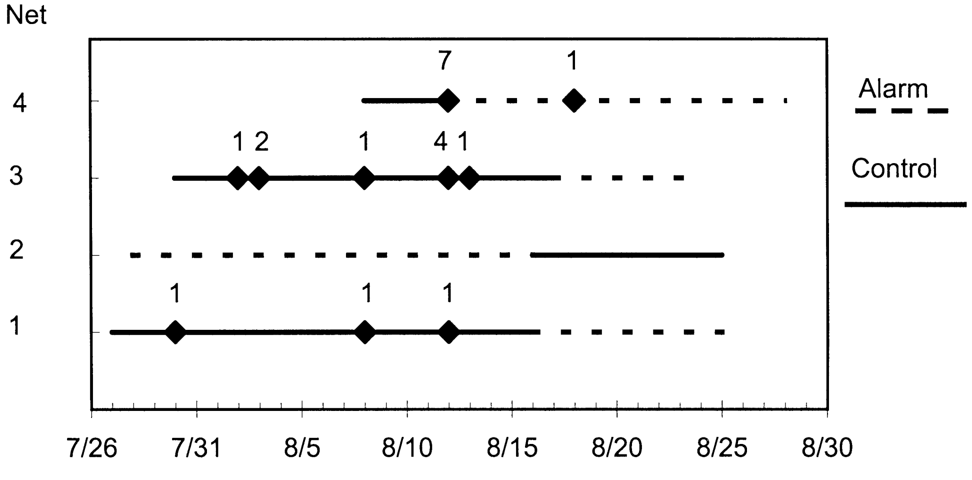

Fig. 3. Fishing effort by net and harbour porpoise bycatch indicated relative to treatment (control versus alarm), 1995.

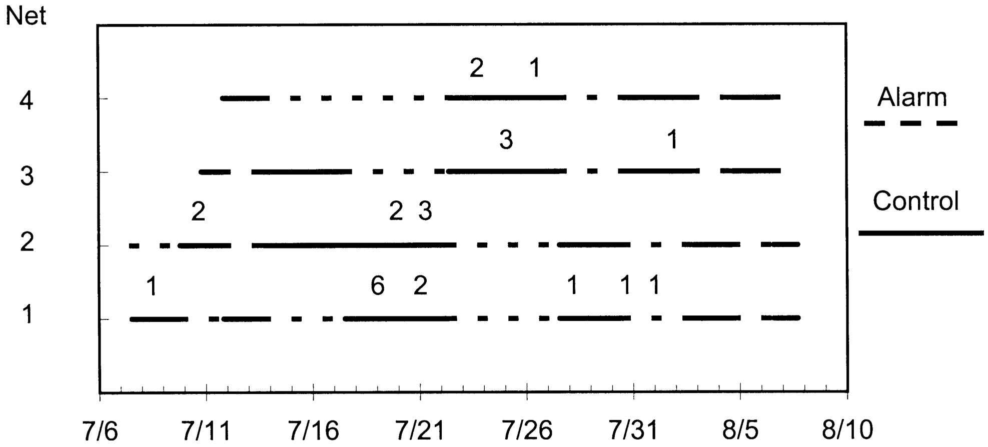

Fig. 4. Fishing effort by net and harbour porpoise bycatch indicated relative to treatment (control versus alarm), 1996.

The expected number of porpoises that would have been caught if alarms were not used was 38 (0.365 × 103ND), as compared to the 20 which were observed taken.

The distribution of porpoise catches and fishing effort for 1996 is shown in Fig. 4. During 1996, only one harbour porpoise was taken in an alarmed net and 28 were taken in control nets in 13 different ND (Fig. 4). In 1996, the CPUE of harbour porpoises for alarmed and control nets was 0.016 and 0.467 per ND, respectively. The CPUE was 29 times greater in control nets than alarmed nets. This represents a 97% reduction in harbour porpoise bycatch. The alarmed and control effort and harbour porpoise catches were more evenly distributed in 1996 (Fig. 4) than in 1995. The chi-square analysis revealed that the probability of a porpoise entanglement in an alarmed net ($P_{active} = 0.016$) was significantly lower than the probability of an entanglement in a control net ($P_{control} = 0.217$) ($\chi^2 = 11.2$, df = 1, $p = 0.001$). The odds ratio was 16.6 (95% CI 2.9-93.5) implying that the odds of a porpoise take in a control net was 16.6 times greater than in an alarmed net. Thus, 56 harbour porpoises would have been expected to be taken in the fishery had no alarms been used in 1996.

In 1997, 12 harbour porpoises were taken during 180ND of fishing effort using alarmed nets compared to an expected 79 harbour porpoises if there had been no alarms, based on extrapolating from control catch rates from 1995 and 1996 (CPUE = 0.42 per ND). The observed bycatch reduction was 85% for 1997. A total of 59 harbour porpoises were collected during the fisheries; two porpoises dropped out of the nets before they could be retrieved. All sex and relative age categories were represented in the animals collected (Table 3). Ten of the 14 porpoises caught in alarmed nets were single entanglements of only one individual. The porpoises entangled in the control nets appeared to be uniformly distributed along the length of the nets but most were located near the lead line or bottom third of the net.

Table 3

Sex and relative age data for harbour porpoise collected from 1995-97.

Category	1995	1996	1997	Total	Alarmed bycatch
Adult female	4	3	2	9	2
Subadult female	2	10	3	15	4
Adult male	5	4	1	10	1
Subadult male	6	10	5	21	6
Calf	2	1	1	4	1
TOTAL	19	28	12	59	14

Harbour seal bycatch

The bycatch of harbour seals in alarmed and control nets from 1995-97 is presented in Table 4. Three harbour seals were caught during the 1995 fishery, all in alarmed nets. In 1996, nine harbour seals were caught, including four in alarmed nets and five in control nets. In 1997, 13 harbour seals were taken, all in alarmed nets. The CPUE value for harbour seal catch for all three seasons combined was 0.068 per ND for alarmed nets and 0.042 per ND for control nets. No significant differences in catches of harbour seals in alarmed versus control nets were obtained when pooling the 1995/96 data ($\chi^2 = 0.09$, df = 1, $p = 0.76$). The fact that 20 harbour seals were caught in alarmed nets indicates that they were not deterred by the sound.

Table 4

Harbour seal bycatch during the Spike Rock acoustic alarm studies from 1995-97 (entanglements in brackets).

Year	Alarmed	Control	Total
1995	3 (2)	0 (0)	3 (2)
1996	4 (4)	5 (5)	9 (9)
1997	13 (13)	0 no effort	13 (13)
TOTAL	20 (19)	5 (5)	25 (24)

Fish catches

Catches of chinook salmon were extremely low during the course of the 1995 experiment; only 21 fish were caught. Alarmed nets (51ND fished) caught 10 chinook salmon on eight different days and control nets (52ND fished) caught 11 on five different days (CPUE 0.20 and 0.21, respectively). There was no significant difference in catch of chinook salmon between alarmed and control nets in 1995 ($\chi^2 = 0.31$, df = 1, $p = 0.58$). However, the power of the test was low. Under the alternative hypothesis of a 50% difference ($P_{active} = 0.1$ and $P_{control} = 0.15$) the power was 0.15. In 1996, 45 chinook salmon were caught in the fishery. Alarmed (61ND fished) nets caught 21 chinook salmon in 18 ND and control (60ND fished) nets caught 24 in 15ND. There was also no significant difference in chinook salmon catch between alarmed versus control nets in 1996 ($\chi^2 = 0.12$, df = 1, $p = 0.72$). In 1997, 28 chinook salmon were caught including 26 in alarmed nets (180ND) and 2 in control nets (8ND). Forty-four sturgeon were caught in 1995, including 29 in alarmed nets and 15 in control nets. In 1996, 109 sturgeon were caught including 67 in alarmed nets and 42 in control nets. In 1997, 152 sturgeon were caught, all in alarmed nets. Although catches and CPUE for sturgeon were higher in alarmed nets for both 1995 and 1996, the catches between alarmed versus control were not significantly different ($\chi^2 = 1.44$, df = 1, $p = 0.23$).

Seals or sea lions damaged four chinook salmon or 19% of the total catch in 1995. All of the damaged fish came from alarmed nets. In 1996, seals or sea lions damaged 11 of 45 (24%) chinook salmon caught in the fishery which included 6 of 24 (25%) from control nets and 5 of 21 (24%) from alarmed nets. In 1997, seals or sea lions damaged 7 of 26 (27%) chinook salmon caught in alarmed nets. There was no significant difference in numbers of salmon damaged by pinnipeds in alarmed versus control nets ($\chi^2 = 0.07$, df = 1, $p = 0.79$).

Observational studies

Only the primary findings of the 1996 field observations are given here. The complete details of the study are presented in Laake *et al.* (1998). Over the 27-day period of observations in 1996, 503 positions of harbour porpoise groups were recorded at Spike Rock during 136 hours of observation. Although group size varied from 1-10, groups of 1 or 2 individuals comprised 72% of the sightings. Harbour porpoise sightings were primarily clustered to the north of Net 1, but when Net 1 was unalarmed porpoises were seen closer to the net (Fig. 5). The distribution of distances between porpoises and Net 1 suggested that porpoises were displaced 100-150m from the net when it was alarmed. Laake *et al.* (1998) chose 125m as the radius of the displacement region for testing the significance of an alarm effect. Harbour porpoises were seen within the displacement region on 5 of the 13 days when the net was not alarmed but on only 1 of the 14 days when the net was alarmed (Fig. 5). This demonstrated that porpoises were less likely to surface within 125m of the displacement region when the net was alarmed ($p < 0.01$) (Laake *et al.*, 1998).

DISCUSSION

This study indicates that acoustic alarms reduce the probability of harbour porpoise entanglement in set-nets in the Spike Rock fishing grounds. The results of our 1995-96 studies are similar to those reported by Kraus *et al.* (1995; 1997) in the New England sinknet fishery. The results of the 1995 study were significant but the fishing effort with alarmed and control nets and porpoise catch was not evenly distributed through time. If a significant difference in harbour porpoise abundance occurred in the area during the latter two weeks of the experiment, it could possibly explain the reduced catch rates during that time period. The 1996 experiments were more balanced in the distribution of experimental and control fishing effort through time. The results were similar to 1995 and in fact a more dramatic reduction in porpoise bycatch was observed in 1996. The 1997 study was conducted for a longer period of time than the 1995-96 studies and all nets were alarmed, in part to evaluate whether habituation to the alarms might occur. The results are not, however, clear on this question. It is noteworthy that no harbour porpoises were taken for the first 18 days of the fishery and that 11 of 12 were taken in the last two weeks. Even given higher than expected catches during the 1997 study, the observed catch reduction was still 85%. The question of habituation remains to be answered (see discussion in IWC, 2000). Habituation, even if it does occur, may not necessarily result in significantly higher bycatch rates. It may also not be a problem in fisheries where nets are moved frequently or where fishing seasons are short. Problems with habituation might be expected in those fisheries where nets remain set in the same locations for long periods of time.

The use of acoustic alarms did not appear to affect target catch in the Spike Rock fishery. Catches of both chinook salmon and sturgeon were not significantly different in alarmed or control treatments. There were also no significant differences in harbour seal bycatch between alarmed or control nets. No significant differences in depredation of caught fish by seals or sea lions were noted during the studies although sample sizes were small. Few sea lions occur in the area during the time the studies were conducted and incidentally caught seals were primarily young-of-the-year which are more susceptible to incidental mortality than adults. The ‘dinner bell effect’ of acoustic alarms is a question that still needs to be explored.

The observations of harbour porpoise around the nets during 1996 (Laake *et al.*, 1998) indicated that harbour porpoises were displaced a minimum distance of 125m from alarmed nets. Many porpoises were sighted in the general area to the north within 200-300m indicating that the alarms did not displace them from a large area away from the alarm

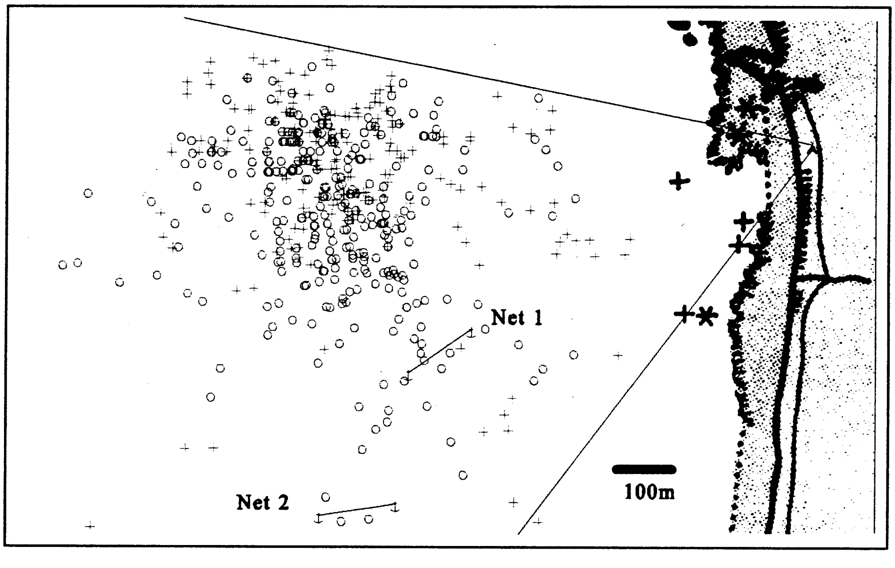

Fig. 5. Positions of harbour porpoise sightings when net No. 1 was not alarmed (circle) and alarmed (+).

source. We propose that the alarms function in an aversive manner by scaring or displacing porpoises away from the sound. If the alarms functioned by alerting animals to the presence of the net, porpoises would be expected to approach closer to the nets than the 125m minimum. Kastelein *et al.* (1995) have shown that harbour porpoises can detect and avoid gillnets under certain conditions. They demonstrated that, when focussed, harbour porpoises are capable of sensing and avoiding gillnets, although not with 100% precision. The fact that the porpoises do not approach closer suggests that they are deterred by the sound rather than by being alerted to the presence of the net.

The field measurements of the alarms at the Spike Rock fishing grounds (Bowles *et al.*, 1997) provide information on the effective range of an alarm and alarmed net. The effective range under typical conditions of ambient background noise would be between 113-293m. This effective range falls within the bounds of the 125m exclusion zone demonstrated by Laake *et al.* (1998). This finding provides further evidence that alarms function by excluding harbour porpoises from a certain area in an aversive manner, and not necessarily by alerting porpoises to an object.

The fishing effort on the northern Washington coast has declined considerably since 1988-89 when large numbers of harbour porpoises were incidentally caught. The observed plus reported catch of porpoises at Spike Rock from 1990-95 has averaged about nine per year (Gearin, unpubl. data). These levels of take are considerably less than previous years and pose no immediate threat to local harbour porpoise stocks based on recent stock assessments (Barlow *et al.*, 1995). The minimum population for the Oregon/Washington coastal Pacific stock is estimated at 22,049 animals, and the Potential Biological Removal (PBR) is 220 (Barlow *et al.*, 1995). If fishing effort returns to 1980s levels, however, due to increased salmon abundance, acoustic alarms may provide a tool to reduce the expected increased porpoise bycatch resulting from increased fishing effort.

We do not suggest that acoustic alarms will function in all types of net fisheries or be effective for other cetacean species. We recommend caution in applying acoustic alarm technology to management situations until they are adequately tested to determine if they will be effective in that particular situation. Furthermore, we do not recommend large-scale usage of acoustic alarms until more is known about the possible effects of large-scale sound transmission and habituation.

ACKNOWLEDGEMENTS

The research was conducted by the National Marine Mammal Laboratory, Alaska Fisheries Science Center of the National Marine Fisheries Service and the Makah Tribal Fisheries Management Division under a cooperative marine mammal research programme between the tribe and the Northwest Regional Office of the NMFS. Funding was provided by the NMFS through the Northwest Regional Office. We thank J. Scordino of NMFS for his recommendation to test alarms in the Makah Fishery and for his continued commitment to fisheries interaction research. The research would not have been possible without the dedicated efforts of the Tribal fishers Rebecca Monette and Daniel Greene Jr. We wish to thank the Makah Tribal Council and D. Sones, R. Svek, S. Joner, D. Greene, J. Cooke, V. Cooke and D. Dailey for their support in this research endeavour. R. Ferrero assisted in field necropsies. We thank B. Norberg and D. Bain for the field sound measurements. Thanks also to S. Jeffries, D. Lambourn, V. Cooke, J. Cooke, N. Vitalis and L. Lehman for help in the field. Earlier versions of this manuscript were reviewed by H. Braham, D. DeMaster, G. Duker, R. Ferrero, R. Gentry, H. Huber, J. Lee, G. McPherson, B. Norberg and J. Scordino. We thank Ed Bowlby and the Olympic Coast National Marine Sanctuary for their cooperation. Portions of the 1996 research were conducted under OCNMS Permit No. 04-96. We thank the IWC, especially G. Donovan and E. Csicsila for their helpful input and editing. Finally, we wish to thank John Goodwin, for without his support these efforts would not have been possible.

REFERENCES

Barlow, J., Brownell, R.L., DeMaster, D.P., Forney, K.A., Lowry, M.S., Osmek, S., Ragen, T.J., Reeves, R.R. and Small, R.J. 1995. US Pacific marine mammal stock assessments. *NOAA NMFS SWFC Tech. Mem.* 219. 162pp.

Bowles, A.E., Anderson, R. and Stinson, H. 1997. Harbor porpoise net entanglement study: Ambient noise and propagation of pinger sounds. Final Report to the National Marine Mammal Laboratory, Seattle, WA. P.O. No.40ABNF601357. [Copies available at NMML, 7600 Sand Point Way NE, Seattle, WA 98115.].

Donovan, G.P. and Bjørge, A. 1995. Harbour porpoises in the North Atlantic: edited extract from the Report of the IWC Scientific Committee, Dublin 1995. *Rep. int. Whal. Commn* (special issue) 16:3-25.

Fleiss, J.L. 1973. *Statistical Methods for Rates and Proportions*. John Wiley and Sons, New York. 223pp.

Frady, T., Northridge, S. and Smith, T.D. 1994. Identifying potential modifications to sink gillnet gear to reduce harbor porpoise bycatch. Report of a workshop held 20-23 September 1994, Falmouth, MA. NEFSC Lab. Ref. Doc. 93-25 NOAA-NMFS, 166 Water Street, Woods Hole, MA 02543. 48pp.

Fullilove, J. 1994. How to make a gillnet 'pinger'. *Natl. Fisherman* May 1994:29.

Gaskin, D.E. 1984. The harbour porpoise, *Phocoena phocoena* (L.): regional populations, status and information on direct and indirect catches. *Rep. int. Whal. Commn* 34:569-86.

Gearin, P.J., Gosho, M., Cooke, L. and Joner, S. 1993. Summary report on marine mammal observations in the northern Washingtn Chinook salmon set-net fishery in 1992. Final report for NOAA, National Marine Fisheries Service, Northwest Regional Office, Seattle, WA 98115. 16pp. [Copies available at NMML, 7600 Sand Point Way NE, Seattle, WA 98115].

Gearin, P.J., Melin, S.R., DeLong, R.L., Kajimura, H. and Johnson, M.A. 1994. Harbor porpoise interactions with a Chinook salmon set-net fishery in Washington State. *Rep. int. Whal. Commn* (special issue) 15:427-38.

International Whaling Commission. 1994. Report of the Workshop on Mortality of Cetaceans in Passive Fishing Nets and Traps. *Rep. int. Whal. Commn* (special issue) 15:1-71.

International Whaling Commission. 2000. Report of the Scientific Committee. Annex I. Report of the sub-committee on Small Cetaceans. *J. Cetacean Res. Manage. (Suppl.)* 2:235-64.

Kastelein, R.A., de Haan, D., Staal, C., Nieuwstraten, S.H. and Verboom, W.C. 1995. Entanglement of harbour porpoises (*Phocoena phocoena*) in fishing nets. pp. 91-156. *In:* P.E. Nachtigall, J. Lien, W.W.L. Au and A.J. Read (eds.) *Harbour Porpoises - Laboratory Studies to Reduce Bycatch*. De Spil Publishers, Woerden, The Netherlands. 168pp.

Kraus, S., Read, A., Anderson, E., Baldwin, K., Solow, A., Spradlin, T. and Williamson, J. 1995. A field test of the use of acoustic alarms to reduce incidental mortality of harbor porpoises in gillnets. Paper SC/47/SM17 presented to the IWC Scientific Committee, May 1995 (unpublished). 28pp. [Available from the Office of this Journal].

Kraus, S.D., Read, A.J., Solow, A., Baldwin, K., Spradlin, T., Anderson, E. and Williamson, J. 1997. Acoustic alarms reduce porpoise mortality. *Nature, Lond.* 388:525.

Laake, J., Rugh, D. and Baraff, L. 1998. Observations of harbor porpoise in the vicinity of acoustic alarms on a set gill net. *NOAA Tech. Mem. NMFS-AFSC-* 84:40.

Lien, J. and Hood, C. 1994. An investigation of acoustic devices to prevent harbour porpoise by-catch in groundfish gillnets, and recommendations from fishermen in the Bay of Fundy for future by-catch mitigation. Report to the Department of Fisheries and Aquaculture, Fredriction, New Brunswick and the Department of Fisheries and Oceans, Halifax, Nova Scotia. 22pp.

Lien, J., Barney, W., Todd, S., Seton, R. and Guzzwell, J. 1992. Effects of adding sounds to cod traps on the probability of collisions by humpback whales. pp. 701-8. *In:* J.A. Thomas, R.A. Kastelein and A.Y. Supin (eds.) *Marine Mammal Sensory Systems*. Plenum, New York. 773pp.

Polacheck, T. 1989. Harbor porpoises and the gillnet fishery. *Oceanus* 32(1):63-70.

Read, A.J. and Gaskin, D.E. 1988. Incidental catch of harbor porpoises by gill nets. *J. Wildl. Manage.* 52(3):517-23.

Reeves, R.R., Hofman, R.J., Silber, G.K. and Wilkinson, D. 1996. Acoustic deterrence of harmful marine mammal-fishery interactions: proceedings of a workshop held in Seattle, Washington, 20-22 March 1996. US Department of Commerce, NOAA Tech. Memo.; NMFS-OPR-10; Y; 68.

Snedecor, G.W. and Cochran, W.G. 1973. *Statistical Methods*. Iowa State University Press, Iowa. 539pp.

Urick, R.J. 1983. *Principles of Underwater Sound*. 3rd Edn. McGraw Hill, Baskerville, New York. xiv+423pp.