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Use of high-frequency imaging sonar to observe fish behaviour near baited fishing gears

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Abstract

A high-frequency imaging acoustic camera was used to observe the behaviour of sablefish (*Anoplopoma fimbria*) and Pacific halibut (*Hippoglossus stenolepis*) around baited fish pots and baited hooks in the deep shelf environment (220–366 m depth) off Oregon. The acoustic camera, tested to a distance of 9.7 m (11.5–15.6 m^2 field of view), provided continuous high-resolution imagery of approaches of fish to the gear, entry into pot tunnels, bait attacks, and escapes in conditions of darkness and high turbidity. Fish inside and beyond the fish pot could also be observed. Fishes, including small individuals and “bait thieves” (>20 cm), could be measured and tracked in the digital images. Concurrent observations with a low-light video camera and infrared lighting yielded a field of view of approximately 1 m^2, limited to just one side of the fish pot. A large proportion of the video tape produced was unusable because of turbidity, and the patterns of fish movement around the pots and baited hooks were poorly characterized by the video camera. The large field of view provided by the acoustic camera showed that a very low percentage of sablefish and halibut approaching the gear were captured. Observations on different gear types, including fish pots with and without tunnel triggers, provide insights into how acoustic camera imagery can be used to improve our understanding of fish behaviour in the natural environment, to design increasingly selective and efficient fishing gear, and to improve bait-dependent stock assessments.

Keywords: Longline; Fish pot; Bait; Acoustic camera; Behaviour; Sablefish; Halibut

1. Introduction

Most advances in the capture of marine fish are made through field trials with fishing gear. However, capture success depends upon the responses of target species to the gear, and with direct observations

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of fish behaviour it should be possible to improve fishing equipment and techniques for increased efficiency and reduced bycatch. Direct observations are especially useful with fixed gear, such as longlines, traps and pots, because fish capture is entirely dependent upon their volitional behaviour. Observations on longlines were made from submersibles more than two decades ago (High, 1980; Grimes et al., 1982). Since then, remotely operated cameras have been used to record the behaviour of fishes near longlines (Fernö et al., 1986; Kaimmer, 1999; He, 1996) and fish traps (He, 1993). Video cameras set together with current meters provided important insights into activity patterns and responsiveness to bait in Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), revealing important differences between the species (Løkkeborg et al., 1989). However, video cameras have limited capabilities in low light, and fishes often avoid lights or behave in abnormal ways when artificial illumination is utilized to make video observations. Illumination with infrared wavelengths, outside the visual capabilities of most fishes, provides for recordings in conditions of darkness (e.g., Olla et al., 2000), but with a range limited to less than 2 m.

New high-frequency in situ imaging sonar systems, often called acoustic cameras, can provide an image over a larger range than traditional video camera systems. They function well in conditions of total darkness, and the images acquired can have sufficient resolution to distinguish individual fish, their basic forms and movement patterns. Moursund et al. (2003) found that an acoustic camera was useful in tracking fish passage at a hydropower facility where conventional underwater cameras would be limited by low light and high turbidity.

This study was conducted to test the feasibility of using an acoustic camera for observations of fish behaviour associated with baited fishing gears including fish pots designed for capture of sablefish (*Anoplopoma fimbria*) and baited hooks directed toward Pacific halibut (*Hippoglossus stenolepis*). These observations were paired with simultaneous observations using infrared illumination and a conventional low-light video camera to compare the relative merits of the two tools. We also provide preliminary observations on the behaviour of sablefish and halibut related to two types of fish pots and baited hooks, and discuss what types of information can be gathered using an acoustic camera.

2. Materials and methods

2.1. Experimental systems

The DIDSON (Dual-frequency IDentification SONar)[1] acoustic camera provides multiple, high-resolution images per second across a 29° fan-shaped sector with a beam depth of 12°. In high-frequency (1.8 MHz) mode, the 29° sector is acoustically divided into 96 beams (0.3° each) and the selected range window is divided into 256 equal bins (e.g., 1.6 cm for a 4 m long window). Thus, the pixels at the center of an image, with a 4 m range window, are ~1.6 cm × 2.6 cm. This is sufficient to show the body shapes of adult fish, while the update rate of six frames per second, used during this study, allowed each individual fish to be tracked through the image. The 12° depth of the acoustic beams limits images to acoustically reflective objects that pass within a distance equal to 10% of the range above or below that fan, and the view provided is integrated into a single plane. Because better range resolution (limited by 256 range bins) was more important than showing the small wedge of area within a few meters of the camera, we never set the near edge of the image below 2.4 m. Objects in the resulting null area close to the camera were not directly imaged, but could produce shadows on the image. The acoustic camera system used in this study included a computer hard drive to autonomously record the image data. Power was provided by three 13.2 V, 9 Ah NiMH battery packs in a titanium pressure housing, and a pressure switch turned on the camera at 20 m depth to save power and recording space during launch.

The acoustic camera was used in two primary configurations designed for autonomous operation on the sea floor. The first was in fixed orientation at the end of a long beam with the intent of viewing the area around fixed gear (one fish pot or five baited hooks) attached to the opposite end of the beam. The second system was an independent, rotating arrangement designed to aim

[1] Mention of a commercial product does not imply its endorsement by the U.S. Government.

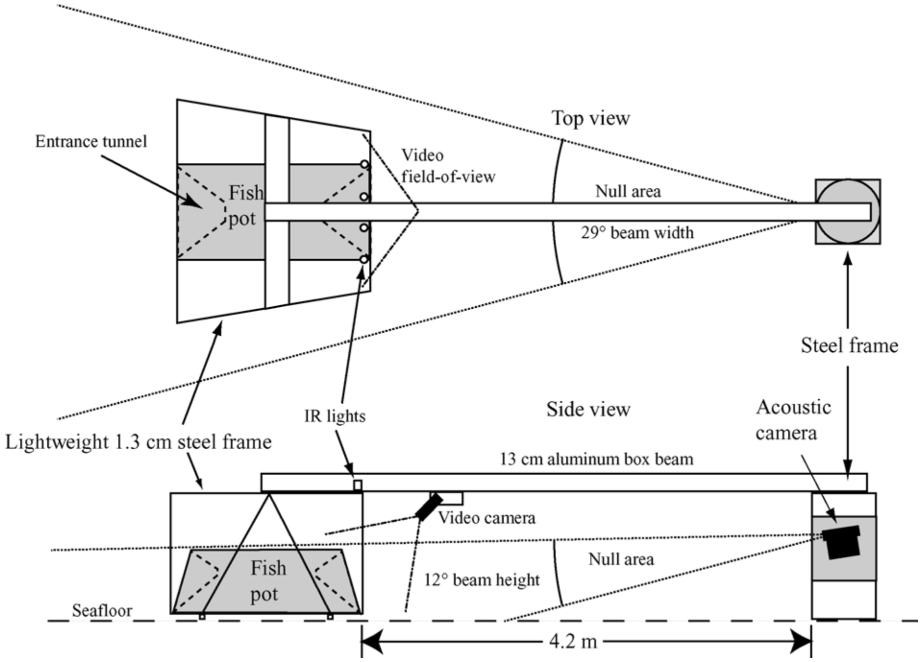

Fig. 1. Fixed configuration of the acoustic and video cameras designed to observe the behaviour of fishes around a fish pot. The fish pot was replaced with a section of ground line with five hooks for observation of fish approaches to hook gear (see text). Top view shows the wedge-shaped field of view provided by the acoustic and video cameras.

the camera continuously in the down-current direction for the purpose of observing fish that approached the camera base, which was baited.

In fixed configuration (Fig. 1) the acoustic camera was attached to a rigid frame comprised of a vertical camera tower, a horizontal aluminum beam, and an open frame large enough to hold a fish pot. The camera tower was 1.2 m high and made from steel angle bar (5 cm). The pot frame component was constructed with a steel angle-bar base and vertical supports of round bar (1.3 cm diameter). The frame was 1.2 m high, 1.5 m wide on the camera end, and 2.1 m wide on the far end. The small bar construction and trapezoidal shape (in overhead view) was designed to produce the smallest possible acoustic shadow in the DIDSON image and to reduce interference with fish behaviour. The wide stance of the frame also helped to maintain the upright orientation of the gear. The aluminum beam (13 cm square tubing) provided resistance to twisting and had sufficient strength to lift the heavy gear, batteries, and fish catch with a two-part bridle made of floating line attached to the two ends of the beam. The transducer "lens" of the acoustic camera was 75 cm above the bottom, oriented horizontally with a downward tilt of ~8°, and 4.2 m away from the nearest end of the pot frame. Depending upon the camera range chosen (Table 1), this distance allowed the entire pot to be inside the acoustic image along with 0.8–2.3 m of the surrounding area. The beam and pot frame top were above the view of the camera.

The gear with fixed orientation was also equipped with infrared lighting units and a video camera (Fig. 1). The lights consisted of four infrared (880 nm wavelength) LED clusters attached to the top of the pot frame directly over the end of the fish pot closest to the acoustic camera. The video camera was an ICCD (intensified charge-coupled device) with a Gen III extended-blue intensifier in an underwater housing with dome port. The camera was attached to the lower side of the beam, 103 cm away from the front of the pot frame and aimed directly at the tunnel of the fish pot. In this arrangement the video camera recorded fish approaching the tunnel nearest to the acoustic camera and provided a comparison of the two camera systems. The recorder for the video camera (Sony Hi-8 camcorder in long-play mode) was enclosed in a cylindrical titanium pressure

Table 1
Summary of gear deployments designed to test the operation of an acoustic camera for observations of fish behaviour related to baits and baited fishing gear

Deployment no.	Gear type	Date	Depth (m)	Set time (PST)	Range of camera view (m)	Bottom temperature (°C)	Current pattern
Sablefish ground							
1	FO-SP	15 May 2004	366	08:42–14:16	3.4–7.8	6.5–5.6	N 7–9 cm/s to slack to S 5 cm/s
2	RO	15 May 2004	366	16:55–20:10	5.2–9.7	5.7	S to W, steady 6–9 cm/s
3	RO	16 May 2004	366	07:30–10:05	5.2–9.7	5.8	S 2–5 cm/s to NW 5–8 cm/s
4	RO	16 May 2004	366	10:50–13:10	5.2–9.7	5.7	Steady N 13–15 cm/s
5	FO-SP	16 May 2004	366	14:50–20:00	2.6–7.1	5.7	E 9–11 cm/s to NE 7–9 cm/s to N 6–8 cm/s
Halibut ground							
6	FO-MP	17 May 2004	240	06:40–12:40	2.6–7.1	6.5–6.7	S 12–15 cm/s to W 6–8 cm/s to NW 19–21 cm/s
7	FO-MP	17 May 2004	220	14:15–20:00	2.6–7.1	6.9–6.6	N 14–16 cm/s to E 7–9 cm/s to S 9–12 cm/s
8	FO-HO	18 May 2004	235	07:19–09:15	3.4–7.8	6.6	S 12–15 cm/s to S 8–10 cm/s
9	FO-HO	18 May 2004	235	10:30–12:30	2.6–7.1	6.6	SW 8–10 cm/s to W 12–14 cm/s

Gear types include an acoustic camera with fixed orientation (FO) observing a standard pot (SP), a modified pot (MP) or hooks (HO), and an acoustic camera with rotating orientation (RO) and no fixed target.

housing along with batteries powering the infrared lights and the camera. When used with a fish pot the canister was secured inside the pot. When used with hook gear, it was attached to the frame which otherwise held a pot.

In the rotating configuration (Fig. 2), the acoustic camera was mounted in an open, cylinder-shaped aluminum frame suspended between hard floats providing 30 kg of lift and a steel pedestal weighing 120 kg (60 cm square base plate and center post). A stainless steel swivel was used to attach the center of the camera frame to the top of the pedestal post. The suspension system was designed to place the camera lens 60 cm off the bottom and maintain a horizontal view. Large vanes (marine grade plywood 12 mm thick) attached to the sides of the camera frame and extending 45 cm beyond the camera lens were designed to keep the camera oriented in a down-current direction without obstructing the acoustic field. Six bait bags with approximately 10 kg (total) of chopped frozen

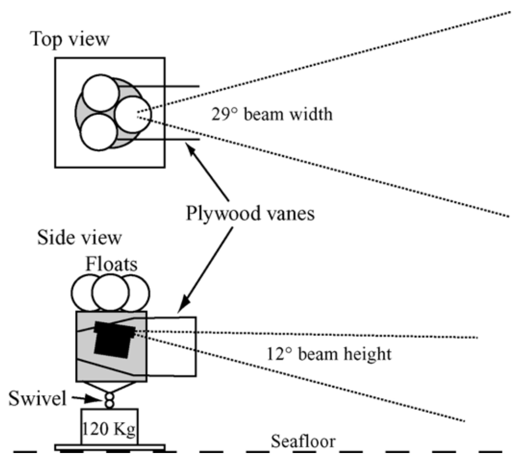

Fig. 2. Acoustic camera in the rotating configuration used to observe approaches of fishes to bait bags placed around the base plate. Vanes and the swivel on the camera frame were designed to orient the camera in the downstream direction of bottom currents.

squid (*Loligo opalescens*) and herring (*Clupea pallasi*) were attached to the base of the camera frame immediately prior to deployments. Observations made in the rotating configuration were with slightly longer range (5.2–9.7 m) than with the fixed configuration (Table 1).

Two types of fish pots were used in this study. The first was a standard rectangular pot (183 cm long × 109 cm wide × 66 cm high) used in the directed sablefish fishery off the coast of Oregon. This pot was constructed with 13 mm round steel bar and 5 cm (square) nylon mesh (#42 twine), with a soft tunnel in both ends made from 2.4 cm (square) mesh (#42 twine). One stainless steel escape ring (10 cm diameter) was sewn into the center of each side of the pot to release undersized fish. A bait sock ∼15 cm in diameter was attached to the top of the pot, and extended nearly to the pot floor when filled. The second pot type was identical to the first except that the tunnel was modified with a rectangular set of plastic trigger fingers (76 cm × 15 cm) (Neptune Marine Products, Seattle, WA) often used in pots for Pacific cod in Alaska (Carlile et al., 1997).

In this study, the trigger fingers were installed to test their effectiveness for capturing sablefish and Pacific halibut. The pots were baited with a combination of chopped and whole squid and herring on the sablefish ground, and with squid, herring and octopus (*Octopus dofleini*) on the halibut grounds. Approximately 10 kg of fresh bait (total) was placed in the bait sock, in perforated 4 l plastic jars, and in separate bait bags both suspended and loose in the pot for each gear set.

Hook gear was also viewed with the acoustic and video cameras in the fixed configuration. A V-shaped arrangement of ground line (9 mm diameter) was created between the bottom of the acoustic camera tower and cross-members of the pot frame bottom at the most distant side. A 2 m long section of heavy elastic cord connected the apex of the ground line to the camera tower and allowed stretch in the gear. Five circle hooks (no. 12/0) were attached along the ground line at approximately 1 m intervals with short nylon gangions. One hook was located near the apex of the ground line close to the acoustic camera, and two more were located on each branch of the two sections extending into the steel frame. Two of the baited hooks were within view of the video camera. Hooks were baited with pieces of octopus (∼150 g), and a bait bag with octopus, squid and herring was suspended from the top of the empty pot frame to help attract fish.

2.2. Deployments

DIDSON and video recordings were made at two sites on the continental slope about 20 nautical miles off the central coast of Oregon. The first site (45°02′N latitude, 124°30′W longitude) was selected for its known abundance of sablefish. Depth was 366 m (200 fm) and the bottom was relatively flat sandy mud. The second site (44°52′N latitude, 124°31′W longitude) is a fishing ground for Pacific halibut, with depths ranging 220–240 m (120–130 fm) on flat muddy sand bottom. Nine deployments of the acoustic camera gear in different configurations were made 15–18 May 2004 (Table 1) from the F/V *Michele Ann*, a 22 m sablefish/Dungeness crab boat. Fish pot gear was set four times. Hook gear was set twice, and the rotating acoustic camera was set three times. Range of imaging was set to several different distances (Table 1) depending upon gear configuration and to test resolution.

A SonTek Argonaut MD acoustic Doppler current meter equipped with a temperature recorder was set 1.5 m off the bottom on a taut-line mooring for the duration of acoustic camera observations at each of the two primary research sites. The meter was set with a time-averaging interval of 60 s (sampling once per second) with recordings made every 60 s. The acoustic camera gear was always set at least 500 m away from the current meter mooring to avoid interference between the instruments which operate at similar frequencies (1.5–1.8 MHz). A light, temperature and depth sensor (Wildlife Computers MK7) was attached to the current meter mooring. The nominal light readings from this device were calibrated in the laboratory under green light (550 nm) with an International Light meter (IL 1700) and SHUD 033 sensor.

Both the rotating acoustic camera and the current meter were set with an L-shaped mooring, comprised of a surface float and a buoyant line that descended to the bottom where a dead weight absorbed motion from the surface. From the dead weight, a 150 m section of non-buoyant ground line extended along the bottom to a 3 m long section of heavy chain attached to the base of each instrument. This arrangement prevented interference between the instruments and the ground or float lines. The larger fixed-frame camera system was heavy (∼200 kg) and connected via a two-part bridle to a 10 surface float with a buoyant line at least twice the depth of the water. Seas were generally less than 2 m during the gear deployments, and there was no evidence of surface motion transmitted to the acoustic or video cameras.

Following each deployment, DIDSON data was downloaded to a 3.0 MHz Pentium computer and recorded onto DVD disks. Download time was approximately 15 min for each hour of recording and occupied about 1.3 GB/h of memory.

Each DIDSON record was reviewed in its entirety on a large screen computer monitor to provide insights into how the imagery could be used. Basic observations were noted including the times of first arrival by sablefish and halibut, when fish were hooked or entered pots, and the numbers of fish entering the field of view in each 15 min period after the gear touched bottom. Note that fish appearing in the camera's view may represent individuals milling around the gear and do not necessarily represent independent events. Other general observations were made on fish locations relative to the fish pot and how many fish were inside a pot or struck baited hooks. DIDSON software was used to measure and track fish. DIDSON images were most easily interpreted as moving images, as is the case with video. Video records were reviewed as described for DIDSON images, and the most illustrative direct comparisons are reported below.

To supplement DIDSON and video camera observations on fish pots, standard and modified sablefish pots were set at each of the two primary study sites. The pot types were interspersed and separated by at least 250 m on a single longline marked at each end with a surface buoy and a radar reflector. A dead weight was used below each float to prevent surface motion being transmitted to the pots. Variable numbers of pots were used (see Table 3) depending upon their availability and use in other fishing operations. The pots were baited heavily as described earlier and fished for 12 h. All fishes captured in the pots (except hagfish) were counted, weighed and measured.

3. Results

Light levels at the two study sites were well below those where video cameras function with only ambient light. At the sablefish grounds, light level on the bottom during the daytime ranged 10^{-7} to 10^{-9} μmol photons $m^{-2}\,s^{-1}$ (equal to darkness for the human eye). The daytime light level on the bottom at the halibut ground was somewhat higher (10^{-4} to 10^{-5} μmol photons $m^{-2}\,s^{-1}$), but still within the range requiring illumination for video cameras. Under these conditions and with infrared lighting, the video camera performed adequately but the view was limited to approximately 1 m^2. Moderate-sized fishes such as hagfish (*Eptatretus* spp.) and rockfishes (*Sebastes* spp.) were clearly identifiable, but individual halibut and sablefish could occupy most of the view, and individuals could be tracked only for short periods. The video image was dark, grainy, and obscured completely when turbidity increased with the activity of fish on the soft-sediment bottom.

The acoustic camera required no artificial lighting and provided a viewing area of 11.5–15.6 m^2 using the range settings established for this study. The image showed fish position on the plane of the seafloor, as if viewed from overhead (Fig. 3), and large invertebrates such as seastars and urchins, as well as fishes, could be observed sitting on top of the sediment in some of the gear deployments. Acoustic shadows were an important feature of the DIDSON images. A strong target in the null area would block returns from more distant objects in the same line of view. Often the shadow of a fish, appearing as a dark shape against the brighter seafloor image would be more visible than the image of the fish itself. The height of a fish off the bottom could often be calculated from the height of the camera above the bottom and the relative distances of the fish and its shadow from the camera.

3.1. Fish pots

A typical acoustic recording for the fixed gear configuration (Fig. 3) yielded images showing fish both around and inside a fish pot, the suspended bait bags inside the pot, and the outlines of the pot tunnels. As designed, the frame holding the fish pot cast a relatively small acoustic shadow in the image. The fish pot itself created a significant shadow, but fish on the far end of a fish pot could be observed until the density of fish inside created a dense shadow as is evident in Fig. 3. While the video camera recorded fish exploring and passing through the near-field tunnel, the acoustic

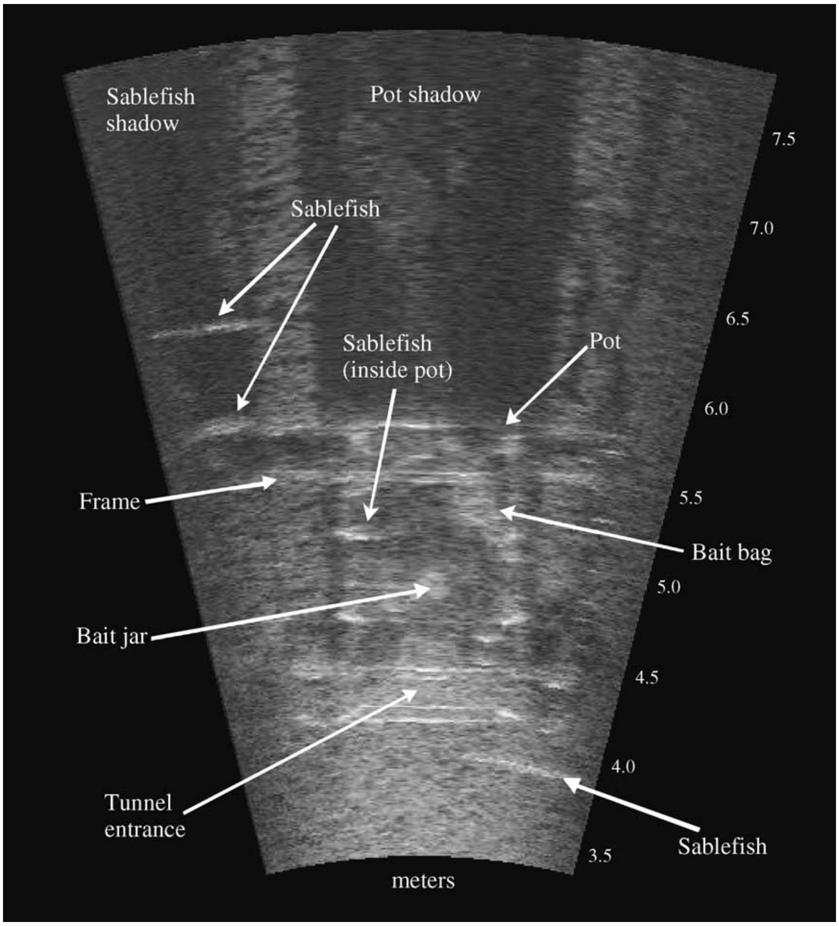

Fig. 3. Example of an acoustic image provided by the DIDSON acoustic camera in fixed configuration and equipped with a standard sablefish pot. Sablefish (average total length = 70 cm), the pot frame, and other labeled features are visible.

camera provided observations on movement inside the pot. However, once more than four or five fish were inside the pot, it was difficult to make an accurate count. The acoustic record also provided observations on small fishes that passed directly through the mesh.

The combination of video camera and infrared lighting provided a field of view of about 1 m^2. This camera gave a clear view of fish approaching the pot tunnel, and those moving at the near-end side of the pot. Sablefish, hagfish, rockfishes and other small fishes and invertebrates were clearly identifiable. DIDSON images provided for less definitive identification of species; however, body shapes and patterns of movement were distinctive for the primary target species and confirmed with the video record. DIDSON imagery alone was sufficiently robust for identification of fishes when their shapes and behaviour are unique, but not when they are very similar, for example with rockfish (*Sebastes*) species.

The standard fish pots caught 9 and 10 sablefish in the two 6 h sets, while sablefish were observed entering the acoustic camera field 2000–5000 times (Table 2). As mentioned earlier, this can represent milling of fish around the fish pot and not fish density, but numbers of fish not entering the pot were substantial. The first deployment of cameras with a standard sablefish pot yielded the largest number of fish observations and was particularly useful for comparisons. The first sablefish was observed with the acoustic camera 3 min after the pot reached bottom, while the first sablefish

Table 2
Fish observed with the acoustic camera and captured with fish pots and hooks set with the acoustic camera in fixed configuration

Deployment no.	Species observed	Time to first appearance (min)	Time to first pot entry or hooked (min)	Total number observed (no. bait attacks)	No. captured (no. lost)	Lengths (cm TL)	Total weight (kg)
Standard pot							
1	SF	3	30	>5000	9	57–77	34.1
5	SF	21	82	>2000	10	52–68	23.1
Modified pot							
6	PH	3	–	231	1 SF	(80)	(4.1)
7	PH	26	–	117	0		
Hooks (5)							
8	PH	1	4	228 (23)	3 (2)	80, 90, 105	14.8[a]
9	PH	26	27	47(5)	1	105	13.7

For hook gear, the numbers of fish landed are shown in parentheses. Lengths of halibut not landed were estimated from the DIDSON images. SF = sablefish, PH = Pacific halibut.
[a] Weight is for the 105 cm halibut landed.

observed with the video camera appeared 6 min after the pot settled. Both cameras recorded the first sablefish entering the pot at 30 min. During that first 30 min, 80 and 15 sablefish were observed with the acoustic and video cameras, respectively. This was under ideal conditions where most of the fish approached the fish pot at the end closest to the cameras. During that time the current was flowing directly toward the cameras (north) and fish approached the south end of the fish pot in the upstream direction. However, highest fish activity around the pot occurred 2 h after deployment when ∼585 entered the acoustic camera image in a 15 min period. During that time the current direction had shifted to the east and most of the fish approached the pot on the west side (still in upstream direction). Because the video camera did not provide a good view of the pot side, only 29 sablefish were observed in the same time interval. After 5 h, the current was flowing south, away from the cameras. During one 15 min interval, 150 sablefish were observed in the acoustic camera image, primarily on the distant end of the fish pot, and only one was observed with the video camera focused on the near end. Clearly, observations with just one video camera provided a seriously distorted picture of how sablefish responded to the fish pot.

A pot modified with plastic triggers in the tunnels was set at the halibut ground and monitored with cameras twice (Table 1). Only one sablefish and no halibut were captured in this pot type (Table 2). Acoustic camera images revealed that sablefish were uncommon at the test site, but halibut were abundant. For example, halibut 50–110 cm total length (TL) entered the field of view 117 times in 6 h during gear set 7. The first halibut arrived in 26 min; maximum activity around the pot occurred at about 2 h, and declined to zero at 6 h. No halibut was observed to touch the pot. The small field trial with fish pots on the halibut ground yielded very few fish (Table 3); however, two halibut entered standard pots.

Table 3
Summary of fish pots set on longlines at the two study sites off Oregon in May 2004, and the fishes captured in standard sablefish pots and pots modified with plastic trigger fingers

Location	Date	Depth (m)	Standard pots set	Modified pots set	Standard pots		Modified pots	
					Sablefish	Other fish	Sablefish	Other fish
Sablefish ground	15 May 2004	290	4	4	27 (6.8)	–	15 (3.8)	1 lingcod
Sablefish ground	16 May 2004	240	8	6	4 (0.50)	1 lingcod	1 (0.17)	1 halibut
Halibut ground	17 May 2004	240	6	5	2 (0.33)	2 halibut 1 lingcod	1 (0.20)	–

Values for sablefish are total numbers captured and the mean catch per pot.

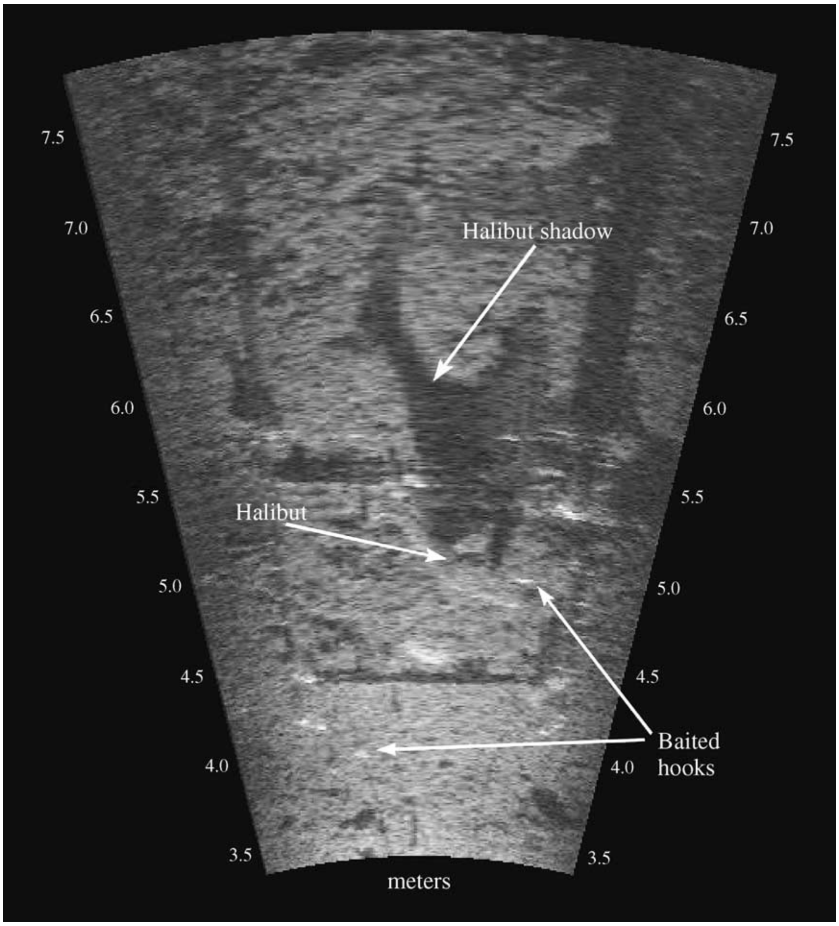

Fig. 4. Example of an acoustic image provided by the DIDSON acoustic camera in fixed configuration and equipped with hooks for Pacific halibut. One halibut (total length = 110 cm), the pot frame, and other labeled features are visible.

Sablefish were captured in both standard pots and modified pots in the two field trials conducted on the sablefish ground (Table 3). A two-way ANOVA showed that the catch rate of sablefish was higher in the first set than in the second ($F_{1,18} = 45.49$, $p < 0.001$), and higher in standard pots than in modified pots ($F_{1,18} = 0.23$, $p = 0.035$), with no significant interaction ($F_{1,18} = 3.34$, $p = 0.084$).

3.2. Hook gear

The acoustic camera was also useful for observing fish around hook gear (Fig. 4). The acoustic shadow created by the frame was very small and fish approaches could be recorded over several meters. Arrival times and directions, bait inspections, latency in attack, social interactions, bait testing, partial bites, hooking, and escapes could all be clearly observed for Pacific halibut which ranged 50–150 cm TL. On the first set of hooks monitored, three halibut were hooked within 9 min. During the 2 h observation period, halibut ranging in size from 50 to 130 cm entered the acoustic camera image 228 times, and 23 bait attacks were observed (Table 2). The second set of hooks resulted in 47 halibut observations, five bait attacks and one capture. All five baited hooks could be observed simultaneously with the acoustic camera, and when the hooks were retrieved to the surface it was possible to observe losses of captured fish. For example, three Pacific halibut were hooked on the first DIDSON set, one escaped in the upper 20 m on gear retrieval, and one escaped at the rail (Table 2). Despite losses, the fish could all be measured from the DIDSON images along with observations on approaches, attacks and hooking behaviour made by each individual.

The video camera was the best tool for identifying the smallest fishes and invertebrates approaching the baits because of the close-up view. Two of the four halibut captured were in view of the video camera; therefore, near-field approaches, orientation, attacks and hooking were observed. However, once a fish was hooked, struggling resulted in high turbidity that rendered the video camera recording completely unusable for long periods. The image provided by the acoustic camera was unaffected by turbidity except for a few seconds in the most extreme cases. The video recording for the first set of hooks was usable about 75% of the time.

3.3. Rotating acoustic camera

The rotating configuration of the acoustic camera demonstrated its potential value for the analysis of behaviour related to bait search. Three deployments, with a range of view extending from 5.2 to 9.7 m from the bait source, showed that appropriate near-bottom alignment of the camera image could be maintained and sablefish were strongly attracted to the bait. In all three cases the first sablefish appeared within 7–8 min, and entries into the field of view increased thereafter. Although the deployments were all made within a radius of 450 m, the patterns of sablefish encounter rates were different in each case, probably reflecting the nature of the scent plume (Fig. 5). In the first deployment (set 2), the number of sablefish entering the image increased to approximately 100 fish per 15 min interval after 45 min and remained relatively steady. More than 650 sablefish entered the acoustic camera field of view in the 2 h observation period. In the second record (set 3), arrivals began slowly but accelerated after 1 h and continued to increase such that 350 entries were recorded in the last 15 min of the set (Fig. 5). At the end of the record, the image was nearly impossible to interpret because of the numbers of fish and acoustic shadows. Many of these shadows were from fish in the null area. Over 1100 sablefish entries were recorded in 2.2 h. In the third record (set 4), during the highest flow period (Table 1), entries by sablefish reached a maximum rate after 90 min, and only 205 fish were observed in 2 h. Fish larger than 40 cm were easily observed and tracked through time with a cursor to demonstrate a spatially explicit record of the track (Fig. 6) and calculation of swim speeds. Other smaller fishes (>20 cm) could be readily detected; these included flatfishes and roundfishes, most likely rockfish and thornyheads. In the low current velocities observed (Table 1), it is unlikely that the acoustic camera was always aligned with current direction, and only one minor shift in orientation (~10°) was observed in the three sets with the rotating DIDSON.

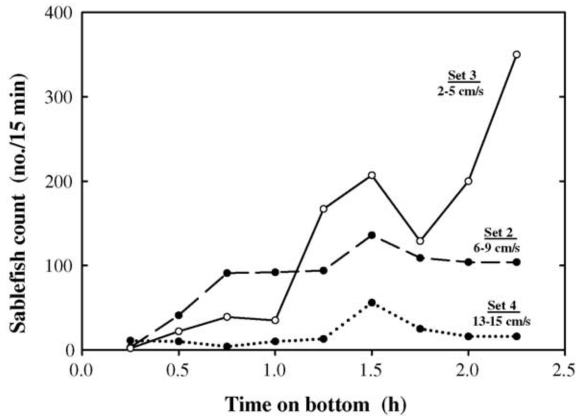

Fig. 5. Numbers of sablefish entering the field of view of the rotating acoustic camera during three 2.5 h deployments on the sablefish ground off Oregon in May 2004. The base of the acoustic camera was baited with herring and squid. Each point represents the number of sablefish entering the field during the previous 15 min, and may represent more than one encounter per individual. Estimated total numbers of appearances were, 675, 850 and 205 for sets 2, 3 and 4, respectively.

4. Discussion

4.1. Utility of the acoustic camera

The acoustic camera used in this investigation had several advantages over the video camera: (1) The acoustic camera had a much larger field of view than the video camera. We used a maximum range of 9.7 m, but it is clear that with large fishes such as sablefish and Pacific halibut a longer range could be used if needed. Fish as small as 20 cm in length were clearly detected with our methods, and a range of 15–20 m could be

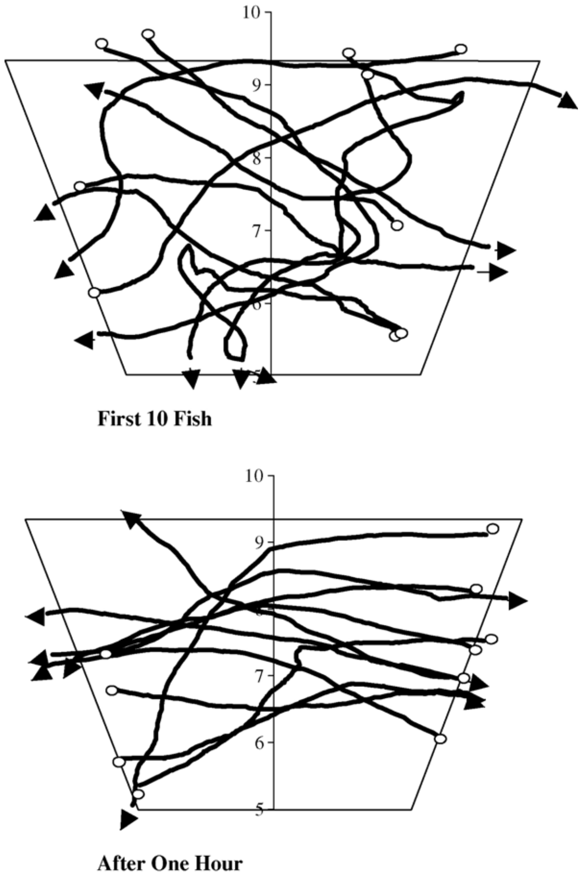

Fig. 6. Tracks for sablefish through the field of view provided by the rotating acoustic camera during deployment number 3 (see Table 1). (Top) First 10 fish observed after the gear was deployed. (Bottom) First 10 fish observed beginning 1 h after the gear was on the bottom.

suitable for some kinds of research. (2) DID SON uses high update frequency for the imagery produced (six frames per second). This allows effectively continuous observation in the field of view, and makes it possible to track fast-moving individual fish. Long range is also provided by standard scanning sonar (He, 1993; Stevens et al., 2000; Premke et al., 2003), but slow update frequencies (typically 15–30 s) often make it difficult to track individual animals. (3) Acoustic tools such as DIDSON allow observations in total darkness (i.e., without artificial lighting) and in turbid conditions. There is little doubt that fish behaviour is influenced substantially by artificial lighting. While infrared illumination allows recordings to be made without behavioural artifacts, infrared wavelengths are rapidly attenuated. (4) The acoustic camera was able to record behaviour on all sides of a fish pot. While an acoustic shadow was produced by fish and some of the fish pot and frame structures fish could be observed inside the pot and at both tunnels until the numbers of fish surrounding the gear obscured the camera view. Multiple cameras have occasionally been used to observe multiple tunnels in fish pots (e.g., Cole et al., 2004), but this increases equipment expense and video processing time, and the field of view around the fishing gear is not captured. (5) The overhead projection for the field of view along with digital format allows for easy digitization of fish pathways and fish can be measured.

The acoustic camera had some limitations. The image is dependent upon the density and surface area presented by an object to the camera. Therefore, when a fish turned directly toward or away from the camera, it was sometimes lost from view. However, meandering motion generally returned the fish to view within seconds. Also, small flatfishes sometimes disappeared from the image because they sat quietly on the bottom or buried into the sediment. Despite this, Pacific halibut were rarely lost from view and invertebrates sitting on top of the sediment such as seastars and urchins were clearly identifiable in acoustic images. While it was difficult to identify all of the fish to species, sablefish, Pacific halibut, rockfishes (collectively) and hagfish were easily distinguished based on their outlines and swimming patterns.

Unlike other sonar systems, the acoustic camera has a null zone close to the lens, with dimensions proportional to the far-range setting chosen. Therefore, to scan a long distance and large area it is necessary to have a substantial distance between the camera and the gear being observed. Also, exact orientation must be maintained because of the relatively narrow breadth of view (29°) and even narrower depth. This was achieved for the present study with a long, rigid beam, which made the overall gear large and relatively heavy. Alignments could be achieved by divers in shallow water or with the aid of an ROV or submersible in deep water. The DIDSON has been mounted successfully in commercial trawls to observe behavioural responses by fishes in bycatch reduction devices (Rose, 2005), and acoustic cameras would be useful in observing fish behaviour around fixed gear such as gill nets, longlines, or structures such as fish weirs and ladders. However, acoustic cameras would probably not be useful in habitats with high physical relief, which would obstruct the acoustic signal.

For autonomous operation the acoustic camera must store image data internally. In our chosen mode of operation the internal memory was filled with 6 h of continuous recording. Longer runs could be achieved with timed recording intervals. Alternatively, a cabled feed to the surface would increase storage capacity and allow live monitoring of the acoustic camera image, but this is a more difficult approach for offshore or continental slope conditions.

4.2. Applications

The acoustic camera will be useful in a variety of ways relevant to the study of fish behaviour and fishing with fixed gear. First, the ability to quantify numbers of fish and track the motions of individuals over a large field of detection will expand understanding of their natural activity patterns, interactions, and responses to environmental variables such as light, temperature, and current velocity and direction. For example, we observed that the numbers of sablefish observed with the rotating DIDSON was inversely related to average current velocity. Løkkeborg et al. (1989) observed a similar relationship between current and numbers of Atlantic cod approaching baits, and we hypothesize that the effective fishing area with baited gear declines with increasing current velocity. Low current velocity creates a large diffuse plume with a high concentration of scent, while high currents produce a more linear plume with a rapid decrease in scent concentration (Sainte-Marie and Hargrave, 1987; McQuinn et al., 1988), although we recognize that the relationship may vary with the amount of bait used.

Catches with baited gear depend upon the active space provided by the bait (Engås and Løkkeborg, 1994), but little is known about how active space should be calculated and how fish search for bait once detected (Bailey and Priede, 2002; Vabø et al., 2004). Acoustic camera equipment will be particularly useful in the required spatial analysis of chemoreception and bait search behaviour. Similarly, an acoustic camera will be helpful in understanding the use of baited cameras for stock assessment (Ellis and DeMartini, 1995; Priede and Merrett, 1996; Willis and Babcock, 2000).

Continuous imagery of fish behaviour under natural conditions (without artificial lighting) can be used to improve the design of baited fishing gear for increased selectivity and reduced bycatch. For example, efficiencies such as the proportions of fish entering pots, attacking baits, being hooked or lost from capture can all be determined with direct observations on gear being tested. In this investigation, large numbers of sablefish and halibut were attracted to fish pots, but a small proportion of sablefish were captured, and halibut rarely touched the fish pots. Also, trigger fingers in pot tunnels appeared to inhibit entry by both of the target species. Earlier studies with fishes and invertebrates (High and Ellis, 1973; Fernö et al., 1986; Furevik, 1994; Jury et al., 2001) show that pot design is critical to capture success, and it is clear that direct observations of different pot modifications will help to make improvements.

Acoustic camera imagery can also be useful in studying hook gear. Our field observations showed that halibut located and attacked baited hooks with the characteristic upstream approach described by others (Kaimmer, 1999; Stoner, 2003). No aggressive interactions were observed near the baits, but investigation of baits appeared to be facilitated by the activities of conspecifics near the fishing gear, corroborating laboratory observations (Stoner and Ottmar, 2004). Only 10% of the fish observed in the acoustic camera view attacked a bait, and only 1–2% were hooked. The attack frequency was much lower than that observed by Kaimmer (1999) (43%); this difference is probably related to the smaller field of view provided by Kaimmer's video camera compared with our acoustic camera. The reader is reminded, that the encounters observed do not necessarily represent independent events in either investigation, but the data help to reveal the effect of spatial scale in behavioural observation.

The two sets of hook gear made in this study were conducted at the same location over a span of just 5 h, but the halibut responses were different, suggesting that we need a better understanding of variation in the active space created by a bait plume as well as variation in feeding motivation (Løkkeborg, 1994; Stoner, 2004). Acoustic cameras make it possible to observe fish behaviour related to different environmental conditions, gear configurations, baits, and soak times.

Direct observations on the performance of fishing gear have been limited primarily to near-field observations with video cameras and artificial lighting. The acoustic camera represents a new tool with which to record continuous images without light over large areas. This tool, which should work equally well with large fishes and invertebrates, will improve our understanding of animal behaviour in the natural environment, and will assist in the design of increasingly selective and efficient fishing gear.

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References

Bailey, D.M., Priede, I.G., 2002. Predicting fish behaviour in response to abyssal food falls. Mar. Biol. 141, 831–840.

Carlile, D.W., Dinnocenzo, T.A., Watson, L.J., 1997. Evaluation of modified crab pots to increase catch of Pacific cod and decrease bycatch of Pacific halibut. N. Am. J. Fish Manage. 17, 910–928.

Cole, R.G., Alcock, N.K., Tovey, A., Handley, S.J., 2004. Measuring efficiency and predicting optimal set durations of pots for blue cod *Parapercis colias*. Fish. Res. 67, 163–170.

Ellis, D.M., DeMartini, E.E., 1995. Evaluation of a video camera technique for indexing abundances of juvenile pink snapper, *Pristipomoides filamentosus*, and other Hawaiian insular shelf fishes. Fish. Bull. 93, 67–77.

Engås, A., Løkkeborg, S., 1994. Abundance estimation using bottom gillnet and longline-the role of fish behaviour. In: Fernö, A., Olsen, S. (Eds.), Marine Fish Behaviour in Capture and Abundance Estimation. Fishing News Books, Oxford, UK, pp. 134–165.

Fernö, A., Solemdal, P., Tilseth, S., 1986. Field studies on the behaviour of whiting (*Gadus merlangus* L.) towards baited hooks. Fisker. Skr. Ser. Havunder. 18, 83–95.

Furevik, D.M., 1994. Behaviour of fish in relation to pots. In: Fernö, A., Olsen, S. (Eds.), Marine Fish Behaviour in Capture and Abundance Estimation. Fishing News Books, Oxford, UK, pp. 28–44.

Grimes, C.B., Able, K.W., Turner, S.C., 1982. Direct observation from a submersible vessel of commercial longlines for tilefish. Trans. Am. Fish. Soc. 111, 94–98.

He, P., 1993. The behaviour of cod around a cod trap as observed by an underwater camera and a scanning sonar. ICES Mar. Sci. Symp. 196, 21–25.

He, P., 1996. Bait loss from bottom-set longlines as determined by underwater observations and comparative fishing trials. Fish. Res. 27, 29–36.

High, W.L., 1980. Bait loss from halibut longline gear observed from a submersible. Mar. Fish. Rev. 42, 26–29.

High, W.L., Ellis, I.E., 1973. Underwater observations of fish behaviour in traps. Helgoländer Wiss. Meeresunters. 24, 341–347.

Jury, S.H., Hunt, H., O'Grady, D.F., Watson III, W.H., 2001. Lobster trap video: in situ video surveillance of the behaviour of *Homarus americanus* around traps. Mar. Freshwater Res. 52, 1125–1132.

Kaimmer, S.M., 1999. Direct observations on the hooking behavior of Pacific halibut *Hippoglossus stenolepis*. Fish. Bull. 97, 873–883.

Løkkeborg, S., 1994. Fish behaviour and longlining. In: Fernö, A., Olsen, S. (Eds.), Marine Fish Behaviour in Capture and Abundance Estimation. Fishing News Books, Oxford, UK, pp. 9–27.

Løkkeborg, S., Bjordal, Å., Fernö, A., 1989. Responses of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) to baited hooks in the natural environment. Can. J. Fish. Aquat. Sci. 46, 1478–1483.

McQuinn, I.H., Gendron, L., Himmelman, J.H., 1988. Area of attraction and effective area fished by a whelk (*Buccinum undatum*) trap under variable conditions. Can. J. Fish. Aquat. Sci. 45, 2054–2060.

Moursund, R.A., Carlson, T.J., Peters, R.D., 2003. A fisheries application of a dual-frequency identification sonar acoustic camera. ICES J. Mar. Sci. 60, 678–683.

Olla, B.L., Davis, M.W., Rose, C.S., 2000. Differences in orientation and swimming of walleye pollock *Theragra chalcogramma* in a trawl net under light and dark conditions: concordance between field and laboratory observations. Fish. Res. 44, 261–266.

Premke, K., Muyakshin, S., Klages, M., Wegner, J., 2003. Evidence for long-range chemoreceptive tracking of food odour in deep-sea scavengers by scanning sonar data. J. Exp. Mar. Biol. Ecol. 285/286, 283–294.

Priede, I.G., Merrett, N.R., 1996. Estimation of abundance of abyssal demersal fishes; a comparison of data from trawls and baited cameras. J. Fish Biol. 49 (Suppl. A), 207–216.

Rose, C., 2005. Tracking fish in trawls with the DIDSON acoustic camera. In: Somerton, D.A., Glendhill, C.T. (Eds.), Report of the National Marine Fisheries Service Workshop on Underwater Video Analysis, August 4–6, 2004. NOAA Technical Memorandum NMFS-FSPO-68, 69 pp.

Sainte-Marie, B., Hargrave, B.T., 1987. Estimation of scavenger abundance and distance of attraction to bait. Mar. Biol. 94, 431–443.

Stevens, B.G., Vining, I., Byersdorfer, S., Donaldson, W.E., 2000. Ghost fishing by Tanner crab (*Chionoecetes bairdi*) pots off Kodiak Alaska: pot density and catch per trap as determined from sidescan sonar and pot recovery data. Fish. Bull. 98, 389–399.

Stoner, A.W., 2003. Hunger and light level alter response to bait by Pacific halibut: laboratory analysis of detection, location and attack. J. Fish Biol. 62, 1176–1193.

Stoner, A.W., 2004. Effects of environmental variables on fish feeding ecology: implications for the performance of baited fishing gear and stock assessment. J. Fish Biol. 65, 1445–1471.
Stoner, A.W., Ottmar, M.L., 2004. Fish density and size alter Pacific halibut feeding: implications for stock assessment. J. Fish Biol. 64, 1712–1724.
Vabø, R., Huse, G., Fernö, A., Jørgensen, T., Løkkeborg, S., Skaret, G., 2004. Simulating search behaviour of fish towards bait. ICES J. Mar. Sci. 61, 1224–1232.
Willis, T.J., Babcock, R.C., 2000. A baited underwater video system for the determination of relative density of carnivorous reef fish. Mar. Freshwater Res. 51, 755–763.