The use of acoustic cameras in shallow waters: New hydroacoustic tools for monitoring migratory fish population. A review of DIDSON technology

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The use of acoustic cameras in shallow waters: new hydroacoustic tools for monitoring migratory fish population. A review of DIDSON technology

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Abstract

European Union legislation, through the Water Framework Directive (2000/60/EC), as well as national legislation, such as the 'Grenelle Environnement' (2007) in France, requires restoration of ecological connectivity in streams to improve free circulation of migratory fish. Different methods (e.g. capture by trap or net, telemetry, hydroacoustics) are used to evaluate the efficiency of fish passes to estimate the migratory species abundance and analyse changes in their within-river distributions. Among these methods, hydroacoustics is non-intrusive, allowing long-term observation and description of fish populations based on physical properties of sound in water. However, the main limit to hydroacoustic tools is their difficulty in identifying species. Initially designed for military purposes, dual-frequency identification sonar (DIDSON) has been used in environmental management for a decade. This acoustic camera uses higher frequencies and more sub-beams than common hydroacoustic tools, which improves image resolution and then enables observation of fish morphology and swimming behaviour. The ability to subtract static echoes from echograms and directly measure fish length improve the species-identification process. However, some limits have been identified, such as automatic dataset recording and the low range of the detection beam, which decreases accuracy, but efficient tools are now being developed to improve the accuracy of data recording (morphology, species identification, direction and speed). The new technological properties of acoustic cameras, such as the video-like visualization of the data, have greatly improved monitoring of diadromous fish populations (abundance, distribution and behaviour), helping river and fisheries managers and researchers in making decisions.

Keywords Acoustic camera, dual-frequency identification sonar, hydroacoustics, migratory fish, monitoring

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Introduction: General context and objectives

Migratory fish species have complex life histories characterized by migratory behavioural feature. In diadromous fish, life history can include alternating periods in water of different salinity, requiring active migrations, for example, between seas and rivers (Verspoor *et al.* 2007), estuaries and rivers (Almeida 1996), or seas and lagoons (Beck *et al.* 2001). In other migratory fish, it can also include long travel within rivers without leaving freshwater (Bagliniere 1999; Radinger and Wolter 2013). Dam building and degradation of habitats and water quality have reduced the distribution and abundance of migratory fish by decreasing the number and area of zones suitable for spawning or growth (Ransom *et al.* 1998; Limburg and Waldman 2009). Most migratory fish are considered threatened or for some of them close to extinction even though they have ecological and societal value (Baglinière *et al.* 2003; Lackey 2009; Limburg and Waldman 2009). So it is important to know their abundance level and its evolution in time.

European Union legislation, through the Water Framework Directive (2000/60/EC) as well as national legislations, such as 'Grenelle Environnement', a law passed in 2007 in France, requires restoration of a good ecological status of rivers (water and habitat quality and connectivity) to improve access of migratory fish. Thus, the presence and abundance of migratory fish are relevant indicators of the good working function and biological integrity of aquatic ecosystems (Karr 1991; Rose 2000). Their complex life cycle and the diversity of different life-history strategies make these species particularly relevant for studying the evolutionary processes of aquatic organism adaptive capacity facing to global change (Rivot *et al.* 2009).

At the watershed scale, managing populations of these species depends on knowledge and understanding of factors influencing their sustainability, that is, fish ecology, such as life-history traits, demography, behaviour and environmental factors (Brehmer *et al.* 2011a). Their study at the watershed scale focuses on two concepts: an ecosystem approach to fisheries (Garcia and Cochrane 2005; Cury *et al.* 2008) and ecological connectivity (Amoros and Bornette 2002). It is therefore important to know the spatial and temporal changes in abundance of these species to assess their status. Predictive models have been developed to monitor fish stock, such as the simple Maximum Sustainable Yield (MSY), used notably in North America in salmon population studies (Fair *et al.* 2004). Nevertheless, limitations of these theoretical methods have been proved (Sissenwine 1978; Forbes and Peterman 1994; Walters *et al.* 2005), and have led managers and scientists to develop others monitoring methods, such as video-counting (Shardlow 2004; Meynecke *et al.* 2008; Perrier *et al.* 2010), and fish traps (Baglinière *et al.* 2005). These techniques cannot be used on many rivers due to high turbidity and expensive human and/or material resources. So, despite their limits, notably in species identification, hydroacoustic methods have been increasingly used in fish ecology studies at sea (Kracker 2007), in estuaries (Guillard *et al.* 2004; Grothues and Able 2010; Guillard *et al.* 2012b; Martignac *et al.* 2013; Samedy *et al.* 2013) or in river (Duncan and Kubecka 1996; Hughes 1998), providing more accurate monitoring of migratory fish (Burwen *et al.* 1998; Guillard and Colon 2000; Pfisterer 2002; Taylor and Elison 2010). About ten years ago, a dual-frequency identification acoustic camera, the DIDSON (Sound Metrics Corp., Lake Forest Park, WA, USA) (Belcher *et al.* 2001), appeared, enabling more accurate monitoring of migratory fish due to better species identification. This technological improvement leads to the development of a new generation of hydroacoustic devices: the acoustic cameras. This innovation is now exploited by several companies which also tested high-frequency devices in fisheries science topics, such as the BlueView Technologies ProViewer D900 (Cronkite *et al.* 2008) or the Kongsberg Mesotech Ltd. M3 sonar (Melvin *et al.* 2012). Nevertheless, whatever hydroacoustic method is used, it is restricted to a population level, as individual fish are not sampled, preventing analysis of life-history strategy through individual studies.

Thus, this review details the advantages and disadvantages of common hydroacoustic methods, describes this recent technology and the interest of acoustic camera techniques for fish monitoring. In the conclusion, properties of both techniques in biological monitoring studies are compared.

Common hydroacoustic methods for fish monitoring

Advantages

Acoustic systems are the only way to penetrate the aquatic environment over great distances. Echosounders are electronic devices that transmit acoustic pulses through a transducer into water. When a pulse is emitted into the environment, it spreads until it meets a target with a different density from the propagation environment. Thus, fish and other objects can be detected (Simmonds and MacLennan 2005). The acoustic pulse is reflected from this target and returns to the transmitter. The transducer acts as a receiver, detecting some of the returning energy. Echosounders can emit acoustic pulses at several frequencies, but only acoustic waves of the initially emitted frequency are received (Lucas and Baras 2000). The detected acoustic echoes are displayed on an echogram, on which target echoes may be represented by coloured patches which colour scale refers to the strength.

Hydroacoustic methods are widely used in fisheries management to monitor fish stocks efficiently because they are quantitative, non-invasive, fast and synoptic (Foote 2009). They convert physical measurements into relevant ecological units describing the fish population (Trenkel *et al.* 2011), minimizing the disturbance on its behaviour or its integrity in comparison with capture methods. Nevertheless, acoustic emissions on sea ecosystem contribute to the noise pollution phenomenon of oceans, which impacts living marine organisms (Myrberg 1990; Dotinga and Oude-Elferink 2000). The influence on fish behaviour is more important when the platform moves: in this case, the avoidance of the populations could be a source of bias (Fréon and Misund 1999). The time between emission and reception of the pulse provides an estimate of the distance between the target and the transducer. Used vertically in marine or lacustrine environments, echosounding can estimate fish density from the energy reflected from fish inside a given water volume (Simmonds and MacLennan 2005). Fish density is generally too high, however, to allow visual counting of individuals on the echogram. Echo-integration, which integrates the return-echo strength in the echosounder's sampled volume, is used to estimate the number of fish in the detection beam (Simmonds and MacLennan 2005). This method has been used efficiently in numerous studies of marine fish populations (Josse *et al.* 1999; Brehmer *et al.* 2006b; Doray *et al.* 2010) or lake fish population monitoring (Guillard *et al.* 2006; Winfield *et al.* 2009; Mehner *et al.* 2010; Guillard *et al.* 2012a), among numerous references. Furthermore, echo properties provide descriptive information about the targets themselves. Target Strength (TS), the difference (in decibels) between emission and reception, is proportional to the echo intensity (Simmonds and MacLennan 2005). According to Ona (1999), a relation between target size and echo response exists. Many equations relating echo strength to fish length have been published, such as the common equations of Love (1971, 1977), whose general formulas to estimate length of individual fish are still used in multispecies population approaches (Boswell *et al.* 2008; Emmrich *et al.* 2012). TS must be used with caution, however, especially when fish diversity is high, because if two fish of different species have the same length, their TS could differ (Ona 1999; Horne and Jech 2005). Indeed, more than 90% of the scattered energy is reflected by the swim bladder, a gas-filled organ whose shape and size differ among species (Foote 1980; McClatchie *et al.* 1996). Moreover, relations between TS and length are complex and variable because they depend mainly on position of the target (Ona 1999; Horne 2003). Therefore, these relations must be approached statistically (Simmonds and MacLennan 2005). Many equations have been published for common freshwater fish (Kubecka and Duncan 1998; Lilja *et al.* 2000; Knudsen *et al.* 2004; Lilja *et al.* 2004; Frouzova *et al.* 2005). Authors have integrated several variables acting on the relation between TS and fish length to increase the accuracy of estimates, such as the fish orientation in the beam (Kubecka and Duncan 1998; Lilja *et al.* 2000; Frouzova *et al.* 2005). Thus, hydroacoustics can describe the structure of a population; size distribution, cohort organization and distribution in the water column can be consequently observed at small spatial scales (Brehmer *et al.* 2003; Bertrand *et al.* 2010; Guillard *et al.* 2012a).

In horizontal beaming, hydroacoustic methods can estimate a proxy of the abundance of migratory populations when other techniques cannot be applied (e.g. excessive turbidity preventing visual counting). Furthermore, when using a fixed transducer, fish can be counted while minimizing effects on their behaviour (Mercer and Wilson 2009), except for some clupeids such as shads which may react to ultrasounds (Gregory *et al.* 2007). Fish must be large enough and separated enough to be individually identified, which makes counting inappropriate for schooling small fish. Hydroacoustic technologies have been considerably improved over time (Rudstam *et al.* 2012; Stanton 2012) (Fig. 1). Single-beam sonar has been used since the 1970s to count salmon passages in large rivers (Johnston and Steig 1995), but the informations extracted of the data recorded are very restricted. During the 1980s, dual-beam echosounders (Fig. 1) were used to monitor fish (Dahl and Mathisen 1983; Eggers 1994; Kubecka 1996). This system, using one narrow and one wide concentric beams, was especially designed to evaluate the actual TS regardless of the distance of the fish to the beam axis by comparing the echoes received in each one of the beams. Therefore, it provides more information than single-beam units, such as the distance from the target to the centre of the beam, increasing the accuracy of length estimates (Lucas and Baras 2000; Rudstam *et al.* 2012).

In the early 1990s, split-beam sounders were developed. The beam is divided into four quadrants, which increased the reliability of data about the position of fish in the water column, allowing to estimate fish orientation and swimming direction (Arrhenius 2000). Split-beams were initially designed for accurate estimate of the TS through the measurements of its distance to the beam axis by comparing phase variations between the quadrants. But it appeared soon that this device could also describe the path inside the beam and track the fish movements. Nowadays, this kind of echosounder is currently used to count upstream migrations of salmon (Mulligan and Kieser 1996; Ransom *et al.* 1998; Pfisterer 2002; Xie *et al.* 2002; Cronkite *et al.* 2007), particularly where migrations are spread, and passage rates are low (less than 2000 fish/hour) (Enzenhofer *et al.* 1998).

Recent sonars increase the number of beams, and then widen the angle of detection, increasing the echogram resolution (Gerlotto *et al.* 1999, 2000; Brehmer *et al.* 2011b), but cannot easily

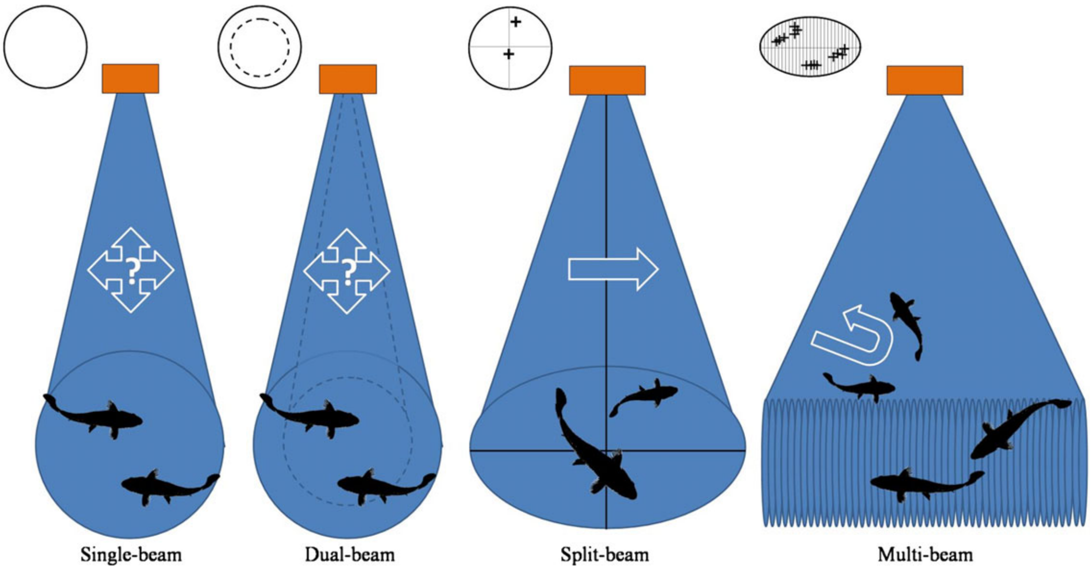


Figure 1 Different echosounders used in fish population studies, and the level of information recorded about the position of the fish.

measure TS of single targets, unlike split-beam echosounders. However, multibeam devices have been used to monitor fish populations in shallow waters (Gerlotto *et al.* 1998; Guillard 1998; Brehmer *et al.* 2006b, 2011b). Some multibeam sonar integrates TS values, but its large physical dimensions and capacities can only be used by offshore scientific vessels for now (Trenkel *et al.* 2008). The properties of multibeam sonars could be also helpful to distinguish pelagic and bentho-pelagic fish schools (Brehmer *et al.* 2006a).

Ultimately, hydroacoustics can provide quantitative (abundance or density estimates), and qualitative (direction, speed, activity rhythm, length) assessment of migratory fish populations without greatly interfering with their behaviour, but these methods are still limited by the uncertainty in identifying species.

Disadvantages

Indeed, the main limit of hydroacoustic methods concerns the identification of fish species. Reviewing acoustic approaches, Horne (2000) concluded that true identification is impossible when using only acoustic waves. Nevertheless, good knowledge of migration behaviour, ecology and biological characteristics of fish present in the monitored river can allow the indirect identification of targets. Thus, length differences (extracted from TS distributions), fish morphology, migration period or position of fish in the water column have been used to distinguish species (Burwen and Bosch 1995; Burwen *et al.* 1998; Guillard and Colon 2000; Burwen *et al.* 2003; Miller *et al.* 2005; Brehmer *et al.* 2006a; Martignac *et al.* 2013). However, rivers and estuaries can host several species whose sizes and migration periods overlap, which increases the difficulty in using acoustic technology to estimate abundance of each species (Hughes 2012). Most of these studies are consequently combined with complementary validation methods, such as video or visual recording (Enzenhofer *et al.* 1998), fishing with nets, traps or hooks (Ransom *et al.* 1996; Burwen *et al.* 1998; Guillard and Colon 2000; Romakkaniemi *et al.* 2000; Pfisterer 2002), or electro-fishing (Hughes 2012). High turbidity, local environmental characteristics (e.g. river width, bank shape), specific differences in catchability or low fish densities, however, can prevent the use of these validation techniques. Furthermore, the quality of echogram data can be corrupted by parasites such as echoes of bubbles, drifting debris or a static solid surface (e.g. river bottom, rocks), which risk being misinterpreted as fish (Brehmer *et al.* 2006a). The bottom emits an echo which strength is several orders of magnitude higher than a fish echo. Indeed, one echo transmitted by a desired target could be hidden by this strong acoustic return (Maxwell and Gove 2004; Hughes 2012). In the case of marine shallow waters (such as mangrove or reef environments), numerous parasites and strong return of the bottom echo make fish echoes difficult to track (Guillard and Lebourges 1998). Data from echosounders cannot describe swimming direction of fish schools and furthermore tends to underestimate fish biomass when fish are in schools (Guillard *et al.* 2010).

Description of DIDSON technology

High-frequency sonar: an acoustic camera

An acoustic camera is a multibeam high-frequency sonar with a unique acoustic lens system designed to focus the beam to create high-resolution images (Fig. 2). Unlike common hydroacoustic methods, skin and fins are better perceived by acoustic camera's very high frequencies. Thus, fish morphology and swimming behaviour can be visualized (Baumgartner *et al.* 2006). Consequently, parasite echoes such as those from bubbles or debris can be visually identified and deleted from the echogram. In fact, the shape of a fish and its non-linear movement differ from echoes of debris drifting with the flow (constant velocity and direction). Measurements of size from the recorded data can be made directly from fish body images, without the uncertainty and inaccuracy of TS conversion.

Originally developed by the University of Washington (USA) Applied Physics Lab, DIDSON creates video-like images (Belcher *et al.* 2001, 2002b). Its initial uses were to help supervise divers in turbid waters (Elliott 2005), detect obstacles or mines (Belcher *et al.* 2002a), observe underwater construction such as pipelines (Belcher 2006) or inspect marine vessel hulls (Vaganay *et al.* 2005).

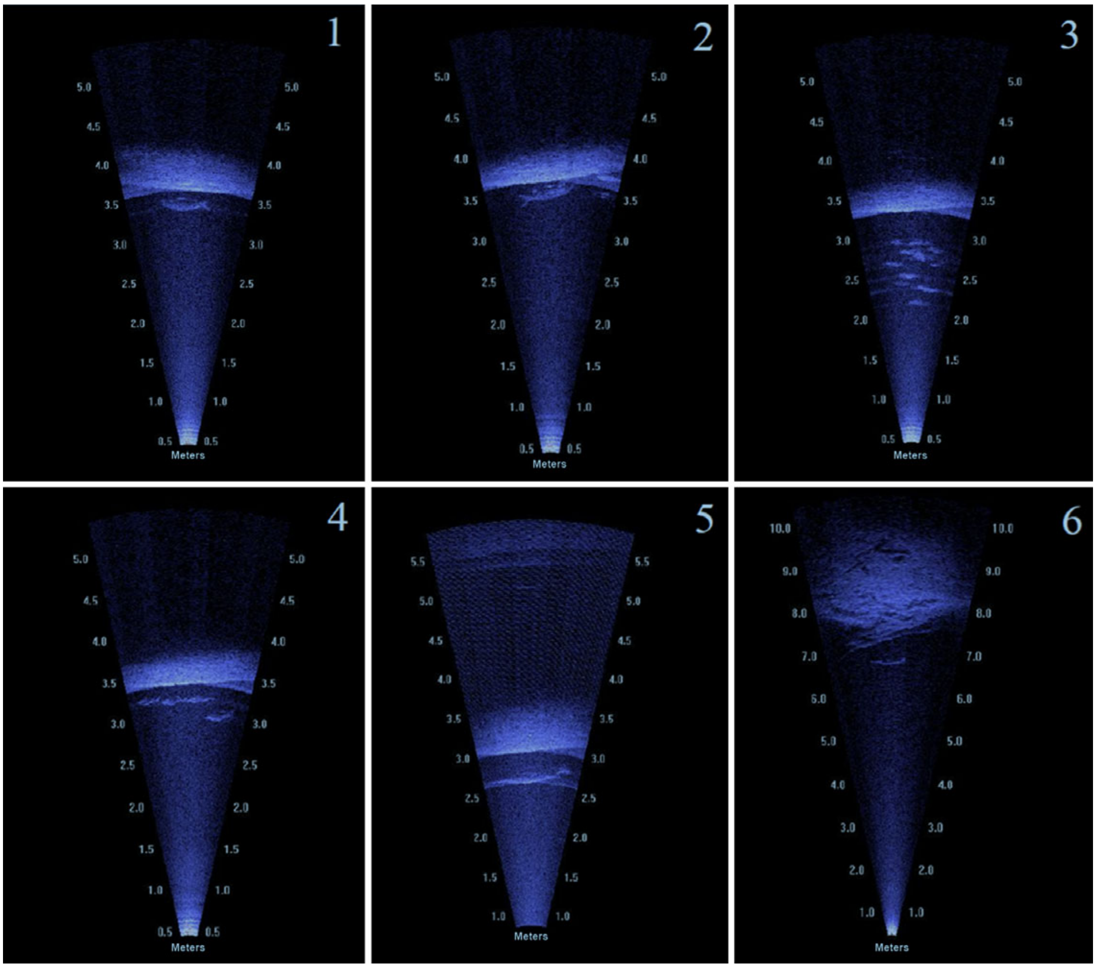


Figure 2 Snapshots of data recorded by DIDSON: (1, 2) large fish (70 and 77 cm), (3, 4) fish schools, and (5, 6) longnose gar (*Lepisosteus osseus*, Lepidosteidae), identified by their length and body shape (Hughes 2012).

The acoustic lens can focus on targets as close as 1 m away. One of two emission frequencies can be used: 1.8 MHz (high-frequency mode) and 1.1 MHz (low-frequency mode). The high-frequency overall beam is divided into 96 beams (0.3° horizontally × 14° vertically) with range settings from 12 to 15 m (Maxwell and Gove 2004; Cronkite *et al.* 2006; Pipal *et al.* 2010b; Hughes 2012), while the low-frequency beam is divided into 48 beams (0.5° horizontally × 14° vertically) with range settings up to 40 m (Fig. 3). The field of a DIDSON camera covers 29° horizontally and 14° vertically for both frequencies (Maxwell 2007). A long-range DIDSON camera can increase range settings up to 33 m at high frequency (1.2 MHz) and up to 80 m at low frequency (0.7 MHz) (Lilja and Orell 2011).

The pulse width is range-dependent and varies from 4.5 to 144 μs. Frame rates can be set up to 21 frames per second. Control and playback software is organized like a digital video programme (Maxwell and Gove 2004). The data are collected and displayed in two dimensions, with resolution in the X and Y dimensions (horizontal and range), but not in the Z-dimension (vertical) (Hughes 2012). In horizontal use, when the beam is perpendicular to the bank, the DIDSON camera provides information about the distance to and movement direction of fish but not about their positions in the water column (Fig. 1).

Recording and processing of DIDSON data

Dual-frequency identification sonar software (Sound Metrics Corp.) is used to control the frequency, and ping rate of the emission. The program also manages the recording and processing of data. An electronic rotation device can be added to the acoustic camera, allowing the sonar to be tilted in the X and Z dimensions, with a 0.1° precision to optimize beam coverage and detection.

Setting and processing tools

The software has tools to optimize data acquisition and facilitate data processing (Cronkite *et al.* 2006; SoundMetrics Corporation 2010):

1. Playback images: the software has a reader similar to a digital video program (Maxwell and Gove 2004). Data visualization can be accelerated during periods without fish passages.
2. Background subtraction (Fig. 4): this tool removes static echoes from the echogram, highlighting mobile fish traces on a dark background (Lilja and Orell 2011). In this way, fish echoes can be extracted from the background noise (including parasite echoes of the bottom), increasing the efficiency of their interpretation (Mercer and Wilson 2009). An equivalent of this tool exists in the Echoview software for echosounding data.

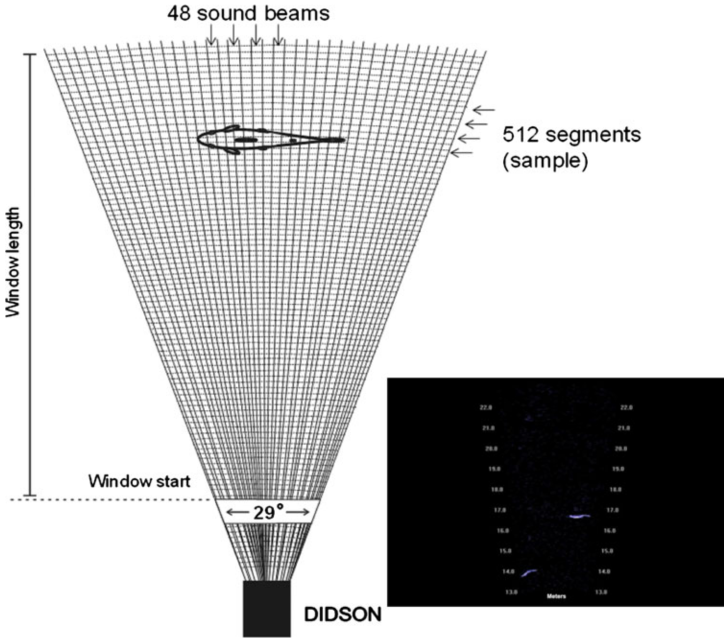


Figure 3 Schematic representation (from above) of a DIDSON frame in low-frequency mode (1.1 kHz) and an image of a DIDSON screen with two salmon swimming from right to left (Lilja and Orell 2011).

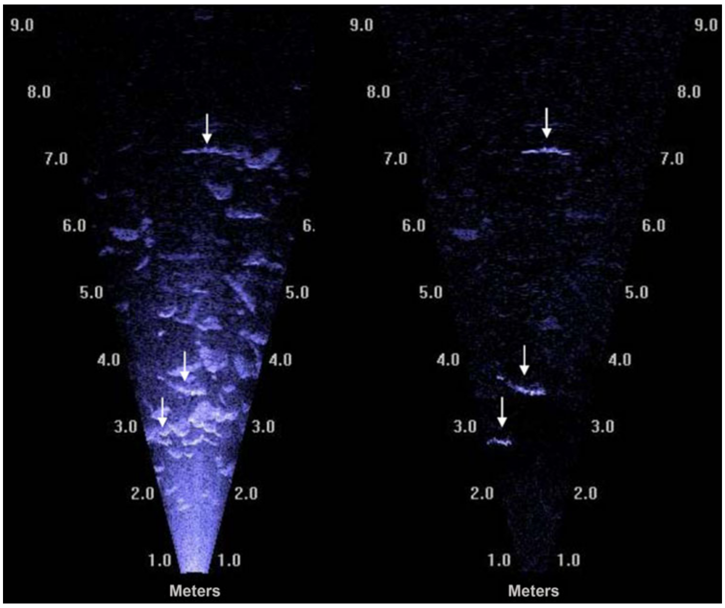


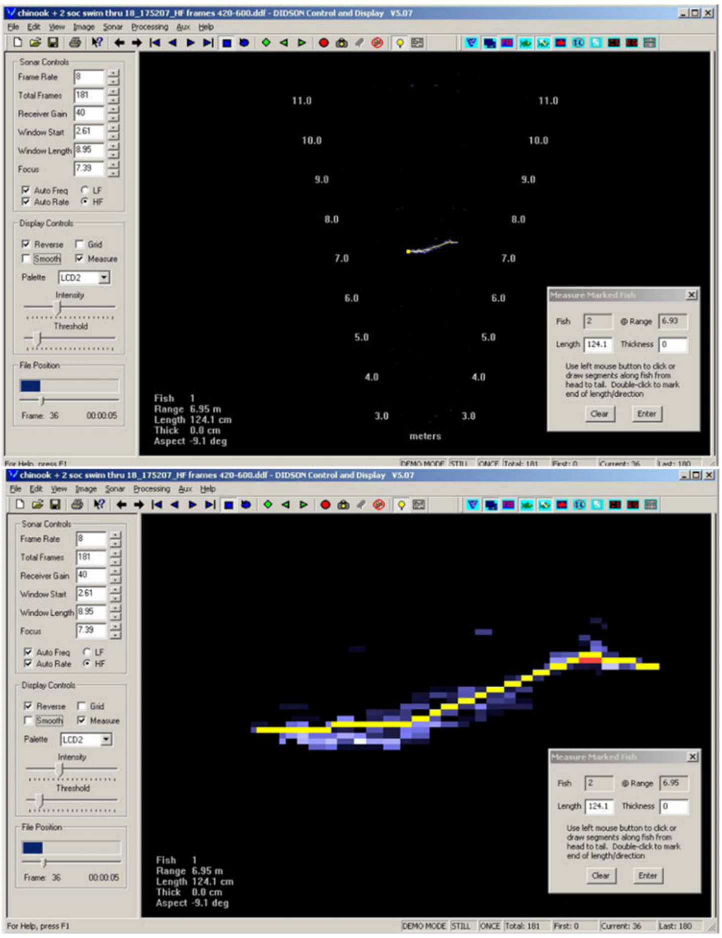
Figure 4 High-frequency DIDSON images of three fish (noted with arrows) swimming over a rocky cobble background (left) and the same three fish with the static background removed (right) (Maxwell and Gove 2004).

3. Convolved Samples Over Threshold (CSOT) tool: this module creates a smaller version of the original recording, retaining fish passages and deleting periods of inactivity. Thresholds for minimum and maximum cluster sizes can be set (in cm²) to distinguish small and big fish or to filter out macrophytes, debris and other parasitic echoes. Cluster sizes can be adapted to target species, for example, minimum cluster sizes of 250 cm^2 to distinguish sea trout (*Salmo trutta*, Salmonidae) and 300 cm^2 to distinguish Atlantic salmon (*Salmo salar*, Salmonidae) (Davies 2009).
4. Correct Transmission Loss: this option equalizes the intensity of fish echoes detected near the transducer and those detected further away. Without this correction, fish recorded near the sonar appear brighter than those detected further away (Lilja *et al.* 2010). The Time Varied Gain (TVG) function ensures this compensation role in common echosounders.
5. Mark fish (Fig. 5): fish length can be measured by drawing a line along its body. The estimated length is automatically exported to a text file.
6. Echogram mode (Fig. 6): an echogram, similar to those recorded by split-beam sounders, can be displayed. However, DIDSON echograms only show targets detected by the central beam; not peripheral beams.
7. Timer data entry: files are large, around 14–18 $MB.min^{-1}$ (Maxwell and Gove 2004; Lilja *et al.* 2008; Pipal *et al.* 2010b). Consequently, long-term monitoring requires high-capacity hard drives, and sampling strategies adapted to reduce data size. The *Timer data entry* function defines sampling strategies according to study conditions (e.g. species behaviour, water-level changes, species migration pattern). Data acquired from chosen time slots provides relevant information about population movements, creating smaller files. For example, sampling 10–20 min per hour is sufficient to estimate the number of migrant sockeye salmon (*Oncorhynchus nerka*, Salmonidae) (Maxwell and Gove 2004; Cronkite *et al.* 2006; Lilja *et al.* 2008). Nevertheless, estimation of population abundance is more relevant when migration rate is constant, and fish densities are high (Cronkite *et al.* 2006). With this technique, an experienced operator looking for sea trout and salmon larger than 35 cm can process 24 h of data in 50–125 min (Davies 2009).

Extraction of fish data from DIDSON records

Dual-frequency identification sonar software has no tool to automatically detect fish from recorded data (Rakowitz 2009). Several methods have been tested using the modules described previously to count individuals during migratory fish population studies.

The echogram mode provides faster visualization of movements in the detection beam at low



chinook + 2 soc swim thru 18_175207_HF frames 420-600.ddf - DIDSON Control and Display V5.07

Frame Rate 8
Total Frames 181
Receiver Gain 40
Window Start 2.61
Window Length 8.95
Focus 7.39
☑ Auto Freq ○ LF
☑ Auto Rate ● HF
☑ Reverse ☐ Grid
☐ Smooth ☑ Measure
Palette LCD2
Frame: 36 00:00:05

Fish 1
Range 6.95 m
Length 124.1 cm
Thick 0.0 cm
Aspect -9.1 deg

Measure Marked Fish
Fish 2 @ Range 6.93
Length 124.1 Thickness 0
Use left mouse button to click or draw segments along fish from head to tail. Double-click to mark end of length/direction

chinook + 2 soc swim thru 18_175207_HF frames 420-600.ddf - DIDSON Control and Display V5.07

Frame Rate 8
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Use left mouse button to click or draw segments along fish from head to tail. Double-click to mark end of length/direction

For Help, press F1
DEMO MODE STILL ONCE Total: 181 First: 0 Current: 36 Last: 180

Figure 5 Illustration of the DIDSON software fish-marking tool to measure length of fish images in normal (top) and zoom (bottom) modes (Burwen *et al.* 2007).

migration rates (Balk *et al.* 2011). High migration rate and high-density populations prevent an efficient count of individuals (Cronkite *et al.* 2006).

According to the literature, visual counting of fish on DIDSON images is the most efficient and common method. Data are processed with two DIDSON software tools to optimize fish detection: transmission loss correction, and background subtraction (Lilja *et al.* 2010). CSOT is also useful to reduce the amount of data to process (Davies and Griffiths 2011). One method used in several studies (Cronkite *et al.* 2006; Davies *et al.* 2010; Lilja *et al.* 2010; Davies and Griffiths 2011) has the following steps: (i) recorded data are viewed at high speed (up to ten times the original frame rate) until a fish is detected; (ii) playback is stopped and the window is zoomed on the echo; (iii) fish images are scrolled in the zoom window to find the clearest display; and (iv) a line is drawn along the body with the *Mark Fish* option. Once validated, the mark is added to a text file that describes fish length, distance, species (if visually identified), behaviour (e.g., migrating, milling, predating) and comments.

Several alternative software programs can process DIDSON data. Sonar5-Pro® (Lindem Data Acquisition, Oslo, Norway) (Balk and Lindem 2012) has tools for dual-beam and split-beam sounders to display echograms, track fish echoes automatically and extract tracks into a database (Balk and Lindem 2012). This program has recently added a new module to process multibeam sounder data (Balk and Lindem 2002; Balk *et al.* 2009). Like the Sound Metrics Corp. software, Sonar5-Pro® makes DIDSON data (echogram and video displays) visible, manually tracking fish echoes and extracting information into a database. An automatic tracking tool is available. It has several settings (e.g. number of consecutive pings, number of ping gaps, cluster size), but it enables consecutive echoes to be grouped into a track. Sonar5-Pro® can extract all

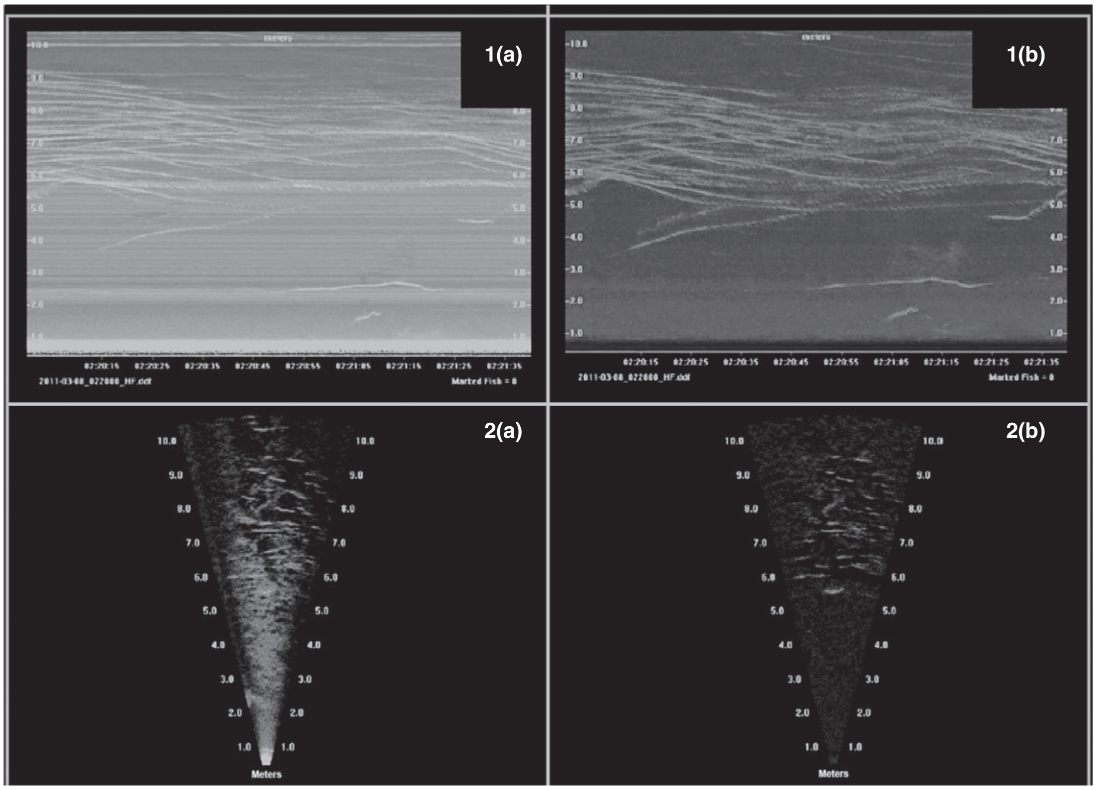

Figure 6 Echogram visualization (1) and DIDSON screen view (2) of DIDSON data, with (B) and without (A) background subtraction (Hughes 2012).

available data in DIDSON files (Fig. 7). Similarly, Echoview software (SonarData Inc., Hobart, Tasmania, Australia) also visualizes and exploits DIDSON data. Some Echoview tools perform semi-automated data analysis (Han *et al.* 2009; Kang 2011) and some are similar to the DIDSON software, such as the background subtraction tool. Coded in Matlab (MathWorks, Novi, MI, USA), tracking algorithms automatically analyse DIDSON data like any other sonar data. All of these programs count fish passages, provide information on estimate fish length (Han *et al.* 2009) and can describe fish behaviour (Kang 2011), but they are too recent to know and compare their performance.

Relevance of DIDSON data

Dual-frequency identification sonar is the subject of many studies focusing on the relevance of interpretations extracted from it by comparing its data to those from other capture methods (net, electro-fishing) or observations (underwater cameras).

Counting individual fish

Comparing counts by acoustic camera to those of visual counting demonstrate the former's reliability when beam coverage is total (entire section). Holmes *et al.* (2006) conclude that fish counts produced by DIDSON are as accurate as visual counts, even when migration rate is high. Nevertheless, densities can influence the reliability of estimated fish numbers (Cronkite *et al.* 2006). At low densities and passage rates, camera's counts are more accurate than visual counts, notably in turbulent conditions. In contrast, at high densities and migration rates, the sonar count can be underestimated due to fish shadows passing close to the transducer (Maxwell and Gove 2004). According to these authors, salmon numbers estimated from DIDSON data are generally consistent with counts from commercial fisheries. Likewise, Hateley and Gregory (2006) note that, despite the risk of confusion with drifting debris, silver eel (*Anguilla anguilla*, Anguillidae) counts from acoustic camera's data are remarkably consistent with estimates from trap captures and then permit to

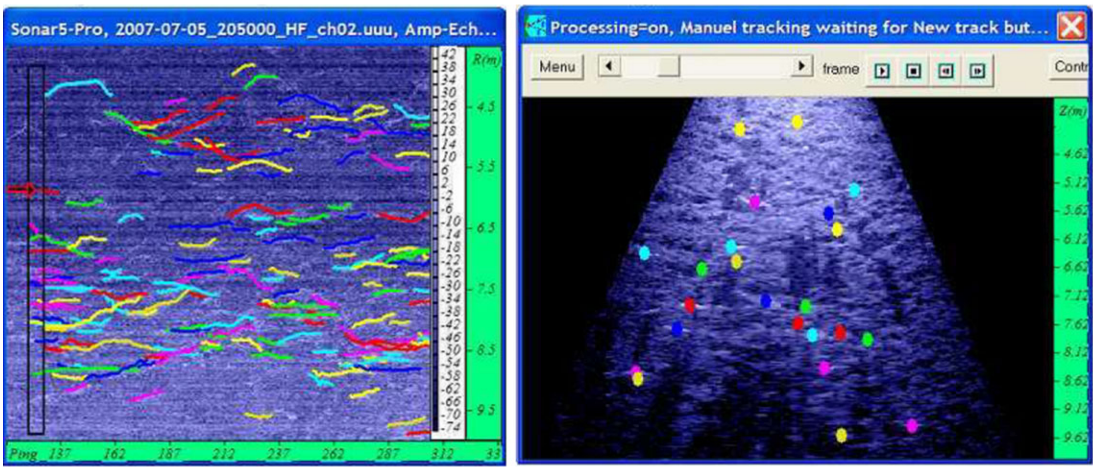

Figure 7 Sonar5-Pro® views of DIDSON data. Left: echogram with tracks detected by the automated tracking tool; right: DIDSON viewer plotting output from the tool (Balk *et al.* 2009).

have long data series without impacting the ecosystem. The risk of counting several times an echo from the same fish must be taken into account, that is, multipass hypothesis as defined by Brehmer *et al.* (2006a). To reduce its bias, site conditions must be carefully chosen (part 3.1.1).

Estimating fish length

Several authors observed the passage of large fish of known length (salmonid adults being a good model because they are usually longer than 30 cm) into the sonar detection beam and compared the lengths estimated by the software to manually measured lengths (Cronkite *et al.* 2006; Burwen *et al.* 2007; Davies *et al.* 2010) (Fig. 5). High-frequency DIDSON estimates were relatively similar to measured lengths of both free-swimming and tethered fish (Burwen *et al.* 2007), but uncertainties were identified. Length estimates from DIDSON data tended to overestimate the length of fish shorter than 68 cm and underestimate that of fish longer than 68 cm (e.g. 40-cm fish would be estimated as 3.3 cm (SE = 0.7) longer, 90-cm fish would be estimated as 2.5 cm (SE = 0.9) shorter) (Burwen *et al.* 2007). These uncertainties as a function of fish length can be explained by differences in receiver sensitivity between acoustic beams. Sub-beams far from the central axis are less sensitive than those close to it (Fig. 8). Consequently, the length of large fish with part of their bodies outside the central axis will be underestimated (Burwen *et al.* 2007; Davies *et al.* 2010).

In low-frequency mode, DIDSON detection range increases (up to 40 m) but results in larger

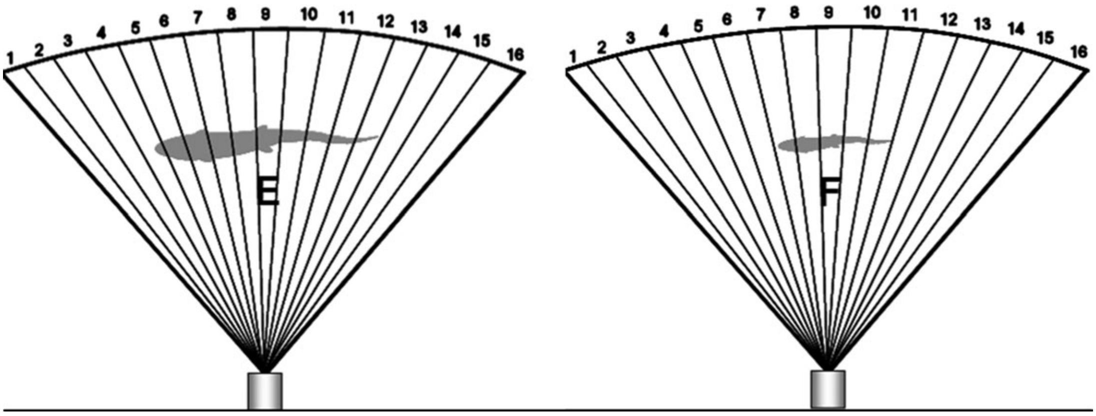

Figure 8 If fish E is exactly twice as long as fish F and both are detected at the same distance from the transducer, fish E will appear less than twice as long as fish F because the reflective surface of the larger fish extends further off-axis, where power is reduced (Burwen *et al.* 2007).

differences between estimated and manually measured lengths (10–20% less) due to the lower resolution, which decreases accuracy of estimates (Lilja *et al.* 2010). Furthermore, it is possible that the weakest echoes, returned by the caudal fin (10–11% of the body length of Atlantic salmon and sea trout), are too weak to be considered when estimating length (Lilja *et al.* 2010).

This bias can result from (i) uncertainty in what data DIDSON software uses to estimate length (e.g. fork length, total length or something in-between) when conditions are not optimal (e.g. low-frequency mode, high noise due to turbulences or air bubbles, long distance from the receiver, high population density); (ii) beam dispersion, which increases with distance; (iii) lower resolution of detections at the furthest range of the sonar, decreasing measurement accuracy; or (iv) 2-cm measurement steps included in the Mark Fish tool (Cronkite *et al.* 2006).

According to Burwen *et al.* (2007), comparison between known lengths of free-swimming fish and DIDSON estimates had a standard error of 5.1 cm for a range of salmon adults from 55 to 118 cm. However, these authors agree that the factors mentioned above generally produce moderate errors in DIDSON length estimates. In the same way, (Cronkite *et al.* 2006) showed a small but significant difference of 1.6 cm between the mean measured fork length of tagged fish and DIDSON estimates. Furthermore, in other studies, fish size-distribution was similar between DIDSON estimates and measurements from net captures or electro-fishing (Hughes 2012).

Species identification

Length estimates by DIDSON software provide reliable clues to species identification (Fig. 2). The addition of morphological and behavioural characteristics increases its accuracy. If the range of differences in length between species is higher than the standard deviation, simple size thresholds can be sufficient to distinguish species. Even if length ranges overlap, an estimate of species composition is possible by modelling distribution curves of length estimated by DIDSON (Fleischman and Burwen 2003).

Operator effect

Like in other method requiring the expertise of an observer, fish distinction from debris echoes, length estimates, and species determination from acoustic camera's images may differ depending on the operator. Comparison of results showed that variability in observations due to operator bias remained low (6% error), due mainly to fatigue or interruptions in viewing (Cronkite *et al.* 2006). These errors can be reduced by increasing operator experience. Observer bias was highest for length estimates and equalled an average of 5.1–5.9 cm and 4.8–6.5 cm in high and low-frequency modes, respectively, for fish from 30–80 cm (Davies *et al.* 2010). These authors recommend that operators calculate the mean of multiple measurements from several frames of fish views to increase the accuracy of the fish length estimates.

Technological improvements for identifying species

Although acoustic cameras provide high-quality images, subjective identification of species is disputable and depends on observations of remarkable morphological characteristics or particular echo signals (Langkau *et al.* 2012). Consequently, individuals from two species that have similar shape and size (e.g. sea trout and Atlantic salmon) can barely be distinguished despite a good knowledge of species ecology. Currently, tools are being developed and optimized to improve species determination:

Identifying eels

Eels have a particular morphology (snake-like) and swimming behaviour (Webb 1982) that make them recognizable on DIDSON videos and echograms. Consequently, a computer tool has been designed to distinguish silver eel echoes from debris echoes (Mueller *et al.* 2008). The tool has four steps to classify DIDSON data to identify eels: (i) image processing, (ii) target tracking, (iii) parameter selection and (iv) classification. Threshold parameters are defined during phase 3: mean cluster area (A) in cm²; mean border length (B) in cm; mean of the intensity variation coefficient (standard deviation of pixel intensity/mean pixel intensity) in dB; mean compactness ($C = B^2/4\pi A$); and the X-axis velocity, approximately parallel to the flow, in cm/s (Mueller *et al.* 2008). The setting of this tool using characteristics of species that live in the study system could provide identification clues.

Interpreting acoustic fish shadows

Fish passing in the detection beam reflect a part of emitted sound: consequently acoustic shadows are created behind the fish body (Langkau *et al.* 2012). These shadows are strongly related to object shapes and can be considered a criterion for identifying fish species (Fig. 9). By placing a plate with a 45° ground angle facing the beam, the shadow of fish moving parallel to the flow are observable on DIDSON images with correct proportions. In this way, morphological characteristics (e.g. fin position and size, profiling, lateral compression) can be observed and proving clues to identify species. A computer-imaging process classifies the shadows according to their shapes and to species present in the river. Furthermore, shadow study provides information about the position of fish in the water column (Balk and Lindem 2012). Nevertheless, this method has not proven effective for fish shorter than 20 cm, and has not yet been tested in the field (Langkau *et al.* 2012).

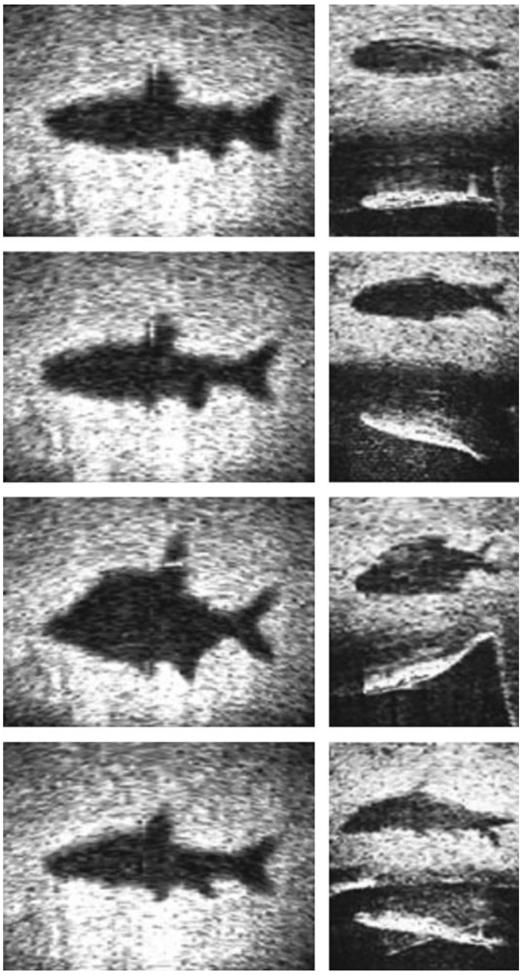

Figure 9 Acoustic shadows recorded by DIDSON of 50-cm stainless-steel templates (left) and living fish (right). From top to bottom: trout (*Salmo trutta*, Salmonidae), chub (*Leuciscus cephalus*, Cyprinidae), bream (*Abramis brama*, Cyprinidae), and barbell (*Barbus barbus*, Cyprinidae) (Langkau *et al.* 2012).

Studying frequency of caudal fin beating

Some studies focused on beat frequency of the caudal fin to identify species (Mueller *et al.* 2010), because each species has a specific one. Beat frequency of fish in a steady-swimming mode is calculated on the recorded echograms. Each beat appears as a punctual change along the fish outline (Fig. 10). No correlation has been observed between fish length, its behaviour and the frequency beat. This technique seemed able to distinguish two species of Canadian salmon of similar length ranges (*O. nerka* and *O. tshawytscha*, Salmonidae), but Mueller *et al.* (2010) note that the environment must not be too noisy so that high-quality DIDSON images are produced.

Limits of DIDSON

The first limit concerns the minimum size of targets detected by DIDSON. Most studies used the DIDSON camera to detect medium-to-large organism, up to 20 cm. The few authors focusing on small organisms restricted analysis to targets larger than 5 cm (total length) for fish (Mueller *et al.* 2006) and 2 cm (total length) for nekton (Kimball *et al.* 2010). The restricted maximal range is also an important limit for monitoring fish populations: site conditions must be carefully selected.

The DIDSON camera records data in only two dimensions. Consequently, in case of horizontal use, the vertical distribution of fish cannot be described (Hughes 2012). However, fish movements are described in the two other axes, which ensures counting of all the fish passing through the beam (Cronkite *et al.* 2006).

Dual-frequency identification sonar files are large because data are often recorded during long-term or permanent monitoring studies, which usually require a sampling strategy.

Sonar maintenance is also an important consideration to ensure reliable and usable data. The submerged DIDSON lens can be obscured by the salt of sea water or become clogged with silt (Maxwell and Gove 2004) or pollen (Lilja *et al.* 2010) (Fig. 11). Dirtying of the lens prevents emission of acoustic waves without stopping data recording. Thus, the camera has to be regularly removed

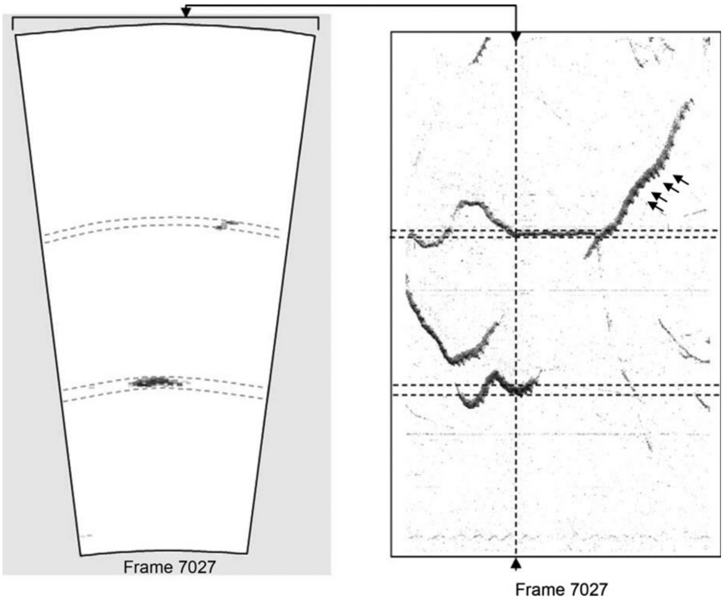

Figure 10 Snapshot of the DIDSON screen (left) and its corresponding echogram view (right) during the passages of two fish. Arrows indicate discontinuities in the acoustic trace of fish, signals of each caudal fin beat. The range increases from the bottom to the top. Frequency beats can consequently be calculated (Mueller *et al.* 2010).

Figure 11 Photo of the DIDSON lens: clean (left) and covered by drifting pollen (right) (Lilja *et al.* 2010).

from the water to have its lens cleaned. The DIDSON camera can also be placed in a protective case (Pipal *et al.* 2010a).

The efficiency of automated tracking by DIDSON software depends highly on population abundance. Furthermore, verification is necessary to ensure that tracked objects are fish and not parasite echoes. Milling behaviour and a weak signal-to-noise ratio can reduce the accuracy of automatic counting (Balk *et al.* 2011). Also, velocity needs to be manually calculated (Hughes 2012).

Dual-frequency identification sonar lacks tools to automatically track fish, whereas previous generations of echosounders have such tools (Pipal *et al.* 2010a). All fish have to be manually counted and measured to ensure that the data exported are reliable (Pavlov *et al.* 2009; Lilja *et al.* 2010). Software modules are under development to meet this need.

Common scientific echosounders and sonars need to be calibrated to be used and to know their accuracy and precision levels (Foote 2009). The principles of standard-target calibration are well known for scientific echosounders (Foote *et al.* 1987) and multibeam sonars (Foote *et al.* 2005), which use acoustic properties of fish echoes. The beam pattern of the acoustic camera can be checked following these procedures. Nevertheless, the acoustic camera uses image properties, such as cluster area or body length, but does not use acoustic properties in the same way as common echosounders and sonars. Consequently, no calibration process has been already defined for acoustic cameras for the time being, rendering less certain the quality of recorded data over time, particularly for the shortest targets, and reducing the reliability of using acoustic properties of fish echoes.

Monitoring of migratory fish populations: an ecological purpose for the acoustic cameras

Considering the characteristics described previously, acoustic cameras can provide much information for ecological monitoring studies, in a same way as multibeam sonars are now used (Brehmer *et al.* 2006c). Five essential conditions have been defined to use hydroacoustic methods for estimating the number of migrant fish (Maxwell 2007):

1. Fish must cross the detection beam.
2. Fish must migrate actively and unidirectionally. Fish passing back and forth in front of the beam may be counted several times, introducing bias.
3. The bottom profile should be as flat as possible, with a laminar flow.
4. The bank must be steeper than the river channel; otherwise, the beam may reach the fish but will not reflect back to the transducer.
5. If the studied species is not the only one in the system, it is necessary to estimate the relative abundance of each species using differences in their behaviours or size ranges.

Installation of acoustic cameras on study sites

Recommended study-site characteristics

Study sites must be carefully chosen and be suitable to the sonar characteristics to optimize data recording and minimize operational problems. Several authors (Maxwell and Gove 2004; Maxwell 2007; Balk *et al.* 2011) have published recommendations about:

River morphology. If the site is located in a river, the river must have one single branch to detect all fish. The bottom must be flat (no mounds or obstacles) and the substrate must be sand, mud or small gravel. Rocks must be rare on the detection beam because they may create blind spots where fish cannot be detected (Brehmer *et al.* 2006c; Pipal *et al.* 2010b). Water flow must be uniform and non-turbulent to avoid bubble echoes (Maxwell 2007; Mercer 2012) and fish milling behaviour (Enzenhofer *et al.* 1998; Hughes 2012). In large rivers (width up to 50 m), the bank needs to be steep enough to fit an acoustic beam from near the bank to the maximum distance of fish passage (Maxwell 2007). In even larger rivers, a deflector weir may need to be set up in the channel to ensure that all the fish cross the detection beam. Fish must actively migrate through the site, and the sonar should not be located in a pool to avoid capturing milling behaviour, which can reduce the accuracy of counting (Pipal *et al.* 2010b). It is recommended to begin beam mapping before selecting a site to ensure that all fish beyond a certain length can be detected as unique targets. This mapping defines the maximum range of the beam and ensures that no blind zone is created by obstacles (Burwen *et al.* 2007).

Site position in the watershed. For a spawning migration survey, the site should be located downstream from any tributaries or river sections where spawning occurs to ensure that the entire population is monitored (Pipal *et al.* 2010b). Thus, the site must be located relatively close to the mouth of the river but also upstream of the tidal-influence zone to avoid large daily changes in water level, which can reduce sampling efficiency (Daum and Osborne 1998).

Those operating the sonar should remain near the site to intervene quickly in case of exceptional events (e.g. floods, high rainfall) (Pipal *et al.* 2010b) or to maintain the equipment (Lilja *et al.* 2010).

Positioning and settings of acoustic cameras

Tilt of the camera should be adapted to site characteristics to ensure proper beam coverage of the channel. The tilt should be optimized as a function of the bank slope and shape of the channel section. If the beam angle is too steep, the sample zone may be limited to only a small portion of the channel (Fig. 12). If it is angled too high, it may lose the ability to detect fish migrating close to the stream bottom (Pipal *et al.* 2010b). The channel profile must not require the beam to be either too steep or too shallow. In an ideal situation, the upper part of the sonar beam edge follows the water surface and the bottom is reached for the entire field of view (Lilja *et al.* 2010).

Recommended components

The basic equipment required for successful operation of a monitoring study of migratory species using high-frequency sonar includes a DIDSON unit, sonar mount, pan and tilt rotator, laptop

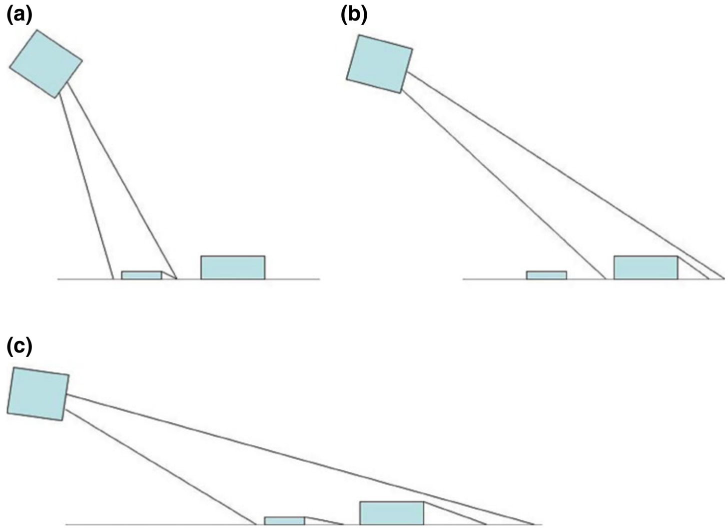

Figure 12 A schematic illustration of consequences of DIDSON tilt settings on target ensonification on a bottom (side views) (Pipal *et al.* 2010b).

computer, data-storage device with associated cables and a weather-proof storage box (Pipal *et al.* 2010b). Furthermore, the sonar can be protected by an aluminium housing to protect it from large debris travelling downstream during high-flow events. Several fixation units have been designed and described in the literature (Fig. 13). The most frequent system used in migratory salmonid monitoring is a support adapted to the flat slopes of large rivers. Two devices have been described: a tripod (Enzenhofer and Cronkite 2000; Pipal *et al.* 2010b) and an H-mount (Maxwell and Gove 2004; Lilja *et al.* 2010; Mercer 2012). Both systems, ballasted, can adjust the sonar height to site conditions but make the sonar tilt settings difficult. Deflector weirs (Fig. 14) can force the fish to migrate into the beam to ensure that all the population movements are recorded (Enzenhofer and Cronkite 2000; Cronkite *et al.* 2006). These deflectors are often used in studies in large rivers, because the range of high-frequency detection is limited (Maxwell and Gove 2004).

Monitoring examples

Acoustic cameras are innovative equipment that has been used by several research laboratories and

Figure 13 Two different DIDSON fixation supports: left: an aluminium H-mount (Mercer and Wilson 2009); right : a tripod-style DIDSON mount (Pipal *et al.* 2010b).

Figure 14 Cross-section of a DIDSON hydroacoustic site on the Horsefly River (Canada), using a deflector weir. Photograph by J. Lilja (Cronkite *et al.* 2006).

management organizations to monitor fish populations (abundance, within-river distribution) for a decade. The Alaska Department of Fish and Game uses this device to monitor salmon migration (counting) in many rivers (Maxwell and Gove 2004). The Fisheries Research Board of Canada also tested the effectiveness of a DIDSON for monitoring salmon migration in British Columbia (Cronkite *et al.* 2006). In other countries where professional salmonid fisheries represent important economic resources (Scandinavia, Russia), acoustic cameras are used with success (Pavlov *et al.* 2009; Lilja *et al.* 2010; Lilja and Orell 2011; Pavlov *et al.* 2011).

Migrations of other species have also been monitored and described with these cameras. Upstream anadromous migrations of sea lampreys (*Petromyzon marinus*, Petromyzontidae) (Davies and Griffiths 2011) and downstream catadromous migration of silver eels (Hateley and Gregory 2006; Mueller *et al.* 2008; Bilotta *et al.* 2011) have been published. Furthermore, eel migrations are efficiently recorded up to a range of 20 m for fish up to 90 cm long. Smaller eels (up to 70 cm) can be easily identified up to a range of 15 m (Hateley and Gregory 2006).

However, acoustic devices seem to have an impact on the Clupeidae fish family. Monitoring studies on shad migration showed that this family species displays weak avoidance behaviour when fish detect acoustic waves, up to 120 kHz (Dunning *et al.* 1992; Nestler *et al.* 1992), including DIDSON's (Gregory *et al.* 2007). Indeed, fish of the subfamily *Alosinae* (Clupeidae family) can detect frequencies up to 3 kHz, unlike other fish (Wilson *et al.* 2008). These authors described the tendency of *Alosinae* juveniles to acquire avoidance behaviour after exposure to odontocete predator echolocation (Mann *et al.* 2001). Some monitoring methods have attempted to use this particularity to count migrating shads, but they have disturbed migratory dynamics (Gregory and Clabbum 2003).

Besides estimating the abundance of migrating fish, acoustic cameras obtain data about fish behaviour and predation, such as: fish-pass effectiveness (Baumgartner *et al.* 2006), active avoidance behaviour in front of a trap (Baumgartner *et al.* 2006) or pelagic trawl net (Rakowitz *et al.* 2012) or predation behaviour of piscivorous predators (fish or birds) that use fish passes to hunt prey (Baumgartner *et al.* 2006). The recorded data can increase understanding of predator-prey relations by showing the behaviour of forage fish schools (Handegard *et al.* 2012).

Does acoustic cameras replace, or instead complement, common hydroacoustic methods?

The Alaska Department of Fish and Game was the first organization to compare the performances of different hydroacoustic tools. The 2002 study compared DIDSON to (i) Bendix sonar (single-beam), used in Alaska rivers since the 1970s, (ii) split-beam sonar, tested for a few years and (iii) visual counting performed from observation towers (Maxwell and Gove 2004). The study concluded that the camera seemed immune to many problems that plague other sonars, including fish changing aspect-tilt angle, remaining for long periods in the sonar beam and travelling downstream. Its wide horizontal beam allows wider viewing of fish behaviour than previous sonars. Thus, DIDSON has replaced other acoustic equipment used

Table 1 Human and material cost-effectiveness, efficiency and impact on fish and migratory dynamics of the most common devices used to monitor migratory fish populations in rivers and estuaries. The efficiency of each method is symbolized by gradual colours, from black (weak efficiency or negative impact) to white (high efficiency or no negative impact).

		Acoustic methods					Visual methods		Capture methods	
		Single-Beam Echosounder	Dual-Beam Echosounder	Split-Beam Echosounder	Multi-Beam Echosounder	Acoustic cameras	Visual counting	Video-counting	Trapping in fish passes	Net or electro-fishing
Individual fish	Counting fish	░	░	□	▓	□	░	□	▓	■
	Exhaustiveness of population abundance estimation	░	░	░	■	□	□	░	▓	■
	Describing individual behaviour	■	▓	░	▓	□	▓	□	■	■
	Individual-fish approach	■	■	■	■	■	■	■	□	□
	Impact on fish (integrity and/or behaviour)	□	□	□	□	░	□	□	▓	■
Fish school	Estimation of stock in fish school	□	□	□	□	■	■	■	■	■
	Describing school behaviour	■	■	▓	□	▓	■	■	■	■
Target description	Identifying species	■	■	■	■	░	░	░	□	□
	Measuring length	▓	▓	▓	■	░	■	░	□	□
Device adaptability	Human cost-effectiveness	░	░	░	░	▓	■	▓	■	□
	Material cost-effectiveness	░	░	░	▓	▓	□	■	■	□
	Independent of environmental conditions	□	□	□	□	□	■	▓	░	▓
	Transposable whatever site characteristics	░	░	░	░	▓	■	■	■	░

to monitor salmon migration in Alaska (Maxwell and Gove 2004).

Other studies have been performed to compare acoustic cameras to common split-beam acoustic devices (Maxwell and Gove 2004; Xie *et al.* 2005; Pipal *et al.* 2010b; Balk *et al.* 2011; Hughes 2012), and they have clearly showed the advantages of DIDSON (Table 1):

1. Its wider beam (29° × 14°) detects fish better than those of split-beam devices, even close to the transducer (Maxwell and Gove 2004; Burwen *et al.* 2007; Pipal *et al.* 2010b).
2. Fish-movement changes and swimming behaviour are clearly apparent on DIDSON images, whereas they cannot be easily extracted from the echograms of previous sounders (Maxwell and Gove 2004). In the echograms of split-beam devices, fish-movement direction can be hidden by saturation of the echogram with parasite echoes or during high-density population movement (Maxwell and Gove 2004; Cronkite *et al.* 2006). Thus, in the case of behavioural researches, acoustic cameras are useful tool. Moreover, acoustic cameras are efficient to characterize fish behaviour in trawl (Handegard and Williams 2008), spawning behaviour (Grabowski *et al.* 2012), predation behaviour (Price *et al.* 2013) or spatial distribution (Shen *et al.* 2013).
3. DIDSON's background subtraction tool can remove static echoes. Fish movement can consequently be recorded throughout the beam, even beyond the contact zone and the bottom (Balk *et al.* 2011). In contrast, the reception of split-beam sounders is often saturated by strong echoes from the bottom (Maxwell and Gove 2004; Hughes 2012).
4. Manual size measurement provides useful information up to a range of 12 m (Maxwell and Gove 2004; Burwen *et al.* 2007), although the measurement step in DIDSON software is 2 cm × 2 cm (Cronkite *et al.* 2006). Beyond 12 m, measurement accuracy decreases as target fuzziness increases.
5. DIDSON is easier to operate than other split-beam sounders. Its settings and echo visualization, based on an image of fish shape, improve data interpretation by even inexperienced operators. These characteristics minimize operational mistakes and consequently improve the relevance of the data collected (Lilja *et al.* 2010).

However, acoustic cameras and split-beam sounders have certain limitations in common

(Table 1). Solutions have been designed and tested to address some of those of cameras, such as sampling strategies to reduce data volumes and processing times, computer methods to improve species identification and improvement of data-processing tools.

In certain environment like shallow coastal waters, mangrove, reefs, that is, mainly shallow waters environment (Blondel 2009), acoustic cameras seem to be particularly adapted (Frias-Torres and Luo 2009). In the same way, fish aggregation under Fish Aggregating Devices (FAD) (Josse *et al.* 2000) could be studied with such technology, combined with common acoustic devices, and greatly improved our knowledge of these traps. Whereas, in other environment (i.e. lakes, seas, large rivers), cameras do not yet appear more efficient than existing echosounders but rather as a complementary tool that can improve species identification (Guttormsen *et al.* 2010). Although echo-integration can be applied to echograms to estimate fish density and biomass in lakes and seas, acoustic cameras cannot estimate biomass and then cannot map fish population distribution, because this information cannot currently be extracted from the recorded data (Hateley and Gregory 2006). Furthermore, fish position and trajectories in three dimensions cannot be recorded in camera data. Likewise, when monitoring fish in rivers too wide to be covered completely by acoustic camera, a split-beam sounder, which can detect fish up to 250 m away (Pfisterer 2002), can be combined with a camera, which can help in species identification (Hughes 2012).

Conclusion

Despite some limitations, acoustic cameras, such as DIDSON, seem an accurate and cost-effective method to obtain abundance estimates for management purposes. Cameras meet the expectations of scientists and managers for ecological monitoring of fish populations in rivers and estuaries. It improves the understanding of fish behaviour via direct ‘video-like’ visualization of passages in the detection beam, does not affect the migratory behaviour of most species and allow the ownership of long data series, necessary in long-term monitoring in a changing world. Furthermore, its wide beam angle and background subtraction tool optimize image interpretation. Acoustic cameras are particularly useful for identifying fish species, a major limitation of current acoustic methods. These characteristics make the DIDSON an efficient tool in several applications where fish populations are difficult to observe using common methods, such as marine shallow water applications. Improvement of data-processing tools will eventually address the main limitations of DIDSON described here. Acoustic camera technology thus appears to be the most efficient monitoring method in rivers and estuaries up to 20 m wide and a useful complementary tool for identifying fish species in other ecological uses.

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