School of Doctoral Studies in Biological Sciences

University of South Bohemia in České Budějovice
Faculty of Science

Fish detection with modern sonar systems

Ph.D. Thesis

Mgr. Michal Tušer

Supervisor: Prof. Jan Kubečka, Ph.D.

Biology Centre of the AS CR, v.v.i.

Institute of Hydrobiology

České Budějovice 2013

This thesis should be cited as:
Tušer, M. 2013: Fish detection with modern sonar systems. Ph.D. Thesis Series, No. 5. University of South Bohemia, Faculty of Science, School of Doctoral Studies in Biological Sciences, České Budějovice, Czech Republic, 79 pp.

Annotation

This dissertation thesis was focused on improving the methodology to detect fish with modern sonar systems in lakes and reservoirs. The first part of the thesis is aimed to the vertical beaming acoustics with a key focus on the acoustic dead zone and its practical solution. The second part deals with the fish orientation in reservoir's open waters and its consequences in horizontal beaming acoustics. The last one dedicates to the DIDSON multi-beam sonar and its reliability in detection and sizing of fish.

Declaration [in Czech]

Prohlašuji, že svoji disertační práci jsem vypracoval samostatně pouze s použitím pramenů a literatury uvedených v seznamu citované literatury.

Prohlašuji, že v souladu s § 47b zákona č. 111/1998 Sb. v platném znění souhlasím se zveřejněním své disertační práce, a to v úpravě vzniklé vypuštěním vyznačených částí archivovaných Přírodovědeckou fakultou elektronickou cestou ve veřejně přístupné části databáze STAG provozované Jihočeskou univerzitou v Českých Budějovicích na jejích internetových stránkách, a to se zachováním mého autorského práva k odevzdanému textu této kvalifikační práce. Souhlasím dále s tím, aby toutéž elektronickou cestou byly v souladu s uvedeným ustanovením zákona č. 111/1998 Sb. zveřejněny posudky školitele a oponentů práce i záznam o průběhu a výsledku obhajoby kvalifikační práce. Rovněž souhlasím s porovnáním textu mé kvalifikační práce s databází kvalifikačních prací Theses.cz provozovanou Národním registrem vysokoškolských kvalifikačních prací a systémem na odhalování plagiátů.

České Budějovice, 22.4.2013 Michal Tušer

This thesis originated from a partnership of Faculty of Science, University of South Bohemia, and Institute of Hydrobiology, Biology Centre of the ASCR, supporting doctoral studies in the Biology of Ecosystems study programme

Přírodovědecká fakulta
Faculty of Science

Financial support

Biology Center of the Academy of Science of the Czech Republic – RVO: 60077344

EEA Financial Mechanism and the Norwegian Financial Mechanism from Iceland, Liechtenstein, and Norway – CZ 0091

Grant Agency of Czech Republic – GA206/07/1392, P504/12/1186

Grant Agency of the Academy of Science of the Czech Republic – IAA600117502

Grant Agency of the University of South Bohemia – 145/2010/P

Ministry of Education, Youth and Sport of the Czech Republic – CZ.1.07/2.3.00/20.0204

National Agency of Agricultural Research (NAZV) – QH81046

Acknowledgements

I would like to express my very great appreciation to my supervisor, Jan Kubečka, for introducing me to the great world of science. With his never-ending enthusiasm, Jan provided me valuable consultations, moral and financial support, and most importantly he tried to always help me when most needed. I wish to acknowledge Josef Matěna, the former director of Institute of Hydrobiology (BC AS CR, v.v.i.), who provided me a place to work and financial support from the beginning of my studies. My special thanks belong to Jarka Frouzová and Helge Balk for their valuable discussion and for bringing new perspectives to the field of underwater acoustics. I am also obliged to all my present and former colleagues of FishEcU team for their help and mainly for a pleasant atmosphere during our tough fieldworks. Last but not least, I would like to thank my family and friends who always stood by me through the good and bad times.

List of papers and author's contribution

The thesis is based on the following papers (listed thematically):

I **Tušer M**, Balk H, Mrkvička T, Frouzová J, Čech M, Muška M, Kubečka J, 2011. Validation of current acoustic dead-zone estimation methods in lakes with strongly sloped bottoms. Limnology and Oceanography: Methods 9, 507-514 (IF_{2011} = 1.535, 5-year IF_{2011} = 2.010)
Michal Tušer was responsible for field acoustic measurements, data assembly and processing, statistical analysis, and writing the manuscript.

II **Tušer M**, Prchalová M, Frouzová J, Čech M, Peterka J, Jůza T, Vašek M, Kratochvíl M, Draštík V, Kubečka J, 2013. Simple method to correct the results of acoustic surveys for fish hidden in the dead zone of an echosounder. Journal of Applied Ichthyology 29, 358-363 (IF_{2011} = 0.869, 5-year IF_{2011} = 1.240)
Michal Tušer was responsible for data assembly and processing, statistical analysis, and writing the manuscript.

III **Tušer M**, Kubečka J, Frouzová J, Jarolím O, 2009. Fish orientation along the longitudinal profile of the Římov reservoir during daytime: Consequences for horizontal acoustic surveys. Fisheries Research 96, 23-29 (IF_{2009} = 1.531, 5-year IF_{2011} = 1.887)
Michal Tušer was responsible for field acoustic measurements, data assembly and processing, statistical analysis, and writing the manuscript.

IV **Tušer M**, Frouzová J, Balk H, Muška M, Mrkvička T, Kubečka J. Evaluation of potential bias in observing a fish by a DIDSON acoustic camera. (unpublished manuscript)
Michal Tušer was responsible for field acoustic measurements, data assembly and processing, statistical analysis, and writing the manuscript.

Declaration of originality

The co-authors fully acknowledge that Michal Tušer is the first author of all papers presented. Most of the processing as well as most of the statistical analysis was performed by Michal Tušer. He also made a major contribution in writing the manuscripts. All papers contain original results. All co-authors consent to the publication of the papers in the dissertation of Michal Tušer and one author on behalf of all co-authors hereby supports this statement with his signature.

Prof. Jan Kubečka, PhD.

Contents

1 Introduction

1.1 How to reach the underwater world

The underwater world has already fascinated quite a few people, yet still retains most of its secrets about its inhabitants dwelling below its surface. The reason why is clearly evident. We as humans do not naturally belong into this environment, thereby lacking an authentic experience of living there (i.e. we live outside, except for short visits as scuba divers). Moreover, as our awareness of the world is vision based, and specifically light for human vision can penetrate only a few meters below the water surface, our direct observational capability is quite confined to that edge. Most of the information about underwater life must be obtained indirectly, with regard to what we are able to pull out of water. Therefore, the study of fish biology and ecology, what sort of animals they are, where and how they live, is quite a challenging task, revealing facts slowly and reluctantly.

Advances in imaging technologies, nevertheless, have expanded the boundary of human activity and perception to those areas that have been out of our reach for a long time. The exploration of underwater environments is an example of successful applications of novel imaging technologies. Only two approaches, optical or acoustical, enable us to look below the water surface. Both ways have naturally their pros and cons. The former one can precisely distinguish the accurate size, species of the fish and therefore is particularly useful when a mixture of species inhabit the water (Harvey et al. 2010). The major flaw of optical devices is their strong dependence upon light availability in water, which is rapidly attenuated with increasing depth due to suspended particles.

The acoustical approach is similar in many respects to that of light, but in water sound can propagate over much longer distances far beyond the range of vision, even in environments with zero-visibility (Simmonds and MacLennan 2005). Generally speaking, a sonar (a term for any device that uses sound for the remote sensing) transmits an acoustic pulse concentrated in a certain direction through a transducer. The pulse travels through the water environment and is scattered by the objects with different homogeneities than that of the surrounding medium. Consequently, a backscattered sound, called an echo, returns back and is detected by a receiver of the sonar. The received signal contains information about the ensonified objects. This concept offers a possibility for remote sensing within the environment. The best advantage is that with a sonar device one can search large volumes of water in a short time, completely by unobtrusive way for fish or other aquatic life forms. Unfortunately, most conventional sonars (single-, dual- or split-beam) cannot determine fish size or shape, and therefore species, and are influenced with factors such as background noise, boundary conditions (surface, bottom, and other structures), aeration, water temperature, and turbidity (Simmonds and MacLennan 2005). As a result, the acoustic data are technically complex to collect, analyze, and interpret (Jech and Michaels 2006; Jech and Michaels 2007), and this has an inhibiting effect on our ability to fully exploit the advantages of acoustic techniques for fish monitoring.

Historically, the greatest progress and development of underwater acoustics took place in marine environment mainly due to the military activities and commercial fisheries driven by human's need for food and nutrition (Simmonds and MacLennan 2005). In the course of time, underwater acoustics became important even in freshwater ecosystems. However, there are major differences between these two environments, and the transition from marine to freshwater acoustics had to entail distinct approaches. The marine ecosystem is unique by its vast volumes of the pelagic water, inhabiting by large shoals (schools) of fish or other marine animals. Additionally, these vast oceanic fish communities are usually comprised of several, depth-separated species (e.g. Swartzman et al. 1994; Massé et al. 1996; Huse et al. 2012). On the contrary, the freshwater environment represents a wide spectrum of habitats from streams, rivers, smaller ponds to large lakes. In terms of acoustics, those water systems are confined in open water more than that of the marine ecosystems. Thus, the freshwater acoustics more often collides with boundaries, such as surface and bottom. Among other differences between fresh water and marine ecosystems we can take into account more pronounced gradients of abiotic factors, such as temperature, as well as biotic factors, such as temporal and spatial distribution of multispecies communities of fish. Due to the disparities mentioned above, the usage of acoustic techniques in the freshwater environment is more challenging task and requires novel approaches to be applied.

1.2 Vertical beaming acoustics

In traditional echo-sounding, a sonar beam is oriented vertically downwards to the bottom of sea or lake, observing a depth distribution in targets of interest through the whole water column (Brabrand 1991; Auvinen and Jurvelius

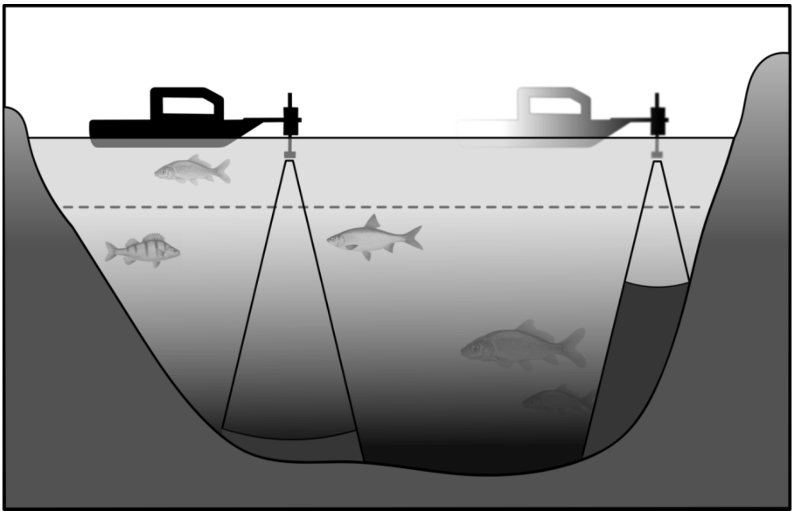

Figure 1. An illustration of vertical beaming surveying with the indication of both regions where a sonar fails to detect fish (the region below the surface is indicated by dashed line; the region close to the bottom is indicated by a darker color in the beams).

1994). Unfortunately due to physical characteristics of the beam pattern, a sonar fails to detect fish in two regions, below the surface, unless an acoustic pulse is fully formed, and in a close proximity of the bottom (Fig. 1; Scalabrin et al. 2009; Totland et al. 2009). The former can be solved by utilizing horizontal beaming techniques (Kubečka and Wittingerová 1998; Knudsen and Sægrov 2002), and that will be discussed later on. The latter, however, is a persistent theoretical and mainly practical problem in the reliable detection of fish or other aquatic animals dwelling close to the bottom of sea or lake.

The region where we are not able to detect fish is called an acoustic dead zone, and was firstly described by Mitson (1983) for a flat horizontal bottom. In principle, it is assumed that an acoustic wave spreads spherically in all directions through water. First, the wave strikes perpendicularly to the bottom at the closest range from the transducer. After that, as that signal continues, there will be a time delay between the first contact and the edges of that pulse striking the bottom. Thus, as the bottom is acoustically a strong reflector, the first bottom echo will obscure the weaker echoes arriving afterwards. Moreover, if a bottom is sloping, the dead zone increases its volume because there is a larger range of depth between the first contact and the beam's edges (Kloser et al. 2001). Above all, the extent of the dead zone is dependent upon the beam pattern of the transducer deployed and the bottom characteristics (Mitson 1983).

The acoustic dead zone on a flat horizontal bottom was theoretically defined as a height of the half length of the transmitted pulse, referring only for the center of the beam (Mitson 1983). This issue is more elaborated in the study of Ona and Mitson (1996) with a focus on the acoustic pulse and its sampling volume. After that, a theoretical dead-zone estimation was also deduced (Kloser et al. 2001) and later on extended with the calculations of its sampling volume (Patel et al. 2009). These calculations consider only the sonar's central beam with a fixed nominal angle, yet the energy regime of the beam pattern is complex and unique for each transducer. Moreover, the calculations are based on the assumption that the first observed echo of the bottom arrives from the radial ray that is perpendicular to the bottom. Unfortunately, it may not be accomplished in the situations with quite a high slope of the bottom, typically occurring in the freshwater ecosystem.

Other side of this issue lies in a practical approach to addressing the dead zone. At present, the dead zone can be reduced, but not totally eliminated, by several acoustic-based approaches including the use of narrow beams, short pulses, or employing deep-towed transducers (Kloser 1996; Scalabrin et al. 2009; Totland et al. 2009). Unfortunately, there are only two ways to potentially obtain still-hidden information within the dead zone. The first and simplest method is based on the extrapolation of acoustic data from the layer immediately above the dead zone (Ona and Mitson 1996; Rose 2003). However, this mathematical approach does not take into account the possibility that this zone can be occupied by an ecologically distinct fish community than that of the layer above (Godø and Wespestad 1993; McQuinn et al. 2005). The second approach is to directly sample the fish close to the bottom using bottom trawls (e.g. Aglen 1996; Aglen et al. 1999; Yousif and Aglen 1999). Unfortunately, the applicability of this method is limited in habitats with a complicated topography (Cooke et al. 2003; Jones et al. 2012; Rooper et al. 2012), thus in the majority of freshwater lakes and reservoirs, and by the trawl designs (McQuinn et al. 2005).

1.3 Horizontal beaming acoustics

As previously mentioned, the vertical echo-sounding also fails to detect fish and other objects in the region right below the water surface. The extent of the missed zone, called an acoustic blind zone, is defined firstly by a transducer depth, where the device is not affected by surface disturbance, and secondly by a distance from the transducer when an acoustic pulse is fully formed, known as the near-field distance (Simmonds and MacLennan 2005). Additionally, after the pulse is properly formed, the sampled water volume is negligibly low. Thus, the vertical beaming acoustics is inappropriate for monitoring fish in rivers, where the depths do not exceed several meters in dimension (Kubečka et al. 1992; Kubečka et al. 2000), or in many lakes, where the fish community often occupy the uppermost layer of the surface (4 m, Kubečka and Wittingerová 1998; Čech and Kubečka 2002; Vašek et al. 2004). This leads to the suitable concept of a sonar beam directed horizontally, thereby monitoring fish in side aspect within that region (Fig. 2; Kubečka et al. 1992; Tarbox and Thorne 1996; Yule 2000; Knudsen and Sægrov 2002).

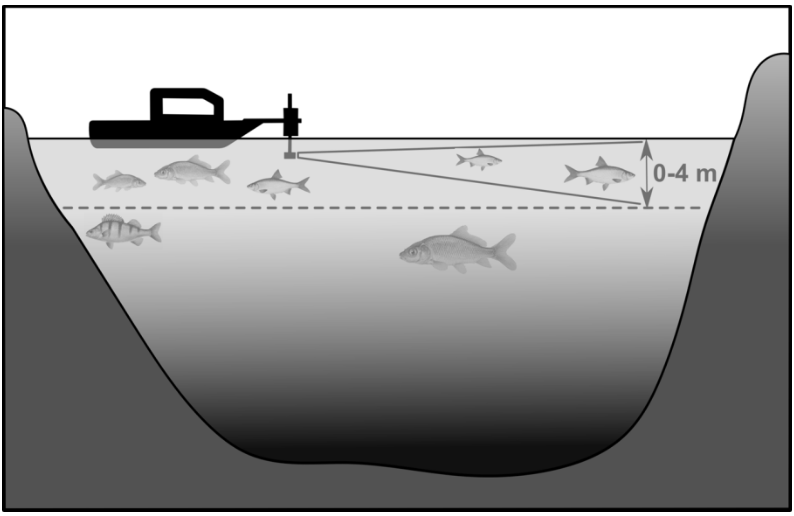

Figure 2. An illustration of horizontal beaming surveying in a lake with fish population living predominantly in the surface layer.

The horizontal mode of a sonar beam, however, encounters many practical problems, such as boundary reverberation (Trevorrow 1998), non-uniform sound propagation in stratified waters (Pedersen and Trevorrow 1999), and most significantly distributional effects from targets of interest (Kieser et al. 2000; Simmonds and MacLennan 2005). Regarding the last mentioned, we cannot assume that fish location or orientation is independent of the observation method. As the conversion of acoustic target strength is immensely dependent on fish orientation in the sonar beam, it requires implications of ecologically based assumptions for diverse habitats. In most riverine applications, we can suppose that fish are oriented along the current as they swim downstream or upstream (Burwen and Fleischman 1998; Kubečka et al. 2000; Lilja et al. 2000). In the case of still waters, random fish orientation is usually assumed (Kubečka et al. 1994; Draštík and Kubečka 2005; Godlewska et al. 2012) devoid of proper verification. The situation could be more complicated in artificial lakes, which are built as impoundments of streams or rivers for diverse purposes (flood control, power generation, drinking water supply, public recreation). These reservoirs are regarded as a combination of many riverine and lacustrine features (Irz et al. 2006). The fact that fish are usually drawn fauna of dammed river combined with reservoir's elongated shape can lead us to the presumption that fish may predominantly swim along the longitudinal profile of that reservoir. Therefore, if the fish orientation in a sonar beam is unknown, the conversion of acoustic echoes to fish parameters will be strongly biased.

1.4 Multi-beam acoustics

Size and species identification of the detected targets presents a major problem for conventional acoustic methods compared to optical ones. A possible, but not complete, way to identify fish specifics is to utilize acoustic responses at different acoustic frequencies (Simmonds and Copland 1989; Simmonds et al. 1996) or to study complicated reflection patterns of fish swimbladders (Simmonds and MacLennan 2005). These approaches are appropriate when the population is comprised of a few distinct species, preferably spatially separated (Foote et al. 1987; Crawford and Jorgenson 1996; Hartman and Nagy 2005). After all, some independent evidence is necessary to clearly determine species. Nevertheless, the size- and species-related information could be better achieved by addressing multi-beam systems with a wide variety of frequencies, ranges and resolutions (Simmonds and MacLennan 2005).

The recent development of high-resolution imaging acoustic systems appears to have the potential to far more exploit the advantage of acoustic surveying (Hateley and Gregory 2006). These devices can produce near-video quality images of fish in zero-visibility water (Moursund et al. 2003; Tiffan et al. 2004; Mueller et al. 2006). Currently, among the most significant sonar devices belongs the dual-frequency identification sonar (DIDSON^{TM}) system, originally developed for the US Department of Defense (Belcher et al. 2001; Belcher et al. 2002). This high-frequency multi-beam sonar is equipped with a unique acoustic lens system designed to create high-resolution images. The image resolution of DIDSON is greater than that of conventional sonars, and can be provided at ranges substantially greater than optical devices can achieve (Willis and Babcock 2000; Stoner 2004), thereby effectively bridging the gap between both two approaches.

The DIDSON system collects multi-beam data from a horizontal array of 96 beams (0.3° horizontal by 14° vertical beam-width, www.soundmetrics.com). Although the obtained data are two-dimensional, the close spacing of each beam and effect of shadowing create the illusion of three-dimensionality. This is caused by the reflection of acoustic energy across the entire curved surface of fish body combined with the high resolution of the system. Consequently, the resulting images show the body depth of fish, thereby giving additional visual data which enable us to differentiate targets. Furthermore, as data can be collected at a high rate (4 – 21 frames per second), the display over time can show motion characteristics of targets, such as the undulation of fish body, with a very high temporal resolution (Moursund et al. 2003; Burwen et al. 2007b). This unique feature of video-like acoustic images allows users to observe a background (habitat) and target of interest within the same transmitted pulse. Thus, the obtained data are more straightforward and interpretable than those obtained by other acoustical methods.

As a result, the DIDSON has been established for numerous investigations in both fisheries research and aquatic ecology. The DIDSON has demonstrated its value with obtaining the estimates of fish size and abundance in fish-passage research (e.g. Holmes et al. 2006; Mueller et al. 2006; Burwen et al. 2007a; Maxwell and Gove 2007; Lilja et al. 2008). Moreover, as the DIDSON system does not require phase measurements, sensitive to noise and boundary effects, to determine target position in the beam, it proved to be a convenient method for studying fish behaviour in a close proximity of structures (Holmes et al. 2006; Boswell et al. 2007a) or within confined spaces, such as at hydropower facilities (Moursund et al. 2003). Furthermore, the DIDSON was used for the observation of fish behaviour around passive fishing gears (Rose et al. 2005) and within active gears as trawls (Graham et al. 2004; Handegard and Williams 2008). Last but not least, this technology was applied in the investigation and imagining of fish habitats (Tiffan et al. 2004; Maxwell and Smith 2007).

On the other hand, the great limitation of the DIDSON system is the arrangement of its acoustic field, represented by a horizontal array of single-beam elements. Due to this arrangement, the quality of a DIDSON image is driven by down-range and cross-range resolution, where cross-range resolution refers to the width and down-range resolution refers to the height of the single visualized point

(Burwen et al. 2010). For instance, as a fish moves in the axis orthogonal to the multi-beam array, the movement of the fish in this domain is difficult to detect. Therefore, the best geometry to obtain high-resolution images of fish, which allows us to distinguish the fish from other objects, is when targets are aligned along the 96-beam plane (Moursund et al. 2003). Even so, the quality of the imaged target will be dependent upon its size, body orientation and distance to the transducer.

Furthermore, the vertical position of a fish in the ensonified volume of water is unknown to the user, and target angle or depth cannot be easily measured (Belcher et al. 2001). To achieve this information about a depth location of the target, the DIDSON transducer can be rotated through 90°, so aligning the beam array vertically rather than horizontally (Enzenhofer and Cronkite 2000). A problem is that the users will lose the horizontal resolution of the targets. Also species identification is not always possible and is especially difficult when fish species are morphologically similar (Belcher et al. 2001; Weiland and Carlson 2003). Last, the fish detection ability of DIDSON system is also affected by environment factors (background noise, boundary conditions, and properties of water) as well as other sonar systems (Simmonds and MacLennan 2005). However, the effect of water temperature and turbidity on signal attenuation and scattering, respectively, are usually small at the ranges covered by the DIDSON system.

Despite the flaws mentioned above, the introduction of a multi-beam sonar, especially into horizontal beaming acoustics (Gerlotto et al. 2000; Brehmer et al. 2003; Simmonds and MacLennan 2005), may overcome some problems of the conventional techniques (boundaries interferences, uncertainty of target strength/aspect/fish size conversion, bubble and invertebrate interference). Unfortunately, the current capabilities for handling and processing DIDSON data are limited, not verified, and lack the functionality needed to adequately support the growing number of DIDSON users.

2 Aim of the study

This dissertation thesis was generally focused on improving the methodology of detecting fish with modern sonar systems in the freshwater ecosystem, especially in lakes and reservoirs. The first part of the thesis was focused on the conventional vertical echo-sounding with a particular emphasis on the acoustic dead zone and its practical solution (Paper I, II). The second deals with the orientation of fish in reservoirs' open waters and its consequences for horizontal beaming acoustics (Paper III). The last part is oriented on the accuracy and precision of multi-beam sonars (DIDSON) for gaining biological information about fish (Paper IV). The specific objectives of individual parts were:

I To measure empirically the extent of acoustic dead zone on different sloping bottoms, to verify whether current dead-zone estimation methods on these bottoms are valid there, and potentially to provide recommendations for a practical approach to measure dead-zone heights.

II To explore the fish community within the acoustic dead zone in detail using benthic gillnet, and to affirm whether the height of a fish captured just above the bottom by gillnet can be used to estimate the proportion obscured in the dead zone so that acoustic survey information can be corrected accordingly.

III To testify the assumption of random fish orientation in the lacustrine zone of a reservoir and to compare the orientation of fish in the lacustrine and tributary zones.

IV To investigate the performance of DIDSON in observing fish of various sizes and body aspects at different positions of the acoustic field, and to ascertain how detection probability and length measurement in a DIDSON beam array depend on fish size, spatial orientation and range from the transducer.

3 Results

This doctoral dissertation includes the following four papers - three already published (Paper I - III) and one unpublished (Paper IV). All the papers are appended and referred to in the text by their Roman numerals.

PAPER I

Validation of current acoustic dead-zone estimation methods in lakes with strongly sloped bottoms

Tušer M, Balk H, Mrkvička T, Frouzová J, Čech M, Muška M, Kubečka J (2011): Validation of current acoustic dead-zone estimation methods in lakes with strongly sloped bottoms. Limnology and Oceanography: Methods 9, 507-514

Inland water bodies contain extremely steep-sloped bottoms compared with those typically occurring during marine vertical surveys. These steep bottom slopes can cause high acoustic dead zones, biasing our estimates of living organisms. The studies so far have used the assumption that the first contact between the acoustic wavefront and bottom will be at the point where the radial ray from the transducer is normal to the bottom (90°), which we refer to as the normal ray assumption (NRA). Nevertheless, as acoustic energy dramatically decreases laterally due to the beam's pattern, this assumption may not be fulfilled further from the acoustic axis. It is reasonable to believe that the methods assuming the NRA can fail at quite steep slopes. We installed a calibration benthic gillnet of known height at sites with different bottom slopes, ranging from 12° to 50°. The gillnet's float-line served as a good visible marker above the monitored lake bottom and was successfully used for measuring the acoustic dead-zone height empirically. By comparing the observed and modeled dead zones based on the NRA, we can show that the current methods for their estimation are invalid at quite sloping angles. We conclude that the current dead-zone estimation methods are not always applicable for surveying inland water bodies with extremely steep bottom slopes. Installing a simple calibration net as an off-bottom marker can provide help for in-situ dead-zone measurements.

PAPER II

A simple method to correct the results of acoustic surveys for fish hidden in the dead zone

Tušer M, Prchalová M, Mrkvička T, Frouzová J, Čech M, Peterka J, Jůza T, Vašek M, Kratochvíl M, Draštík V, Kubečka J (2013): A simple method to correct the results of acoustic surveys for fish hidden in the dead zone. Journal of Applied Ichthyology 29, 358-363

In lentic freshwater systems, vertical acoustics may underestimate fish abundance in the acoustic dead zone where fish detection capability is limited. To estimate this bias, the height of fish above the lead-line of a benthic multi-mesh gillnet (1.5 m high) was used to quantify both the vertical distribution of fish near the bottom and the proportion residing within the acoustic dead zone. The study was carried out at the percid-dominated Biesbosch Reservoirs in the Netherlands. Acoustic dead zones were estimated at 7 cm above flat bottoms, and 12–34 cm above 8° sloped bottoms at depths of 5–27 m, respectively. Depending on the habitat, 36 to 75% of the gillnet catch by number was present in the acoustic dead zone, representing 5–51% of the biomass. Near-bottom depths were highly preferred by ruffe *Gymnocephalus cernua*, often used by perch *Perca fluviatilis* and pikeperch *Sander lucioperca*, plus seemingly devoid of smelt *Osmerus eperlanus*. The total amount of fish hidden in the acoustic dead zone was estimated to be 13–39% of the whole water column. The proportion of biomass obscured in the dead zone was lower (1–12%). The conclusion is that undetected fish in the acoustic dead zone can seriously bias density assessment, which can be corrected by concurrent sampling with benthic gillnets.

PAPER III

Fish orientation along the longitudinal profile of the Římov reservoir during daytime: Consequences for horizontal acoustic surveys

Tušer M, Kubečka J, Frouzová J, Jarolím O (2009): Fish orientation along the longitudinal profile of the Římov reservoir during daytime: Consequences for horizontal acoustic surveys. Fisheries Research 96, 23-29

The orientation of fish in a horizontal plane has important consequences for estimating their true size from horizontal acoustic records. The aim of this work was to verify the assumption that during the daytime fish are randomly orientated in the lacustrine zone of the canyon-shaped Římov reservoir and to compare distributions of fish orientation between the lacustrine and tributary (riverine) zones. Fish orientation was acoustically surveyed at fixed locations using the SIMRAD EK 60 split-beam echo sounder (elliptical beam, 120 kHz) with a horizontally aligned transducer. The horizontal aspect (angle between the fish body and the transducer axis) was used to describe their orientation. The conventional single-echo detector (SED) and the cross-filter detector (CFD) were applied. No trend was found along the reservoir when comparing records from four sites processed with the conventional SED. At all sites, most fish appeared to move predominantly in directions perpendicular to the central axis of the acoustic beam, i.e. the side-aspects (90°) of fish prevailed over other aspects. The CFD registered tracked fish several times more often than the SED. In the lacustrine zone the frequency distribution of fish aspect appears very similar when recorded by sonar beams oriented parallel to and across the longitudinal axis of the reservoir (criss-cross-beaming experiment). In the tributary zone, beaming perpendicular to the longitudinal axis of the reservoir revealed a significantly higher proportion of fish moving along the longitudinal axis. Therefore, the assumption of random fish orientation is not applicable in the tributary zones of such reservoirs.

PAPER IV

Evaluation of potential bias in observing a fish by DIDSON acoustic camera

Tušer M, Frouzová J, Balk H, Muška M, Mrkvička T, Kubečka J: Evaluation of potential bias in observing a fish by a DIDSON acoustic camera. (unpublished manuscript)

Standard acoustic experiments with a fish rotating carousel were conducted to ascertain the dependences of fish detection and their length estimates on fish size, spatial orientation and range from the transducer. Cyprinid fish of known sizes and body orientations were deployed in known positions within a DIDSON high-frequency array of beams. All deployed fish were invariably detected in side aspect. Their lengths were accurate only in the center of the beam array, and were underestimated at the edges of it. In addition, no effect of range was observed. However, when the fish were other than sideways, the detection probability and length estimates strongly declined with diminishing fish size and increasing aspect and distance from the transducer. Moreover, we observed that a wider girth of larger fish can shadow the rest of the body, and dramatically decreased the observed length. We show that the determination of the true fish length is challenging and would not be a trivial task, and we raise the question of where to define fish length along echo intensity of fish. We conclude that including the corrections for length estimates allow DIDSON to obtain more reliable and accurate biological information of fish.

4 General discussion and perspectives

Searching for the true picture of fish communities in lakes or reservoirs is not straightforward because it requires a combination of various methods, from netting, via electrofishing to more sophisticated remote observation devices (Kubečka et al. 2009). The common topic of this dissertation is improvements of acoustic methods of fish detection. These approaches have undergone wide development and diversification in past decades (Simmonds and MacLennan 2005). The development of acoustic methodology is eminent especially because of wide spatial coverage and non-intrusiveness of acoustic surveys. It can be anticipated that fish-friendly remote approaches will gain more and more importance in ecological research in future. Our contribution puts several small but important stones on so far empty places in an extensive mosaic of underwater acoustic applications.

4.1 Vertical beaming acoustics

In the first part, I presented two papers focused on vertical beaming acoustics, addressing the issue of fish detection close to the bottom, namely the acoustic dead zone. Paper I verified the assumptions from the previous studies (Kloser et al. 2001; Patel et al. 2009) to estimate the extent of the dead zone on sloping bottoms, which can commonly occur in lakes or reservoirs. By comparing the observed and modeled dead zones, we learned that the current methods for the dead zone estimation are not always applicable for surveying inland water bodies with extremely steep bottom slopes. Paper I showed that the observed dead zone extent in steeply sloping bottoms varied from 2 to 7 m in height, and could be even higher in deeper waters (> 15 m). Although the observed dead zones for the steepest bottom were smaller than those predicted by Kloser et al. (2001) and Patel et al. (2009), obscured ranges of several meters could enormously bias an acoustic quantitative estimate for the whole system of the lake or reservoir. Unfortunately, many researchers working in these waters are generally not aware of this finding. Many lakes or reservoirs in the temperate zone of Central Europe are thermally stratified, and the majority of fish is located below the surface (Čech and Kubečka 2002; Vašek et al. 2004; Prchalová et al. 2008; Prchalová et al. 2009). Thus, the risk of underestimation of fish quantity may not be considered to play an important role in such waters (Bonar et al. 2009; CEN 2010). On the other hand, the dead zone should be taken into account in either the case of non-stratified water bodies (Prchalová et al. 2006; Paper II) or in the situation when the dead zone is occupied by any significant fish population of cold-water species (Schmidt et al. 2005; Baldwin and Polacek 2011). Also in colder periods of the year when the fish tend to live deeper (Penne and Pierce 2008; Amundsen and Knudsen 2009), the importance of the dead zone even in the above waters becomes high.

In the cases of fish populating the bottom habitats, we shall always face the dead zone. Thus, to estimate the overall fish quantity in a lake, we must deduce the extent of obscured water and consequently determine how many fish are hidden in this zone. As the extent of the dead zone is mainly defined by depth and bottom slope, but also the beam pattern (as was pointed out in Paper I), it is convenient to have an idea about bathymetry to identify places with different slopes. In Paper I, we suggested how to proceed to determine areas where the current dead-zone estimation methods fail, and to measure the dead zone empirically by using a benthic gillnet. This procedure helps us eliminate the unknown effect of the beam pattern. Unfortunately, the proposed survey procedure requires studying a lake's bathymetric map. In the cases of lakes with an unknown bathymetry, obtaining slope information directly via acoustic recordings would be of the great importance. The study of Patel et al. (2009) showed how to exploit the capability of a split-beam sonar to measure the bottom slope, but their model considers only the main lobe of a beam pattern. In future, it will be desirable to include the effect of the whole beam pattern into the model and verify it on larger bottom slopes.

Practical approaches to estimate the quantity of fish hidden in the dead zone are often not available or hard to procure in a complicated topography of a lake or reservoir (Kloser 1996; Kloser et al. 1996). The fact that a benthic gillnet is a convenient method to empirically measure the height of dead zone (Paper I) brought us to the idea of utilizing gillnets also as a method for estimating what a share of fish community occur within the dead zone (Paper II). Using gillnet has an advantage of quantifying depth distribution of fish within a particular layer of water (Vašek et al. 2009, Paper II). The resultant distribution is similar to that provided by vertical acoustics, and consequently it can be easily used to correct the acoustic results (Paper II). Moreover, gillnet can provide additional information about size- and species-specific depth distribution of a particular fish population. So far, it is the only way to obtain all the information mentioned within the dead zone in a complicated terrain of lakes or reservoirs.

Nevertheless, one of main disadvantages of gillnetting or trawling is physical interactions with target species. Estimates of fish population hidden in the dead zone are thus based on what we are able to pull out of water. This does not give us a good response to what is actually within that zone at the time of an acoustic survey. The knowledge of fish living close to or within the dead zone is yet poorly understood in lakes and reservoirs. For future studies, there is a great potential in the use of unobtrusive techniques. Obviously, if light conditions in water are acceptable, advanced optical devices can be used to assess species- and size-related depth distribution of a given population within the dead zone (Jones et al. 2012; Rooper et al. 2012). The next approach to assess fish quantity within the dead zone is a high resolution multi-beam sonar (DIDSON), which could be used in deep-water stationary installations or attached to remotely operated underwater vehicles. With its ability of video-like images, this technique could help us identify targets of interest, but also classify different habitats (Tiffan et al. 2004; Maxwell and Smith 2007).

4.2 Horizontal beaming acoustics

In the cases when fish are surface-oriented, horizontal beaming acoustics can be a more appropriate technique to employ. However, it may be difficult to gain reliable results with horizontal beaming surveying, when the detection and size estimation of fish are strongly dependent on target location or body orientation within an acoustic beam (Simmonds and MacLennan 2005; Godlewska et al. 2012). Therefore, some assumptions are required to be applied (Kubečka et al. 1994; Draštík and Kubečka 2005). A problem is that these assumptions are usually devoid of any biological verification, i.e. whether the ecological context of that assumption is suitable for particular system. In Paper III, we started to study fish orientation using fixed locations directly in lacustrine systems. We revealed that fish body orientation in canyon-shaped reservoirs is different between lacustrine and riverine parts of that reservoir.

The orientation of a fish relates to the type of behaviour it is exhibiting, as well as to the environmental conditions where it lives. In rivers, the main stimulus for fish orientation is the river current that align fish along its direction. In lakes, however, fish are oriented highly variable, and the clues for orientation are largely unknown. Reservoirs, intermediate systems between lakes and rivers (Irz et al. 2006), can combine both types of orientation (Paper III). Thus, there must be a transitional zone where fish switch from longitudinal swimming to complete utilization of the available space (random swimming). Nevertheless, our results covered just several sites along the reservoir, and it was only possible to execute the most promising criss-cross beaming approach at one location of the reservoir. More detailed observations of fish swimming directivity patterns would be desirable. However, even the preliminary results have proven that the directivity patterns change along the longitudinal axis of the reservoir. The swimming seems to be much more random in the lacustrine region compared to the tributary (Fig.3). These findings raised many other questions about fish orientation in space and are basis for further research, e.g. how fish orientate in space, what key factors drive their spatial orientation, is the situation similar in all other reservoirs?

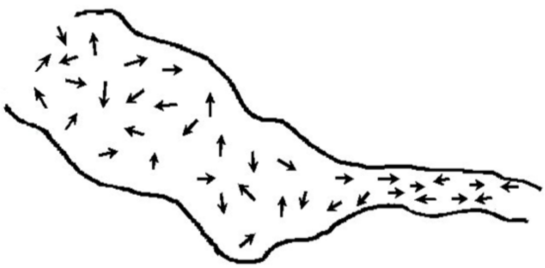

Figure 3. Hypothetical image of fish movement directivity (arrows) in a narrow tributary and wide lacustrine parts of a reservoir based on the finding of the Paper III.

Moreover, in our study we found out that detecting fish with horizontal beaming technique may encounter difficulties in some environments due to the fish aspect dependency upon the mode of observation. The more fish moves toward or outward the transducer, the greater possibility it will not be detected (Paper III). This is the reason why the interpretation and classification of acoustic data in conventional sonar systems becomes often challenging and requires extensive experience and novel complex analysis (Holmes et al. 2006; Jech and Michaels 2006; Boswell et al. 2007b; Jech and Michaels 2007). The situation improved with the introduction of new methods for detecting and processing the targets in low signal-to-noise environments, especially with the cross-filter approach (Balk and Lindem 2000; Balk et al. 2009). Advanced filtering with the cross-filter detector successfully demonstrated that it can help to detect more fish with lower signals (Rakowitz et al. 2009; Paper III). However, even with the use of this cross-filter the sonar failed to detect some targets in less reflective aspects. To improve our received acoustic data, even more advanced filtering methods are required. However, this technology will always be limited with the resolution ability of the device itself. Another solution is the use of stationary upward-looking sonar, where fish are monitored from below, and thus it is less affected by low signal-to-noise ratios. However, the disadvantage of this method is that it covers only small area or volume of surface water compared to that of horizontal beaming and therefore is convenient only for deeper waters.

The main spatial limitation of our study was the fact that we were able to track fish distribution only with fixed-location observations. Both with horizontal and vertical (upward-looking) fixed location approach it is necessary to sample one spot typically for at least several hours. It would be very useful to extent the aspect and directivity measurements of near-surface fish on mobile surveys. The first possibility is the application of several horizontal beams from different directions, similarly as it was conducted by the crisscross beaming experiment (Paper III). The comparison of the signals from independent directions may be able to provide the key information about the orientation of given targets. This could be a good and much-needed way to achieve orientation information for a mobile survey. Next, far more promising techniques are high resolution multi-beam systems, e.g. the DIDSON technology (Moursund et al. 2003; Hateley and Gregory 2006). The greatest advantage of DIDSON is that it can provide video-like images, which enable us to determine directly both size- and angular-related information about the fish.

4.3 Multi-beam acoustics

Paper IV represents the results of a standard experiment with fish rotating carousel in order to verify the reliability of fish detection and length estimates that can be achieved by a DIDSON acoustic camera. For this study, we deployed fish of typical sizes and species occurring in European lakes and reservoirs, i.e. smaller fish than those occurred in spawning-migration monitoring studies (Burwen et al. 2007a; Burwen et al. 2010; Mueller et al. 2010). In the majority of earlier length-measuring studies, the minimal size of fish included was substantially larger than 20 cm (Baumgartner et al. 2006; Burwen et al. 2010). In our experiments, DIDSON sonar was capable to observe all the fish deployed, ranging from minimal size of 10 cm to maximal size of more than half a meter in length. The detection probability and length estimates of the fish, however, markedly depended upon their size, body orientation and range to the transducer.

The results from that study confirmed that the best data in high-frequency mode are achieved when the fish body is situated in near-side aspect, i.e. right across 96-beam horizontal array (Moursund et al. 2003). However, we observed that the accuracy of fish length slightly declined to the edges of the DIDSON's beam array. This effect is most likely caused by the lower energy or by slightly wider beam spacing here (Fig. 4, Ed Belcher pers. comm.). The reliability of detection and length estimate also dramatically declined with decreasing fish size and increasing range, when fish orientation was altered to the transducer. In this respect, we also observed that a various girth along the fish body could cause the acoustic "shadowing" of a target part, thereby enormously shorten length of the particular fish image.

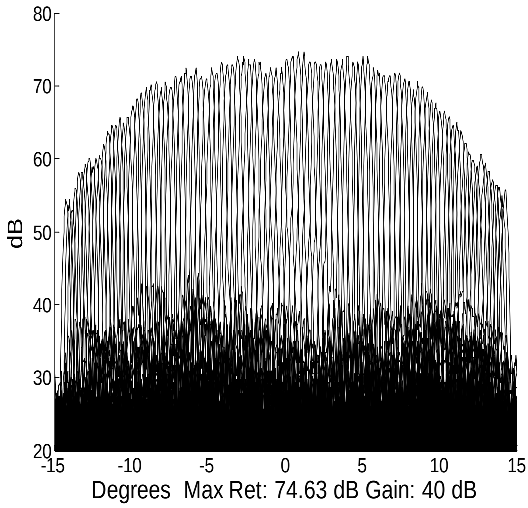

Figure 4. Intensities of a 96-beam array of DIDSON (provided by MacArtney A/S).

Generally, we found out that the ability of DIDSON multi-beam sonar system to detect fish is limited when fish are smaller bodied and are oriented to the transducer with their heads or tails. Thus, the results from DIDSON can be biased in water systems where fish community consists of a wide variety of sizes and fish moves in any direction. For that reason, the DIDSON sonar cannot be a convenient technique for answering the question of various fish orientation in canyon-shaped reservoirs (as have been described in 4.2).

To enhance the performance of DIDSON unit, we should keep in mind that the DIDSON images are still acoustic-based. The quality of these images (or signal-to-noise ratios) could be improved by advanced filtering, such as the cross-filter detector (Balk and Lindem 2000; Balk et al. 2009) or adopting video enhancement techniques (Kim et al. 2006; Kim et al. 2008). Nevertheless, it would be far more promising to focus first on better defining the individual beams or their spacing. Precisely, a vertical dimension of the individual beams is regarded as the greatest disadvantage of DIDSON because they act same as a single beam. Thus, the vertical position of a fish is unknown within the monitored volume of water, and target tilt angle or depth cannot be easily measured (Belcher et al. 2001). Defining a better energy pattern or vertical coordinates of observed target could increase the quality of received acoustic information.

Despite the restrictions mentioned above, DIDSON system is still capable of overcoming some problems of conventional techniques. Moreover, due to a high demand for high-resolution acoustic systems, new concepts are being introduced at a very rapid pace, such as IRIS, a younger brother of DIDSON (www.soundmetrics.com), or other types of multi-beam sonars. Their systems of acoustic field are more complicated, and there will be a need to verify the performance of these new systems under diverse environmental conditions. Hopefully, the problem of quantitative fish sizing and counting in the open water will be handled more successfully with newer generations of high frequency multi-beam systems.

5 Conclusions

Obtaining reliable results for all crucial habitats in freshwater ecosystems still represents a significant challenge, requiring a combination of diverse approaches. The thesis presented herein unifies various acoustic techniques that have the potential to detect fish, with the aim to gain the more accurate picture of fish community living in freshwater ecosystems.

In the first part, we prove that the current dead-zone estimation methods are not applicable on steeply sloping bottoms. Consequently, we recommend a practical solution how to conduct an acoustic survey in water systems with a complicated bathymetry.

In the second part, we sustain that vertical beaming acoustics underestimates the quantity of bottom-dwelling fish community. Hence, we offer the practical approach to examine these benthic habitats, where neither acoustic nor trawl survey can sample an appropriate fish community. By gillnetting in benthic habitats, we can obtain the desired vertical distribution of fish species in the acoustic dead zone, and consequently correct the biased acoustic results accordingly.

Further, we conclude that the assumption regarding random fish orientation for horizontal beaming acoustic is not applicable in the tributary of riverine reservoirs. This premise is based on the discovery of a varying orientation of surface-oriented fish along the reservoir. We affirm that fish randomly move in the lacustrine zone, whereas in the riverine zone their behaviour is likely still stimulated by some current, or a longitudinal shape of flooded valley, which align them along the banks.

In the last study, we demonstrate that the performance of a DIDSON multi-beam sonar in observing fish lose its quantitativeness when the fish are smaller-bodied and are oriented close to head or tail aspects. To solve this problem we propose the relationships to correct or to estimate the risk of false observations.

In summary, we analyzed selected features of the currently available acoustic methods for the study of fish community, and tried to sufficiently understand their applicability. The results presented in this thesis will allow us to enhance our monitoring research and will help us carefully design and analyze acoustic surveys in search for the true picture of fish communities. Last but not least, these findings can provide a sort of feedback to sonar manufacturers for future developments.

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Research papers

I

Paper I

Validation of current acoustic dead-zone estimation methods in lakes with strongly sloped bottoms

Tušer M, Balk H, Mrkvička T, Frouzová J, Čech M, Muška M, Kubečka J

Limnology and Oceanography: Methods 9, 507-514 (2011)
(IF_{2011} = 1.535, 5-year IF_{2011} = 2.010)

LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 9, 2011, 507–514

Validation of current acoustic dead-zone estimation methods in lakes with strongly sloped bottoms

Michal Tušer[1,2], Helge Balk[3], Tomáš Mrkvička[4], Jaroslava Frouzová[1], Martin Čech[1], Milan Muška[1], Jan Kubečka[1,2]*

[1]Institute of Hydrobiology, Biology Center of the Academy of Sciences of the Czech Republic, Na Sádkách 7, 370 05 České Budějovice, Czech Republic

[2]Faculty of Science, University of South Bohemia, Branišovská 31, 370 05 České Budějovice, Czech Republic

[3]Department of Physics, University of Oslo, P.O.Box 1048, Blindern, 0316 Oslo, Norway

[4]Faculty of Economics, University of South Bohemia, Studentská 13, 370 05 České Budějovice, Czech Republic

Abstract

Inland water bodies contain extremely steep-sloped bottoms compared with those typically occurring during marine vertical surveys. These steep bottom slopes can cause high acoustic dead zones, biasing our estimates of living organisms. The studies so far have used the assumption that the first contact between the acoustic wavefront and bottom will be at the point where the radial ray from the transducer is normal to the bottom (90°), which we refer to as the normal ray assumption (NRA). Nevertheless, as acoustic energy dramatically decreases laterally due to the beam's pattern, this assumption may not be fulfilled further from the acoustic axis. It is reasonable to believe that the methods assuming the NRA can fail at quite steep slopes. We installed a calibration benthic gillnet of known height at sites with different bottom slopes, ranging from 12° to 50°. The gillnet's float-line served as a good visible marker above the monitored lake bottom and was successfully used for measuring the acoustic dead-zone height empirically. By comparing the observed and modeled dead zones based on the NRA, we can show that the current methods for their estimation are invalid at quite sloping angles. We conclude that the current dead-zone estimation methods are not always applicable for surveying inland water bodies with extremely steep bottom slopes. Installing a simple calibration net as an off-bottom marker can provide help for in-situ dead-zone measurements.

The reliable detection of fish and other aquatic animals close to the bottom of water bodies is a persistent theoretical and practical problem in estimating their abundance by hydroacoustic methods. Proper detection of fish fails within the so-called acoustic dead zone, where the targets cannot be distinguished from the bottom (Mitson 1983; Ona and Mitson 1996). If the bottom is sloping, the dead zone generally increases in volume because there is a larger range of depth in the beam from the point of the first contact to its edges. Such steep bottom slopes commonly occurring in lakes and reservoirs can cause very high dead zones, thereby reducing our observed water volume and biasing our estimates.

*Corresponding author: E-mail: tuser@centrum.cz

Acknowledgments

The study was supported by the project nr 206/07/1392 of the Grant agency of the Czech Republic and by the project CZ 0091 from Iceland, Liechtenstein, and Norway through the EEA Financial Mechanism and the Norwegian Financial Mechanism. We would like to thank to the reviewer for valuable comments.

DOI 10.4319/lom.2011.9.507

The determination of the extent of a dead zone is straightforward on a hard bottom perpendicular to the beam when the bottom echo creates a distinct peak. The echo of a sloping bottom is more diffuse in the range domain, which complicates the determination of its true depth. The bottom record is dependent upon the transducer's beam pattern and bottom properties (Mitson 1983). Moreover, most studies have only considered the central beam with a fixed nominal angle for dead-zone height (DZ) estimates, yet the beam pattern is complex and unique for each transducer. Modeling the precise theoretical DZ would not be a trivial process and would have to be redone for each transducer.

The minimum height at which fish can be theoretically detected above the bottom is determined by the transmitted pulse length and beam angle (Mitson 1983). This space was defined as a "definite" dead zone, extending to a height of $c \times \tau/2$ above the bottom, where c is the speed of a sound wave in meters per second, and τ is the duration of the transmitted pulse in seconds. This height refers only to the center of the beam. Because the front surface of the transmitted pulse is spherically curved relative to the bottom, the minimum detection height increases from the point of contact with the bottom to the outer edges of the beam.

In terms of acoustic pulse and its sampling volume, Ona and Mitson (1996) looked in detail at fish detection near a flat horizontal bottom with a stable transducer, developing equations for estimating the effective dead-zone volume below the spherical wavefront. Furthermore, they suggested how to extrapolate fish density within the acoustic dead zone using that obtained outside but adjacent to that zone. This study considered only the case of a flat horizontal bottom. However, on the sloping bottom, the dead-zone volume is greater and increases in correlation with the bottom slope.

As regards the issue of the sloping bottom, Kloser et al. (2001) have deduced a theoretical dead-zone computation in the case of pulse reflection from the bottom with a certain slope. They referred to it as the theoretical worst case of DZ, but also mentioned that this height in practice will be something less because of the beam's energy pattern. The study of Patel et al. (2009) extended the calculations of effective acoustic dead zone volume from Ona and Mitson (1996) for a destabilized transducer without motion compensation, or in other words, where the bottom fails to be flat but sloped to the transducer's acoustic axis. The proposed approach determines how to measure the bottom slope directly from the phase information of received echoes, and subsequently estimate the dead zone.

However, these studies assume that the first contact between the acoustic wavefront and bottom will be at the point where the radial ray from the transducer is normal to the bottom (90°). At this moment, the first bottom echo is expected to appear on the echogram. We refer to this as the normal ray assumption (NRA). For an omni-directional transducer, the NRA will always be correct. For a directional transducer, however, the detection of the bottom strongly depends on the energy regime of the beam pattern, when the amount of off-axis energy can dramatically decrease laterally. The NRA is applicable for most marine vertical surveys, which are conducted above a slightly sloping seafloor (<15°). However, no one has ever tested or worked with sloped bottoms as steep as those encountered in canyon-shaped lakes. It is reasonable to believe that the methods based on NRA will be invalid for these extremely steep sloping bottoms.

Also, a practical approach to addressing the dead zone is lacking (Kloser 1996; Kloser et al. 1996). Until now, it is possible to reduce this zone by vertical sounding with the most narrow beam possible, short pulses, or a deep-towed transducer in proximity to the bottom (Kloser 1996; Scalabrin et al. 2009). Furthermore, in current studies important benthic fish species are mainly monitored and estimated by the combination of acoustics and benthic trawling (e.g., Godø 1990; Gauthier and Rose 2005; von Szalay et al. 2007; Mello and Rose 2009). A deep-towed transducer and benthic trawling, however, are of impractical use in water bodies with rugged topography or containing many obstacles (Cooke et al. 2003).

In this article, we address the problem of dead zones occurring on steeply sloping bottoms. The extent of the near-bottom dead zone on the acoustic axis is empirically measured on different sloping bottoms, ranging up to 50°, and the results are compared with estimates based on modeling using NRA. This study aims to provide recommendations for a practical approach to measure dead-zone heights.

Theory

The mechanics of an acoustic wavefront striking a sloping bottom are shown in Fig. 1. If spherical spreading is assumed, the pulse will spread uniformly away from the transducer. The acoustic signal strikes perpendicularly to a sloping bottom (γ = 90°) at the closest distance from the transducer (R). The off-axis angle of this first striking radial ray (θ) equals the angle of the bottom slope (β). At this time, the first bottom echo is observed. As that signal continues, there will be a time delay between the central and outer parts of the beam striking the bottom. The time delay is converted into a distance that is referred to as the DZ. In addition to this parameter, the half-pulse length must be considered (Mitson 1983). The steeper the bottom slope, the more diffused bottom record and higher dead zone due to the larger range of depth in the beam from the point of contact to its edges. The situation presented in Fig. 1 shows a theoretical worst case scenario of a dead zone of an omni-directional transducer. As deducted by Kloser et al. (2001), the geometry of Fig. 1 leads to the result of the DZ:

$$DZ_{NRA} = \frac{R_B}{\sin\left(90-\beta\right)} - R_B \qquad (1)$$

or can be expressed as

$$DZ_{NRA} = R_B \times \left(\left(\frac{1}{\cos\beta}\right)-1\right) \qquad (2)$$

where R_B is the depth of the first bottom-reverberation echo peak (corresponding to R in Fig. 1), and β is the bottom slope. Thus, by increasing the slope β results in increased DZ. This model assumes that the incident angle γ is perpendicular to the bottom.

A directional transducer, however, concentrates energy into the main central beam as a function of its pattern, yielding a cone-like rather than omni-directional pulse spread. In fact, the transducer beam pattern determines how much energy, there will be at any point in the spherical wavefront. The mechanics of the DZ based on an energy-dependent wavefront striking a sloping bottom is shown in Fig. 2. As the transmitted energy is low at the outer parts of the beam that represents the closest distance between the transducer and bottom, the energy of the reflected ray cannot exceed the bottom detection threshold. Next, the first bottom echo will come from a radial ray closer to the main axis at the point where the reflected energy of a particular ray exceeds the detection threshold (Fig. 3). The off-axis angle of that ray (θ), called an effective beam half-angle in this case, will be something less

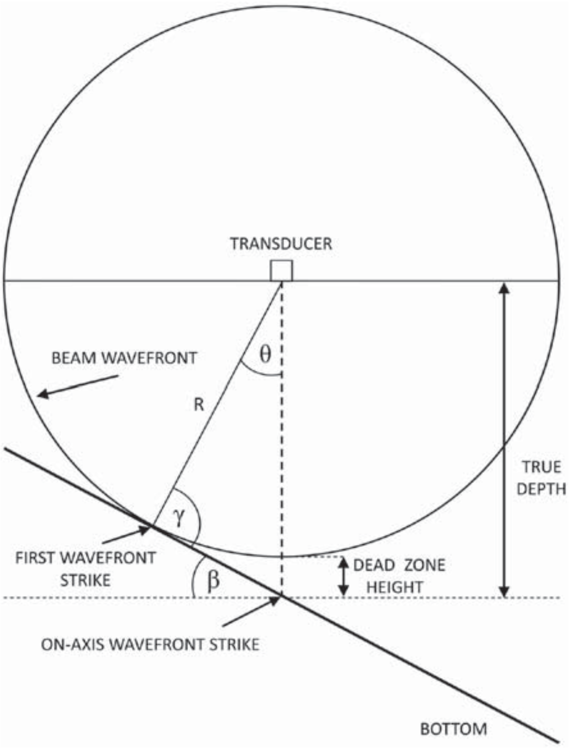

Fig. 1. Mechanics of DZ based on a spherical wavefront striking a sloping bottom. The first bottom echo is observed at the closest distance (R) from a transducer when the wavefront first strikes the bottom. According to these mechanics, the incident angle (γ) of the first striking ray is normal to the bottom (90°) and the off-axis angle of the first radial ray striking the bottom (θ) equals the slope angle of the bottom (β). This occurrence is referred to as the NRA.

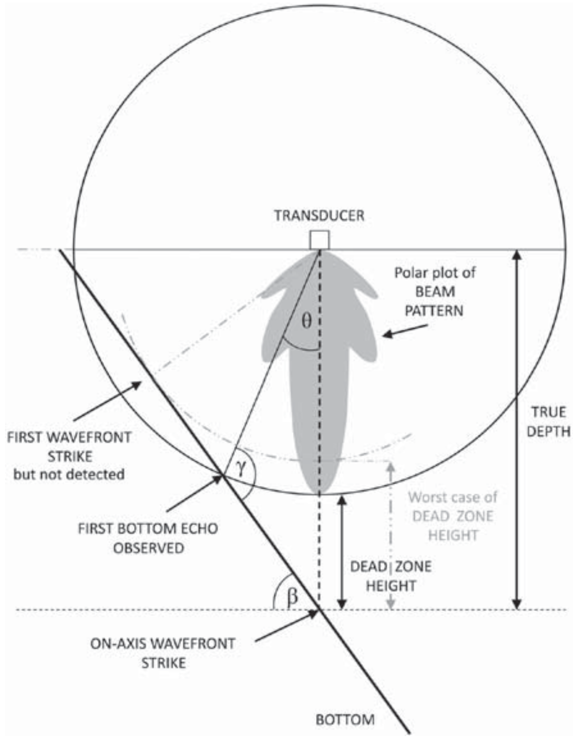

Fig. 2. Mechanics of DZ based on an energy-dependent wavefront hitting a sloping bottom with a polar plot of the beam pattern depicting the transducer energy as a function of the angle. The first bottom echo is not observed at the point where the distance between the bottom and transducer is closest as supposed by the NRA. Due to insufficiency of the transmitted energy at the outer parts of the beam, the reflected energy cannot exceed the detection threshold. The bottom is observed first at a further distance from the transducer, once there is enough energy to exceed the detection threshold. The effective beam half-angle (θ) of the radial ray decreases to less than the slope angle (β). The incident angle (γ) of that radial ray is not normal but greater than to bottom (γ > 90°). As the first bottom echo is observed closer to the place of the on-axis wavefront strike, the DZ becomes smaller than the theoretical worst case calculations according to the NRA.

than the angle of the actual bottom slope (β). The incident angle (γ) of the radial ray will not be normal but obtuse to the bottom. Thus the bottom will be observed at a further distance from the transducer, but closer to the place where the wavefront from a vertical aligned transducer strikes on-axis. Therefore, the DZ will be less than our theoretical worst case calculations according to the NRA (Fig. 1).

If we need to derive the DZ when supposing that the incident angle γ could be any to the bottom, but including the beam angle θ where the first bottom echo can be observed, then based on the geometries of both Fig. 1 and 2, using the Law of Sines and when γ = 90 – θ + β leads to

$$\frac{R_B}{\sin(90-\beta)} = \frac{R_B + DZ}{\sin(90-\theta+\beta)} \tag{3}$$

thus the DZ can be expressed as

$$DZ = R_B \times \left(\frac{\sin(90-\theta+\beta)}{\sin(90-\beta)} - 1 \right) \tag{4}$$

and subsequently modified to the result:

$$DZ = R_B \times \left(\frac{\cos(\theta-\beta)}{\cos\beta} - 1 \right) \tag{5}$$

In a lake, two situations may occur depending on the beam pattern or the effective beam half-angle (θ) and bottom slope (β). On slopes that are smaller or equal to the effective beam half-angle (β ≤ θ), the mechanics of DZ will be the same as in Fig. 1 because there is enough energy to exceed the detection

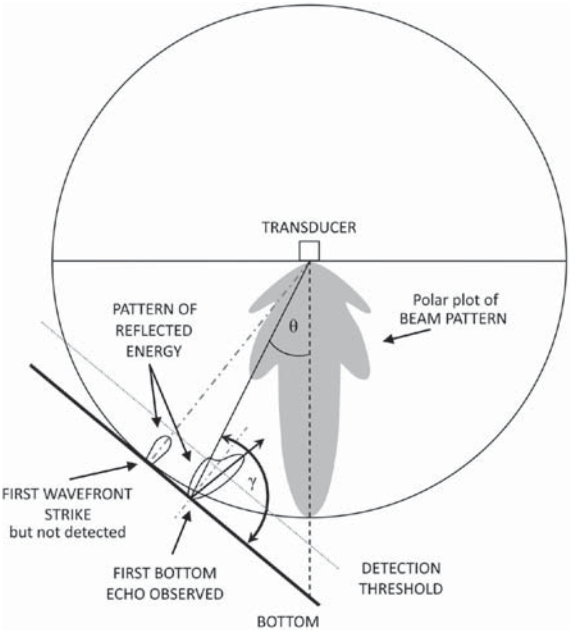

Fig. 3. A schema depicting why the NRA does not work on a sloping bottom. As the transmitted energy is low at the closest distance from a transducer because of the beam pattern, the energy of the reflected ray cannot exceed the detection threshold. The first bottom echo will be observed when the reflected energy exceeds that threshold. At that point, the incident angle of the radial ray will not be normal but greater than to the bottom ($\gamma > 90°$). The effective half-beam angle (θ) means the off-axis angle when the first bottom echo is observed.

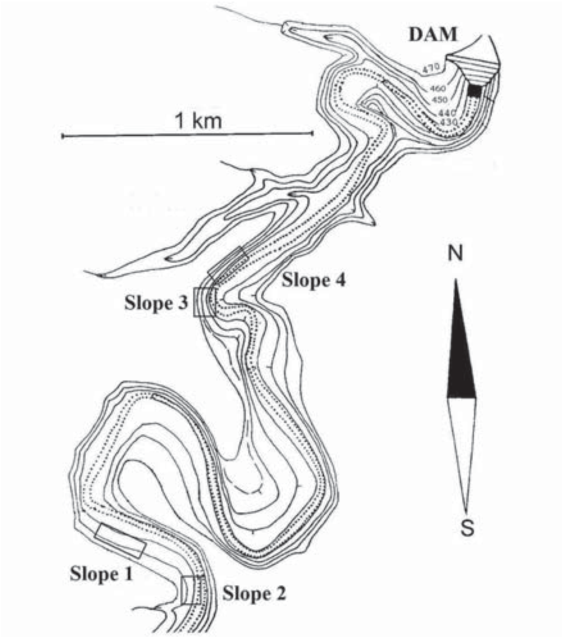

Fig. 4. A bathymetric map shows the lower part of the Římov Reservoir with 10-m isobaths. The highest contour (470 a. m. s. l.) represents the maximum lake level, which is 5 m above that recorded during the surveys. The rectangles indicate the localities where echo soundings of the benthic gillnet were carried out.

threshold in that part of the beam. These mechanics stop working when the bottom slope becomes larger than the transducer's effective beam half-angle ($\beta > \theta$), however. In this situation, the mechanics of DZ will work as in Fig. 2. The transmitted energy in the outer parts of the beam will be insufficient for observation of the bottom until there is enough transmitted energy in the beam close to the main axis to achieve the sufficient amount of reflected energy exceeding the detection threshold (Fig. 3). Therefore, the theoretical DZ estimates according to Ona and Mitson (1996) as well as Kloser et al. (2001) can be reduced on steeper bottom slopes as the amount of off-axis energy decreases.

Methodology

Study areas

The measurement of DZ was carried out at the canyon-shaped Římov Reservoir in the Czech Republic (48°49.800'-48°50.000'N, 14°28.500'-14°28.850'E). According to a bathymetric map (1:50,000) produced before the flooding of the reservoir, four areas with the same bottom slope and parallel isobaths were selected (Fig. 4). The mean bottom slopes of those areas were calculated from a digital version of the bathymetric map using the ArcGIS software.

Hydroacoustic equipment

All localities were acoustically surveyed from a boat with a specially-made transducer holder (Kubečka and Wittingerová 1998). The used hydroacoustic equipment was a circular transducer ES120 7G with 7° nominal beam angle (half-power angle to –3dB points) controlled by the SIMRAD EY 500 scientific split-beam echosounder. The echosounder system worked on a 120 kHz frequency with a 0.1 ms pulse duration (τ) and was calibrated using a 33.2 mm tungsten-carbide sphere (Foote et al. 1987).

Empirical data collection and analysis

The empirical method of dead-zone measurement was based on the calibration benthic gillnet of known height used as a measuring tool. The gillnet was installed at different localities with varying depth and slope and then acoustically surveyed. This gillnet was 1.7 m high (as measured by a diver) and 100 m long. It was installed at a certain depth contour along the isobaths with a given slope. The depth contour was located by keeping of the same range from shore as well as following an echosounding record. After installation, the gillnet was acoustically recorded repeatedly during passages perpendicular to its direction.

The acoustic data were analyzed with the Sonar5-Pro post-processing program (Balk and Lindem 2006).

The gillnet float-line made a strong echo and was thus used as a marker for the 1.7 m distance from the bottom. At each echogram, a record of the float-line echo was found due to its characteristic mushroom-like shape (Fig. 5). The float-line center was determined using the Sonar5-Pro program oscilloscope tools, which finds the maximum intensity signal indicating this location. The volume backscattering coefficient (S_V) of the gillnet float-line was between –5 and –15 dB. Such a target was discernable both on a slightly sloped bottom (Fig. 5a), where the bottom echo was of similar magnitude (–5 dB) but separated by the gillnet height, and a steeply sloping bottom, where the maximum bottom echo amplitude was usually about –12 dB (Fig. 5b). At each float-line record, the ping with maximum of S_V was only included into analysis as the exact float-line center.

The base equation describing the empirically measured height of the dead zone (DZ_{EMP}) was defined as:

$$DZ_{EMP} = D_{TRUE} - R_B = D_{FLO} + GH - R_B \tag{6}$$

where D_{TRUE} is the depth of the true bottom, and R_B the depth of the start of the first bottom-reverberation echo peak (Simmonds and McLennan 2005, Fig. 5.21). D_{TRUE} was calculated from D_{FLO} the actual depth of the gillnet float-line echo peak and GH the gillnet height (1.7 m). The final parameter R_B was determined as a sudden increase of reverberation signal to more than – 60 dB (Fig. 5), which was consistent in the same range in successive pings (Kloser 1996; Simmonds and MacLennan 2005). Thus, the DZ was experimentally measured as the distance between the true and acoustic bottom.

Comparison of the observed dead zones with the model based on the NRA

The model based on the NRA and presented here in Eq. 2 was compared with the empirical data. For this study, the theoretical minimum dead zone - c×τ/2 (Mitson 1983) was not included, but should be added when estimating the total dead zone. Thus, we statistically assume the following model:

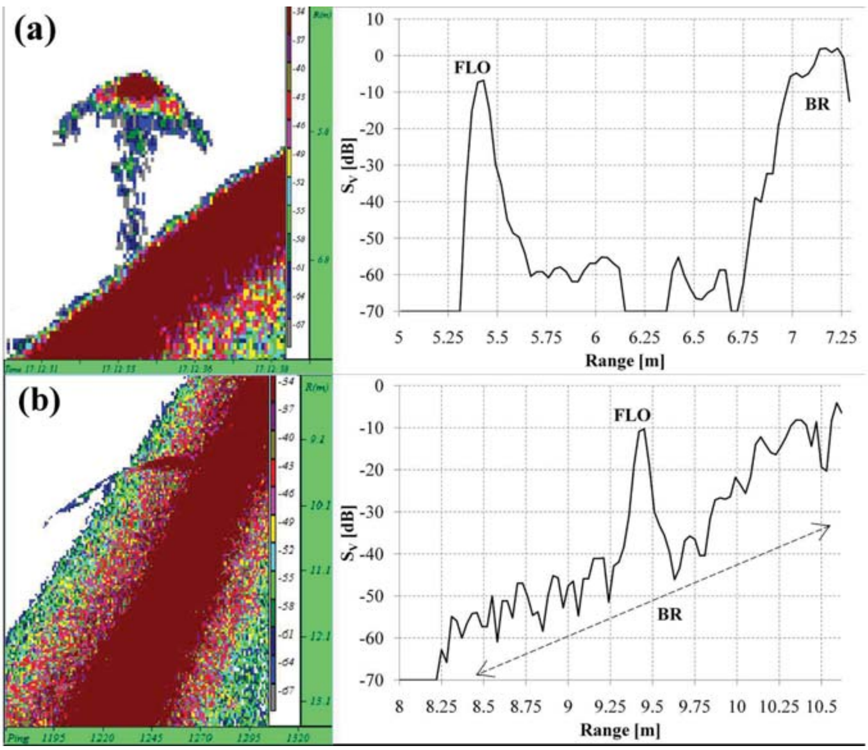

Fig. 5. Mobile survey echograms of the benthic gillnet with a ping-based oscilloscope display of gillnet float-line (FLO) and bottom reverberation (BR) on (a) slightly sloping bottom and (b) steeper sloping bottom at the Římov Reservoir. The mushroom shape of the float-line record is caused by the records of float-line at the margins of the beam (inverted V). S_V signifies the volume of the backscattering strength in decibels.

Table 1. Descriptive statistics of the measured slopes from the digital bathymetric map generated with the ArcGIS software.

Locality	Valid N	Mean	Standard error of mean	Variance	Standard deviation
Slope 1	16436	12.005	0.017	4.598	2.144
Slope 2	15878	19.397	0.028	12.105	3.479
Slope 3	5232	40.095	0.067	23.211	4.818
Slope 4	2531	49.553	0.082	16.831	4.103

$$DZ_i = R_{B_i} \times \left(\left(\frac{1}{\cos\left(\beta + e_i\right)} \right) - 1 \right) \tag{7}$$

where only one error e_i in the model occurs, which is caused by the method of measurement of β. The error in the measurement of R_{B_i} is small and is therefore omitted. Thus, we can rewrite the model into the form:

$$\cos^{-1}\left(\frac{DZ_i}{R_{B_i}} + 1 \right)^{-1} = \beta + e_i \tag{8}$$

where the sample of data are on the left side of the formula. If this form of the model is valid, then each datum will correspond to the slope at a given location according to the NRA. The average of those slopes must be equal to the slope β_0, which was measured from the digital map using the ArcGIS software. Thus we can test by one sample *t* test whether the mean of sample slopes is equal to the slope β_0. If *t* test rejects the hypothesis H0: $\beta = \beta_0$, then the model would be invalidated for the observed DZ and R_B.

In the case of rejecting H0, the alternative hypothesis (H1) predicts the results from the experiment, suggesting the model in Eq. 5 on the assumption that the actual slope is higher than the effective beam half-angle ($\beta > \theta$). Then the observed data worked according to the mechanics depicted in Figs. 2 and 3.

Assessment

Measurements of the dead zone

Dead-zone measurements were carried out at four localities, the slopes of which were on average 12°, 19°, 40°, and 50°, respectively, as measured from the digital bathymetric map (for more details, see Table 1). On those slopes, the benthic gillnet was installed at different depths and subsequently recorded acoustically. From the acoustic signals of the benthic gillnet float-line, the empirical DZ was calculated according to Eq. 6. The observed DZs are shown as points on Fig. 6, depending both on the bottom depth and slope. The former had little influence upon slightly sloped bottoms (12° and 19°, respectively), not exceeding one meter in DZ for the given range of depth (5–19 m). Nevertheless, on steeper bottom slopes of 40° and 50°, the size of the dead zone markedly varied between 2–4 and 4–7 m in height, respectively, even for partial ranges of the depth.

Comparison of observed and modeled dead zones

According to Eq. 2, the theoretical DZs were calculated for the measured slopes and ranges of surveyed depths (lines in Fig. 6), showing how the model fits with the observed DZs. To compare the observed and modeled dead zones, the observed values of DZ and R_B were used in Eq. 8 to obtain the theoretical mean slopes when the NRA is correct. These slopes for the observed DZs were on average 12.8°, 19.8°, 40.9°, and 43.7°, respectively. We used the *t* test for comparing those values from Eq. 8 with the measured slopes from the bathymetric map. Because the sample of data seems to follow normal distribution (for three of the four samples of slopes *P* = 0.19, 0.006, 0.62, 0.14), the application of *t* test is adequate here. The *t* test results are summed up for all slopes in Table 2. The difference between observed and modeled dead zones was not observed at the first three of the four localities (12°, 19°, and 40°). A significant difference was found at the last locality, however, where the data differed by about six degrees of the bottom slope ($t = -12.872$, $P = 10^{-6}$). Such a difference in slope angle is not very significant in terms of measuring the bottom slope; however the DZ can be altered by about 2 m due to this variation. The 2-m difference in DZ is quite significant in such shallow waters. We thus conclude that NRA is inappropriate for applications with bottom slopes of 50°, showing that the effective beam half-angle occurs between 40°–50°.

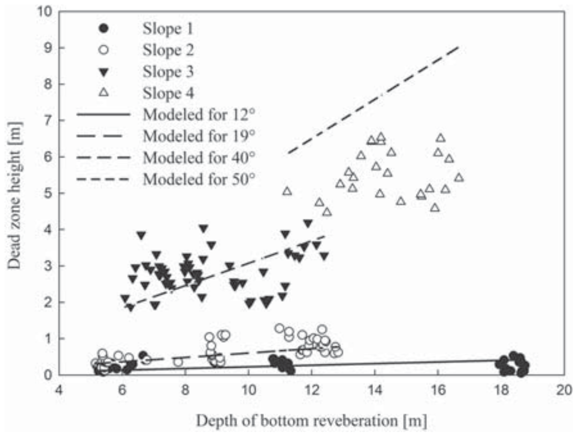

Fig. 6. Empirically measured DZs (points) compared with modeled dead zone for given slopes of the four localities (lines).

Table 2. Results of the *t* tests of single means versus reference constants of the observed slopes at the studied localities.

Locality	Mean	Standard deviation	N	Standard error of mean	Reference	t-value	df	P
Slope 1	12.753	4.236	42	0.654	12.005	1.144	41	0.259
Slope 2	19.799	3.541	62	0.450	19.397	0.896	61	0.374
Slope 3	40.889	3.938	61	0.504	40.095	1.575	60	0.121
Slope 4	43.658	2.335	26	0.458	49.553	–12.872	25	0.000

Discussion

In the irregular river valley of the Římov Reservoir, it is not easy to find well-defined bottom slopes at different depths throughout the whole locality. The steepest slope was located only in a deeper part of the reservoir than most of the more level slopes in our data set. However, even with this data set, there is an apparent dramatic increase of the dead zone in correlation to the depth and slope angle. Thus, all researchers working in canyon-shaped waters should be aware of this finding.

Considerable data variation at steeper slopes could be caused by the rugged bottom in the chosen localities. It was difficult to ensure that the 100-m-long gillnet would be installed at the same depth and slope throughout its whole length. Although equal-sized slope areas were chosen from a bathymetric map of the Římov Reservoir, this procedure fails to avoid small bottom depressions at those areas. The rugged topography of the reservoir bottom may cause that some part of the gillnet could sink into such a depression.

In spite of the inaccuracy of slope estimation, the advantage of using the benthic gillnet of known height enabled us to estimate the true depth of the bottom from acoustic echograms, as the gillnet float-line served as good visible marker in large dead zones. Furthermore, the method showed that it is possible to measure the dead zone resulting from even the steepest slopes (in our case up to 50°).

In marine situations, dead zones can be as high as several tens of meters even on a relatively flat bottom (e.g., Kloser 1996; Aglen et al. 1999; Kloser et al. 2001). In most freshwater conditions, the underestimation of the fish stock due to the dead zone is usually not considered to be significant (Bonar et al. 2009; CEN 2010). The extent of the dead zone in steeply sloping bottoms ranged from 2 to 7 m in height and can be even higher in deeper waters. This phenomenon can have an impact on the data from the acoustic survey of fish living near the bottom. Fortunately, in stratified reservoirs in Central Europe, very few fish live deeper than 5 m during the vegetation season (April-October, Kubečka and Wittingerová 1998; Vašek et al. 2004). The underestimation of fish stock would not be significant in these waters. The problem arises in lakes without stratification, where fish occur in the whole water column. In this case, the herein described method to estimate dead zones at steeper slopes and also fish biomass can prove to be useful or even required.

According to our results, dead-zone estimation methods based on the NRA are not always applicable for surveying inland waters bodies with extremely steep bottom slopes. The effective beam half-angle for a transducer will be difficult to estimate because it depends both on its pattern as well as the bottom reflection pattern.

The effect of the beam pattern is likely to be more important than reflection patterns from different bottom types. If we assume that the bottom echo intensity from a bottom vertical to the acoustic axis is around 0 dB and that a S_V threshold of –60 dB is applied, then this bottom echo will disappear below the threshold at a slope angle corresponding to that where the beam pattern is reduced to the intensity corresponding to the threshold. This off-axis energy drop could indicate a good candidate for the effective beam half-angle. As an example, a change in bottom echo of 20 dB will only cause a change in the effective beam half angle of 2°–3°, which is due to the rapid decrease of the beam intensity at the edges of the acoustic lobe.

In terms of bottom types and their acoustic reflection patterns, the studied reservoir is a flooded deep valley with a former riverbed and rock-bound steep slopes. In small slopes, thin layers of clay soil may occur, whereas steeper slopes of the reservoir are comprised from rocky outcrops combined with stony rubble and former tree stumps, as observed by scuba diving (M. Čech pers. comm.). Any soft sediment on such slopes is usually washed away by water movements (Morris and Fan 1997) and the resulting sloping bottom becomes a hard and rough reflector reflecting echoes from any incident angle (Medwin and Clay 1998). However, the irregular combination of rocks, stones, and tree stumps made this reflection very unpredictable. With our current limited knowledge, the in situ measurements of known calibration gillnet described here can circumvent the complexity of reflection patterns, roughness, and different transducer beams.

Recommendations

We suggest a few important steps before starting to survey an unknown lake with respect to dead zone. First, the lake is divided into a number of equal-sized slopes, which is facilitated by studying its bathymetry. The next step is to estimate the effective beam half-angle from the beam pattern of the applied transducer. A good candidate for this can be the first energy drop down to almost zero, which normally occurs behind the second lobe of the transducer. The third step is to install calibration benthic gillnets at the areas where the bottom slopes are equal or higher than the estimated effective transducer angle. In echograms recorded here, the DZ is measured directly.

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Submitted 20 October 2010
Revised 13 June 2011
Accepted14 October 2011

II

Paper II

Simple method to correct the results of acoustic surveys for fish hidden in the dead zone of an echosounder

Tušer M, Prchalová M, Frouzová J, Čech M, Peterka J, Jůza T, Vašek M, Kratochvíl M, Draštík V, Kubečka J

Journal of Applied Ichthyology 29, 358-363 (2013)
(IF2011 = 0.869, 5-year IF2011 = 1.240)

Journal of Applied Ichthyology

J. Appl. Ichthyol. 29 (2013), 358–363

ISSN 0175–8659

Received: January 20, 2012
Accepted: August 2, 2012
doi: 10.1111/jai.12091

A simple method to correct the results of acoustic surveys for fish hidden in the dead zone

By M. Tušer[1,2], M. Prchalová[1], T. Mrkvička[1,3], J. Frouzová[1], M. Čech[1], J. Peterka[1], T. Jůza[1], M. Vašek[1], M. Kratochvíl[1], V. Draštík[1] and J. Kubečka[1]

[1]*Institute of Hydrobiology, Biology Center of the Academy of Sciences of the Czech Republic, České Budějovice, Czech Republic;* [2]*Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic;* [3]*Faculty of Economics, University of South Bohemia, České Budějovice, Czech Republic*

Summary

In lentic freshwater systems, vertical acoustics may underestimate fish abundance in the acoustic dead zone where fish detection capability is limited. To estimate this bias, the height of fish above the lead-line of a benthic multi-mesh gillnet (1.5 m high) was used to quantify both the vertical distribution of fish near the bottom and the proportion residing within the acoustic dead zone. The study was carried out at the percid-dominated Biesbosch Reservoirs in the Netherlands. Acoustic dead zones were estimated at 7 cm above flat bottoms, and 12–34 cm above 8° sloped bottoms at depths of 5–27 m, respectively. Depending on the habitat, 36 to 75% of the gillnet catch by number was present in the acoustic dead zone, representing 5–51% of the biomass. Near-bottom depths were highly preferred by ruffe *Gymnocephalus cernua*, often used by perch *Perca fluviatilis* and pikeperch *Sander lucioperca*, plus seemingly devoid of smelt *Osmerus eperlanus*. The total amount of fish hidden in the acoustic dead zone was estimated to be 13–39% of the whole water column. The proportion of biomass obscured in the dead zone was lower (1–12%). The conclusion is that undetected fish in the acoustic dead zone can seriously bias density assessment, which can be corrected by concurrent sampling with benthic gillnets.

Introduction

Vertical acoustics have become one of the most frequently used methods for estimating fish abundance in both marine and freshwater systems (Simmonds and MacLennan, 2005). Unfortunately, due to the physical characteristics of acoustic sound waves, this technique is not able to detect fish within close proximity to the lake surface or bottom. In comparison to the surface layer, the acoustic dead zone at the bottom (Mitson, 1983; Ona and Mitson, 1996) is a more complicated issue to address. At present, the acoustic dead zone can be reduced, but not eliminated, by several approaches including the use of narrow beams, short pulses or employing deep-towed transducers (Kloser, 1996; Scalabrin et al., 2009). However, these approaches do not help to answer what remains hidden in the acoustic dead zone. There are only a few methods that can potentially determine this still-hidden value indirectly or directly.

The simplest method is to extrapolate the determined fish density in the layer just above the dead zone into the dead zone (Ona and Mitson, 1996; Rose, 2003). This mathematical approach relies on the assumption that fish close to the bottom are the same species and similarly distributed to fish present above the dead zone. However, this method does not account for the possibility that the fish community composition can vary depending on distance above the lakebed.

The second approach is to use active gear such as bottom trawls to directly obtain data on fish close to the bottom (Gauthier and Rose, 2005; von Szalay et al., 2007; Yule et al., 2007; Mello and Rose, 2009). However, this method is limited by bottom topography, i.e. areas with rugged or steeply-sloped bottoms in which trawling can result in damaged or lost fishing gear (Cooke et al., 2003). This situation is common in freshwater lakes and reservoirs, where these areas can be particularly difficult to sample with bottom trawl gear. Moreover, some bottom trawl designs raise the lead-line above the bottom (e.g. rock-hopper) to avoid slight contours or a soft bottom, which could catch or bury the net (Ingólfsson and Jørgensen, 2006). Trawls of this design possess their own dead zones (McQuinn et al., 2005), thus failing to efficiently catch strictly benthic species (Olin and Malinen, 2003). Further, the vertical opening of a trawl does not necessarily correspond to the height of the acoustic dead zone. Therefore, it is not possible to know which part of the catch originated from the dead zone.

In order to explore the fish community within the acoustic dead zone in detail, we replaced the active gear used in previous studies with passive benthic gillnets. Contrary to trawls, gillnets are able to resolve the vertical distribution of fish on a fine scale in terms of species, size and biomass compositions. We hypothesized that acoustics would underestimate the amount of fish in water bodies where fish populations inhabit benthic habitats. Also, we proposed that the height of a fish captured just above the bottom by gillnet can be used to quantify the proportion obscured in the dead zone so that acoustic survey information can be corrected accordingly.

Materials and methods

Localities

The study was carried out at the Biesbosch reservoirs (De Gijster, Petrusplaat, and Hondred en Dertig) in the Netherlands (see Kubečka et al., 1998 for details). The reservoirs are built as basin-shaped embanked impoundments on the River Meuse. The bottoms of these reservoirs are comprised of two typical areas: flat bottoms or eight–degree sloped areas in circumference (De Graaf, 1975). The reservoirs are thermally destratified artificially by strong aeration, thus fish populations inhabit the whole water columns of all three reservoirs (Prchalová et al., 2006).

Acoustics

Acoustic surveys were conducted at night in a zigzag pattern with a 120-kHz circular transducer ES120 7G with a 7° nominal beam angle controlled by a SIMRAD EY 500 split-beam echosounder. The system was calibrated using a 33.2 mm tungsten-carbide sphere (−41 dB, Foote et al., 1991). The theoretical dead zone height is considered to be 7.3 cm above a flat horizontal bottom according to the formula $(c \times \tau)/2$ (Mitson, 1983), where c is the speed of sound (c = 1450 m. s^{-1}), and τ is the duration of the transmitted pulse (τ = 0.0001 s). The dead zone height for sloping bottoms was calculated according to the equation for the theoretical worst case scenario (Tušer et al., 2011):

$$\mathrm{DZ}_{\mathrm{NRA}} = R_{\mathrm{B}} \times \left(\left(\frac{1}{\cos \beta} \right) - 1 \right) + \frac{c \times \tau}{2}$$

where R_{B} is the depth of the first bottom-reverberation echo peak and β is the angle of the bottom slope. The height of the dead zone for an 8° slope was estimated to be 12–34 cm for depths of 5–27 m, respectively.

All acoustic data were evaluated using the post-processing Sonar5-Pro software (Balk & Lindem, University of Oslo). The threshold applied to the acoustic data was set to −56 dB, which corresponded to a fish length of 3 cm. Lengths of fish targets were identified using Love's (1977) equation calculating dorsal aspect and a frequency of 120 kHz. Areal and volumetric densities of fish of known length were transformed into biomass using an average length/weight relationship for each reservoir obtained from gillnet catches; all species were pooled together for this parameter.

Gillnets

Standard Nordic multimesh benthic gillnets, in accordance with the specifications of Appelberg et al. (1995) and Kurkilahti and Rask (1996), were set on the bottom. The sets of nets consisted of 13 individual panels of one particular mesh size (ranging from 6 to 90 mm knot-to-knot). The original gillnets did not include those with 70 and 90 mm mesh sizes. We added these meshes to promote the capture of large fish with this gear. All gillnets were 1.5 m high and 100 m long. The nets were set on both flat and sloped bottoms at the available depths of 5–27 m before sunset and lifted the following morning after sunrise. All fish were identified to species and measured. Large numbers of individual fish were also weighed for determining species-specific length-weight relationships. The height of each fish captured above the gillnet lead-line was recorded.

Estimation of fish hidden in the acoustic dead zone

We assumed that fish densities in any two depth strata were in a ratio with each other. The fish density within the acoustic dead zone can be estimated from the ratio of total gillnet catches from within and above the dead zone according to the formula:

$$A_{\mathrm{d}} = A_{\mathrm{a}} \times \frac{G_{\mathrm{d}}}{G_{\mathrm{a}}}$$

where A_{d} is the estimated fish abundance or biomass in the dead zone, A_{a} is the acoustic estimate of fish abundance or biomass above the dead zone to a depth corresponding to the top of a gillnet, G_{d} is the gillnet catch in the dead zone, and G_{a} is the gillnet catch above the dead zone (Fig. 1). Thus, we can calculate an estimate of the proportion of acoustically-hidden fish relative to the whole water column (P_{h}) with:

$$P_{\mathrm{h}} = \frac{A_{\mathrm{d}}}{A_{\mathrm{d}} + A_{\mathrm{w}}}$$

where A_{d} is the estimated fish abundance or biomass in the dead zone, A_{w} is the acoustic estimate for the whole water column minus the acoustic dead zone.

Error analysis of A_{d} is based on variance in gillnet catches multiplied by acoustic variance estimates using the standard formula for two independent variables, where the variance of their product is given by:

$$\mathrm{var}(A_{\mathrm{d}}) = \mathrm{var}\left(A_{\mathrm{a}} \times \frac{G_{\mathrm{d}}}{G_{\mathrm{a}}}\right) = \mathrm{var}(A_{\mathrm{a}}) \times \mathrm{var}\left(\frac{G_{\mathrm{d}}}{G_{\mathrm{a}}}\right) + \mathrm{var}(A_{\mathrm{a}}) \times \left[E\left(\frac{G_{\mathrm{d}}}{G_{\mathrm{a}}}\right)\right]^2 + \mathrm{var}\left(\frac{G_{\mathrm{d}}}{G_{\mathrm{a}}}\right) \times [\mathrm{E}(\mathrm{A_a})]^2$$

As the G_{a} and G_{d} are pooled together, the error analysis requires a variance estimate of the ratio in gillnet catches. To obtain the variance of $G_{\mathrm{d}}/G_{\mathrm{a}}$, we assumed that each of n fish had the possibility of being within or above the dead zone and, therefore, each fish could be modeled by the alternative random variable A(p), where p was the probability of fish being within the dead zone. According to this assumption, the ratio of G_{d} and G_{a} equals $\hat{p}/(1-\hat{p})$ and its variance can be then estimated by using an univariate delta method (Greene, 2003), leading to

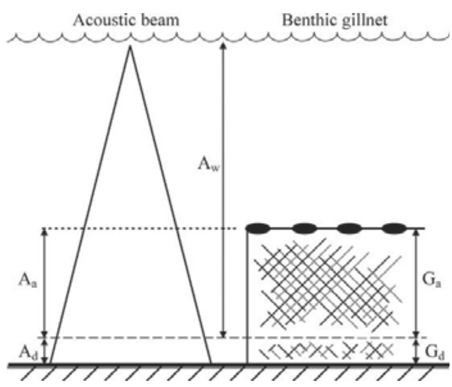

Fig. 1. Scheme depicting layers of depth strata included in calculations of fish quantities determined by acoustics or gillnet. Scheme shows acoustic dead zone upper limit (- - -) and gillnet height (…). Parameter abbreviations as in Materials and Methods section 'estimation of fish hidden in the acoustic dead zone'

the formula:

$$\mathrm{var}\frac{\hat{p}}{1-\hat{p}} = \mathrm{var}(\hat{p}) \times \frac{1}{(1-\hat{p})^4}$$

where variance of $\hat{p}$ equals $\hat{p} \times (1-\hat{p})/n$, supposing the normality of $\hat{p}$, which is suitable due to the large number of observations and central limit theorem.

Results

The total number of fish caught was 1332 individuals (858 and 474 on flat and sloped bottoms, respectively), ranging from 4 to 66 cm in length. Total weight of the catches was 148 kg. Six fish species were recorded in the benthic gillnets: bream *Abramis brama*, perch *Perca fluviatilis*, pikeperch *Sander lucioperca*, roach *Rutilus rutilus*, ruffe *Gymnocephalus cernua* and smelt *Osmerus eperlanus*.

The vertical off-bottom distributions of fish obtained by gillnet had a similar pattern in habitats with both flat and sloped bottoms, and around 50% of fish were caught within 7.5 cm from the bottom within the acoustic dead zone (Fig. 2). The most abundant benthic-community species in both habitats were percid fish, predominantly ruffe, followed by perch and pikeperch (Figs 3 and 4). Percid fish displayed a high affinity for the bottom, while smelt were captured mostly in the top half of benthic gillnets. The most abundant species, ruffe, was small bodied, thus its contribution to the netted biomass was negligible. The largest impact on biomass was made either by bream over flat bottoms (Fig. 4a) or perch and pikeperch over sloped bottoms (Fig. 4b).

The effect of the acoustic dead zone was greater for estimating fish abundance than biomass. Depending on the habitat, the amount of a gillnet catch in the acoustic dead zone ranged from 36 to 75% in abundance, and from 5 to 51% in biomass, within the 1.5-m layer sampled by the gillnets (Table 1). The most sampled species in terms of fish abundance were ruffe, followed by perch and pikeperch.

Fish abundance and biomass in the whole water column were acoustically estimated at 168 ind ha^{-1} and 46 kg ha^{-1}, respectively, above flat bottoms, as well as 246 ind ha^{-1} and 50 kg ha^{-1} above sloped bottoms, on average (Table 2). In the flat bottom habitat, fish density was underestimated by 13% in abundance and 1% in biomass due to the acoustic dead zone. For sloped areas, the underestimation of fish density ranged from 21 to 39% in abundance and from 5 to 12% in biomass.

Discussion

This study presents a method for quantifying fish density in the acoustic dead zone just above the bottom of reservoirs using benthic gillnets. In the destratified Biesbosch Reservoirs, fish occurred close to the bottom (Prchalová et al., 2006) and were thus underestimated during acoustic surveys. In the temperate zone of Central Europe, most lakes and reservoirs are thermally stratified, which means most fish live in the surface layer during the growing season (April–October, Vašek et al., 2004; Prchalová et al., 2008a, 2009a). Thus, the underestimation of fish abundance in these localities due to the acoustic dead zone is not considered to be significant (Bonar et al., 2009; CEN, 2010). However, this situation is not always the case for lakes and reservoirs that are either non-stratified, such as in the present study, or where the fish community is dominated by cold-water species that prefer the deeper and colder waters close to the bottom (Baldwin and Polacek, 2011).

Each way to estimate the proportion of fish in a dead zone has its pros and cons. The simplest approach, extending the fish density from just above the dead zone (Ona and Mitson, 1996; Rose, 2003), is clearly not suitable for freshwater systems like the one studied here, where fish abundance within the dead zone is much higher than in the adjacent layer above.

Benthic trawls usually sample close to the bottom, although a trawl dead zone can also be a problem (McQuinn et al., 2005). The vertical opening of the trawl is usually higher than acoustic dead zones commonly found in freshwaters, and it is difficult to decide which fish in the trawl catch originate from the dead zone. Bottom trawls cannot be used to sample all bottom types found in inland water bodies, and are thus not widely available. Furthermore, start-up costs to procure such bottom trawl gear can be high. In contrast, gillnets usually have lower operating costs, can be installed in various habitats and are easier to deploy than trawls. Therefore, gillnets have been extensively employed to assess fish population in a vari-

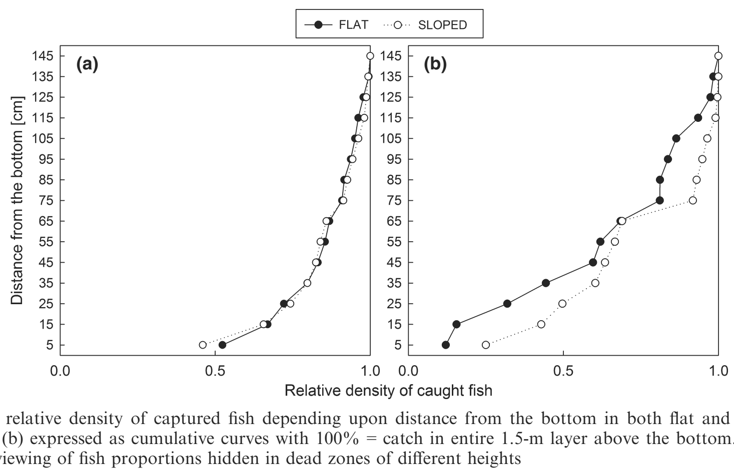

Fig. 2. Distribution of relative density of captured fish depending upon distance from the bottom in both flat and sloped habitats. Abundance (a) and biomass (b) expressed as cumulative curves with 100% = catch in entire 1.5-m layer above the bottom. Cumulative expression of data enables better viewing of fish proportions hidden in dead zones of different heights

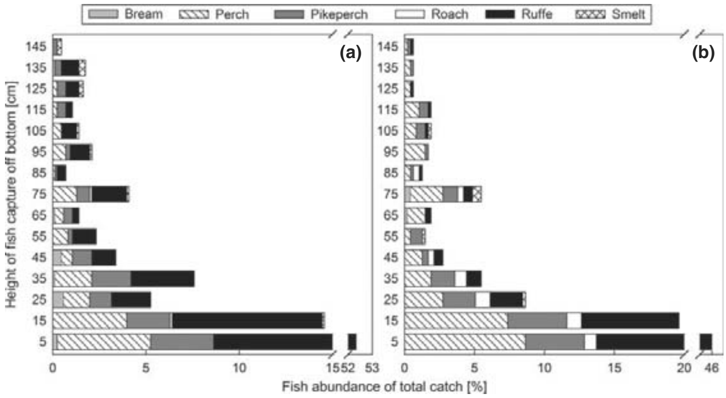

Fig. 3. Distribution of fish abundance according to species and heights of capture from the bottom in gillnets in habitats with (a) flat and (b) sloped bottoms. Catch of all species over all distances adds up to 100%

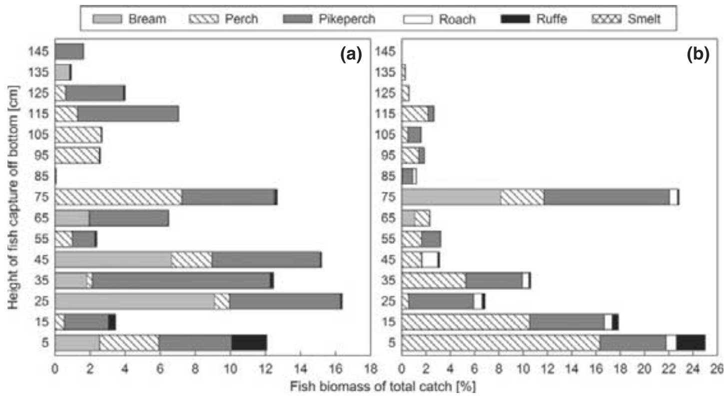

Fig. 4. Distribution of fish biomass according to species and heights of capture from the bottom in gillnets in habitats with (a) flat and (b) sloped bottoms. Catch of all species over all distances adds up to 100%

Table 1
Proportions of fish species in abundance and biomass captured inside (G_d) and outside (G_a) acoustic dead zone for habitats with flat and sloped bottoms. For the sloped bottom, extent of the dead zone depends on acoustic range; therefore, data for only lower and upper limits of the dead zone range in this habitat are shown

	Parameters				Species						
			Layer								
	Habitat	Depth [m]	Type	Height [cm]	Bream	Perch	Pikeperch	Roach	Ruffe	Smelt	**All fish**
Abundance	Flat	5–27	Gd	7	14.3	16.9	11.4	0.0	47.1	0.0	**35.9**
			Ga	143	85.7	83.1	88.6	100.0	52.9	100.0	**64.1**
	Slope	5	Gd	12	0.0	33.6	27.5	25.0	74.4	0.0	**50.0**
			Ga	138	100.0	66.4	72.5	75.0	25.6	100.0	**50.0**
		27	Gd	34	0.0	61.6	63.8	58.3	91.6	16.7	**74.5**
			Ga	116	100.0	38.4	36.3	41.7	8.4	83.3	**25.5**
Biomass	Flat	5–27	Gd	7	11.1	2.0	2.0	0.0	43.4	0.0	**5.4**
			Ga	143	88.9	98.0	98.0	100.0	56.6	100.0	**94.6**
	Slope	5	Gd	12	0.0	36.3	15.1	19.6	72.0	0.0	**25.6**
			Ga	138	100.0	63.7	84.9	80.4	28.0	100.0	**74.4**
		27	Gd	34	0.0	63.3	46.6	43.7	87.9	33.6	**51.2**
			Ga	116	100.0	36.7	53.4	56.3	12.1	66.4	**48.8**

Table 2
Estimates of fish abundance and biomass for individual layers in both flat and sloped bottom habitats

	Parameters			Acoustic estimates			
	Slope [°]	Depth [m]	G_d/G_a	A_a [ind ha^{-1}]	A_d [ind ha^{-1}]	A_w [ind ha^{-1}]	P_h [%]
Abundance	0	5–27	0.6 (±0.13)	46 (±153)	26 (±88)	168	**13.4**
	8	5	1.0 (±0.09)	64 (±83)	64 (±84)	246	**20.7**
	8	27	2.9 (±0.04)	54 (±70)	158 (±204)	246	**39.1**
				A_a [kg ha^{-1}]	A_d [kg ha^{-1}]	A_w [kg ha^{-1}]	
Biomass	0	5–27	0.06 (±0.24)	9.6 (±32.6)	0.6 (±8.4)	46.1	**1.2**
	8	5	0.3 (±0.03)	7.7 (±25.6)	2.7 (±8.9)	50.1	**5.0**
	8	27	1.05 (±0.01)	6.5 (±21.5)	6.8 (±22.6)	50.1	**12.0**

For the sloped bottom, only lower and upper dead zone limits shown. G_d/G_a = ratio between fish amount caught within and above dead zone in a layer corresponding to gillnet height. A_a = acoustic estimate of fish abundance or biomass above the dead zone for a layer corresponding to gillnet height above the bottom. A_d = fish abundance or biomass within a dead zone for a layer corresponding to the gillnet height above the bottom calculated according to Equation (1). A_w = acoustic estimate in an entire water column above the dead zone. P_h = proportion of fish acoustically hidden in the dead zone for the entire water column, calculated according to Equation (2). Standard deviations given in brackets.

ety of inland waters as a basic tool (CEN, 2005). The slightly enhanced processing of a gillnet catch by measuring the height of captured fish can be used for correction biases caused by acoustic dead zones at very little extra cost.

However, as for all other sampling gear, multi-mesh gillnets are not able to give purely unbiased estimates of a fish community (McClatchie et al., 2000). As a passive sampling tool, gillnets are influenced by the catchability of different fish species as well as fish sizes and activity (Finstad et al., 2000). Gillnet estimates are skewed because relatively inactive or small-sized fish are caught less often due to their lower mobility, while larger fish can be over-represented in the catch due to their higher swimming performance (Rudstam et al., 1984; Prchalová et al., 2009b). On the other hand, it is generally accepted that the geometric Nordic gillnet series used here represent a serious attempt to reduce catch size selectivity over a wide range of lengths (Appelberg et al., 1995; Kurkilahti and Rask, 1996; Prchalová et al., 2009b). Moreover, gillnets are usually from dusk to dawn, while acoustics and trawling are usually performed during the darkest night hours in order to avoid fish avoidance and take advantage of loose fish schools (Fréon et al., 1996; Axenrot et al., 2004). To ensure that the determined night fish vertical distribution within the dead zone corresponds with acoustic data at night, it may be worthwhile to use gillnets only during the time frame of the actual acoustic survey.

We did not correct for size selectivity in any of the gillnet catches. Our main goal was to initially estimate what proportion of fish could be recorded in the dead zone by gillnets. More significantly, a proper correction method for size selectivity has not yet been developed (Prchalová et al., 2009b). In cases where there is a strong concern about gillnet selectivity, the proportion of fish in the dead zone can be calculated from the gillnet catch for each individual size group or species.

Due to species selectivity, percids might be overestimated in gillnet catches, as this gear has the tendency to capture spiny species more efficiently (Grant et al., 2004). This feature could be particularly relevant in the sampling of the Biesbosch reservoirs as they are dominated by percid species. However, the study of Prchalová et al. (2008b) has shown that such overestimation is significant primarily within a community with the lowest proportions of perch. Therefore, we did not correct gillnet catches for an overestimation of perch. For ruffe and pikeperch, Prchalová et al. (2008b) found no overestimation.

Gillnetting is the only technique that provides vertical fish distribution results similar to those obtained by vertical acoustics (Vašek et al., 2009). As gillnets are standard for many surveys to gain species density, it is not much extra effort to measure the height of fish captured in a few gillnets used in each habitat. The height of captured fish provides a pattern of fine-scaled vertical distribution of fish species within a depth stratum of interest. Even our study has shown that fish affinity to the dead zone was strictly species- and size-specific. In terms of species vertical distribution, the most plentiful species was ruffe, whose relative abundance increased with depth toward the bottom. Gillnets were able to record populations of strictly benthic species, which were not within reach of acoustic and trawling surveys.

The use of benthic gillnet catches to correct acoustic surveys is also very flexible in dealing with dead zones occurring at different bottom slopes and depths (Tušer et al., 2011). Regarding the acoustic dead zone, however, a more complicated dead zone correction is needed than what we used here. Unlike the reservoirs studied here, in lakes with irregular bathymetry the dead zone may be more dynamic due to the continually changing depth and slope below a survey boat, requiring some kind of mapping approach to correct the measured fish density. It would be possible to define two lines on echograms: one at 1.5 m above the bottom and another based on the algorithm predicting the theoretical dead zone height that took into account the effects of pulse duration, beam angle, depth, and bottom slope. For a given interval of boat travel, e.g. 200 m, it would be possible to calculate the density of fish between the two lines using the acoustic data. Based on the average dead zone height of each interval, the proportion of fish in the dead zone could be predicted with the cumulative distribution functions from the gillnet results, and consequently used to correct the measured density of fish from the predicted dead zone height to 1.5 m above the lakebed.

As shown in this study, benthic gillnets can examine habitats that are not accessible to acoustic and trawling surveys. By using this simple approach, the obtained vertical distribution of fish species can be used to estimate the share of the limnetic fish community hidden in the acoustic dead zone.

Acknowledgements

The study was supported by project No. QH81046 of the National Agency of Agricultural Research (NAZV), institutional support RVO: 60077344, and by project No. 145/2010/P of the Agency of the University of South Bohemia. Special thanks go to Lars G. Rudstam and an anonymous reviewer for their extensive help and expert insights into improving the manuscript. We also thank Dr. Hassan Hashimi for the careful editing of English.

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Author's address: Jan Kubečka, Institute of Hydrobiology, Biology Center of the Academy of Sciences of the Czech Republic, Na Sádkách 7, CZ–370 05 České Budějovice, Czech Republic.
E-mail: kubecka@hbu.cas.cz

III

Paper III

Fish orientation along the longitudinal profile of the Římov reservoir during daytime: Consequences for horizontal acoustic surveys

Tušer M, Kubečka J, Frouzová J, Jarolím O

Fisheries Research 96, 23-29 (2009)
(IF2009 = 1.531, 5-year IF2011 = 1.887)

Fisheries Research 96 (2009) 23–29

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Fish orientation along the longitudinal profile of the Římov reservoir during daytime: Consequences for horizontal acoustic surveys

Michal Tušer[a,b,*], Jan Kubečka[a,b,*], Jaroslava Frouzová[b], Oldřich Jarolím[a,b]

[a] Faculty of Science, University of South Bohemia, Branišovská 31, 370 05 České Budějovice, Czech Republic
[b] Biology Centre of the Academy of Sciences of the Czech Republic, v.v.i., Institute of Hydrobiology, Na Sádkách 7, 370 05 České Budějovice, Czech Republic

ARTICLE INFO

Keywords:
Acoustics
Fish orientation
Fish aspect
Freshwater
Canyon-shaped reservoir
Daytime

ABSTRACT

The orientation of fish in a horizontal plane has important consequences for estimating their true size from horizontal acoustic records. The aim of this work was to verify the assumption that during the daytime fish are randomly orientated in the lacustrine zone of the canyon-shaped Římov reservoir and to compare distributions of fish orientation between the lacustrine and tributary (riverine) zones. Fish orientation was acoustically surveyed at fixed locations using the SIMRAD EK 60 split-beam echo sounder (elliptical beam, 120 kHz) with a horizontally aligned transducer. The horizontal aspect (angle between the fish body and the transducer axis) was used to describe their orientation. The conventional single-echo detector (SED) and the cross-filter detector (CFD) were applied. No trend was found along the reservoir when comparing records from four sites processed with the conventional SED. At all sites, most fish appeared to move predominantly in directions perpendicular to the central axis of the acoustic beam, i.e. the side-aspects (90°) of fish prevailed over other aspects. The CFD registered tracked fish several times more often than the SED. In the lacustrine zone the frequency distribution of fish aspect appears very similar when recorded by sonar beams oriented parallel to and across the longitudinal axis of the reservoir (criss-cross-beaming experiment). In the tributary zone, beaming perpendicular to the longitudinal axis of the reservoir revealed a significantly higher proportion of fish moving along the longitudinal axis. Therefore, the assumption of random fish orientation is not applicable in the tributary zones of such reservoirs.

1. Introduction

For several decades, echo sounders have been employed as important devices for estimating fish-stock abundance and for visualizing their spatio-temporal distributions and behaviour (Simmonds and MacLennan, 2005). Nevertheless, unbiased interpretation and conversion of acoustic parameters, such as target strength (TS), to fish parameters such as length and weight is still not a routine procedure. Many *ex situ* experiments have attempted to relate TS to fish length or weight, and the TS–length regressions derived from these studies are often used in estimations of fish abundance and size (Simmonds and MacLennan, 2005). However, since variability in the TS is strongly influenced by the orientation of the fish's body (i.e. fish aspect) relative to the incident sound wave (e.g. Foote, 1980a, 1980b; Midttun, 1984; MacLennan, 1990; Rose and Porter, 1996; Horne and Clay, 1998; Frouzová et al., 2005), some assumption of fish-aspect distribution in the observed population of targets is always needed for converting TS to fish length (e.g. Kubečka et al., 1994). The orientation of a fish relates to the type of behaviour it is exhibiting, as well as to the environmental conditions where it lives. Therefore, it is important to know the distribution of the orientations of free-swimming fish in various conditions.

In rivers, as well as in many mesotrophic and eutrophic lakes or reservoirs, most of the fish community often lives predominantly within the uppermost layer of the water (4 m, Kubečka and Wittingerová, 1998; Čech and Kubečka, 2002; Vašek et al., 2004) which is suitable for horizontal rather than vertical beaming (Kubečka and Wittingerová, 1998). Horizontal beaming, however, encounters the problem of the different reflectivity of various aspects of the fish (Kieser et al., 2000; Simmonds and MacLennan, 2005). In most riverine situations, fish are assumed to present mostly their side-aspect to the transducer as they swim upstream or downstream through the sonar beam, due to the river current (e.g. Burwen and Fleischman, 1998; Kubečka and Duncan, 1998; Lilja et al., 2000). In lakes and reservoirs, random fish orientation is usually assumed (Kubečka et al., 1994; Draštík and Kubečka, 2005), but

* Corresponding authors at: Faculty of Science, University of South Bohemia, Branišovská 31, 370 05 České Budějovice, Czech Republic. Tel.: +420 737329542; fax: +420 385310248.
E-mail addresses: tuser@centrum.cz (M. Tušer), kubecka@hbu.cas.cz (J. Kubečka).

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doi:10.1016/j.fishres.2008.09.022

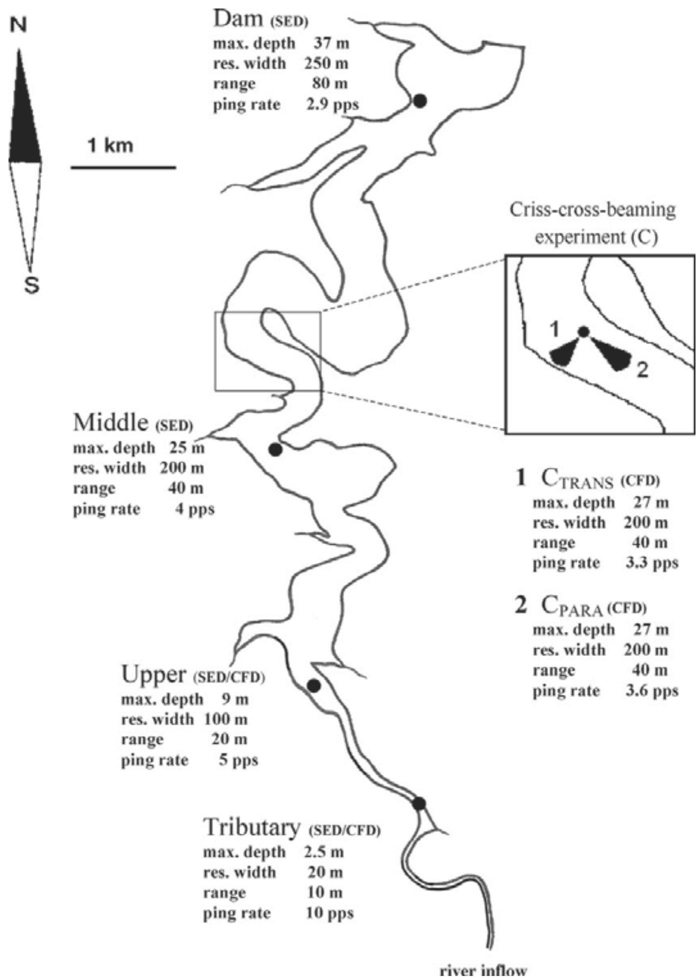

Fig. 1. Map of the Římov reservoir. The four sites along the longitudinal axis of the reservoir (2005) and the criss-cross-beaming experiment (2006) are shown with an indication of the detector used (SED or CFD), maximum depth, reservoir width, surveyed ranges of open water (m), and ping rates (in pulses per second, pps).

without proper verification. The situation could be more complicated in "canyon-shaped" reservoirs, namely artificial lakes formed by damming of rivers, which are more long than wide and where longitudinal swimming of fish may predominate. If the aspect of the fish to the transducer is unknown, the conversion of TS data to fish lengths is complicated. The tributary zone of such reservoirs could be of special interest here as the reservoir gradually merges into the inflowing river.

This study focused on verifying the assumption of random fish orientation in the lacustrine zone of the Římov reservoir and on comparing the orientation of fish in the lacustrine and tributary zones.

2. Materials and methods

2.1. Study sites

The acoustic measurements were carried out in the canyon-shaped mesotrophic to eutrophic Římov reservoir, Czech Republic (48°50′N, 14°30′E; 170 km south of Prague). This reservoir was built by damming the Malše River, the main tributary to the reservoir, and has an area of 210 ha, a volume of $33 \times 10^6\,m^3$ and maximum depth of 45 m. The fish assemblage of the Římov reservoir consists of 34 fish species and 5 hybrids, but only roach *Rutilus rutilus*, common bream *Abramis brama*, bleak *Alburnus alburnus*, perch *Perca fluviatilis*, and ruffe *Gymnocephalus cernuus* have significant population levels in the reservoir (Vašek et al., 2004).

During 7th–12th September 2005, four sites along the longitudinal profile of the Římov reservoir, approximately corresponding to sampling areas used by Vašek et al., 2004, were acoustically surveyed during daytime from 7 a.m. to 6 p.m. (Fig. 1). These sites represented four typical parts of the reservoir. The ranges of open water surveyed from the tributary to the dam were 10, 20, 40, and 80 m depending on the depth and width of the reservoir. On 1st September 2006 during daytime from 7 a.m. to 5 p.m., a criss-cross-beaming experiment was performed in the lacustrine part of the reservoir (Fig. 1), in order to prove the random distribution of fish.

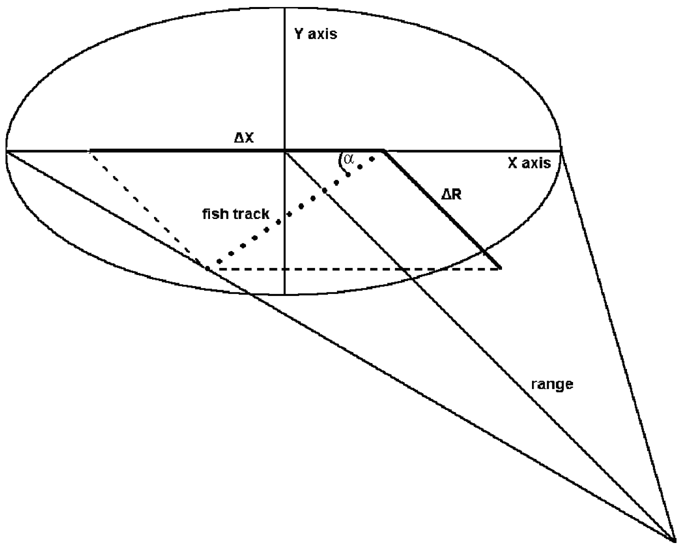

Fig. 2. Sonar projection of a given fish track (•••) with the parameters used in Eq. (1). Fish horizontal aspect (α), the change in range (ΔR), and the distance along the X-axis between the first and last echo (ΔX) are shown.

2.2. Hydroacoustic equipment

All field measurements were carried out with a scientific split-beam echo sounder SIMRAD EK 60. The system operated at 120 kHz frequency with 0.1 ms pulse duration, and with a ping rate of 2.9–10 pulses per second (Fig. 1). An elliptical transducer ES120-4 (4.3° and 9.2° nominal beam angles) was deployed and calibrated using a 33.2 mm tungsten-carbide sphere (−41.0 dB, Foote et al., 1991). The sonar equipment was installed at fixed locations along the reservoir. The transducer was boat-mounted and the boat was moored to the shore. The sonar beam was oriented horizontally across the reservoir, perpendicular to the longitudinal axis. In the criss-cross-beaming experiment, the boat-mounted transducer was based in the middle of the reservoir. For half-a-day its beam was aimed perpendicularly, and for the second half of the day in parallel, to the longitudinal axis of the reservoir (Fig. 1: C_{TRANS}, C_{PARA}). All acoustic data were continuously stored on the hard-drive of a portable laptop for later evaluation.

2.3. Detection of single echoes

All acoustic data were evaluated from the echograms using post-processing software Sonar5-Pro (version 5.9.6, Balk & Lindem, University of Oslo). To detect single-fish echoes, the conventional single-echo detector (SED) was deployed with discrimination criteria as follows:

Min TS = −70 dB
Echo length: min = 0.5, max = 1.8 times the transmitted pulse length
Max beam comp. = 3 dB
Max phase dev. = 10 geometrical degrees of the beam angle (this parameter may fluctuate widely in horizontal records, so setting to the very high value of 10° practically disabled this criterion).

In addition, the ‘cross-filter detector’ (CFD, an alternative to the conventional SED, Balk and Lindem, 2000) was used in the criss-cross-beaming experiment and consequently for reprocessing part of the data set from the Tributary ($Trib_{CF}$) site and the Upper ($Upper_{CF}$) site. The CFD was set with the following parameters:

Step 1 Detector:
Foreground filter = height 5 and width 1
Background filter = height 55 and width 1
Offset +8 dB
Step 2 Refinements (for every echogram, different combinations of these three parameters were used to remove as many unwanted targets as possible—noise, slowly drifting debris, lines of bottom reflections):
Perimeter length: min = 10, max = 10,000 samples around a detected region
Ratio (track length/mean echo length): min = 1, max = 270
Max TS: min = −60 dB, max = −10 dB

Further information about the meaning of CFD and its parameters is provided in Balk and Lindem (2006).

2.4. Fish horizontal aspect

After detecting single echoes, all fish were manually tracked (i.e. target tracking, Brede et al., 1990; Ehrenberg and Torkelson, 1996) in such a way that one fish track meant a series of contiguous single echoes with the same direction of movement in a horizontal plane. When the fish changed its direction of movement while passing through the beam, its track was divided into parts having the same direction. To directly determine the angle of the fish's body with respect to the transducer, we used the horizontal aspect (α) of a given fish track which was simply calculated as:

$$\alpha = \arcsin\left[\frac{\Delta R}{\sqrt{\Delta X^2 + \Delta R^2}}\right] + 90^\circ \qquad (1)$$

where ΔR is the change in range (m), and ΔX is the distance (m) along the X-axis between the last and first echoes (Fig. 2). After adding 90°, the side-aspect of the fish (exhibiting side-on to the

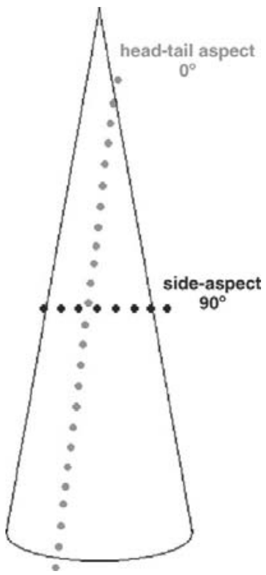

Fig. 3. A projection of two fish tracks (••• and • • •) moving through a sonar beam at different angles. Each point represents one single-fish echo.

transducer) corresponds to 90°, the head-aspect to 0°, and the tail-aspect to 180°. The TS/angle relationships of the interval 0–90° and 90–180° are mirror images of each other (Frouzová et al., 2005), so we converted all aspects to the interval 0° (head–tail aspect) to 90° (side-aspect).

2.5. Statistical evaluation

Combined aspects (0–90°) were used and statistically weighted by the total ping count of the individual track. The statistical weighting allowed us to adjust the contribution of individual cases to the outcome of the analyses. A fish swimming parallel to the acoustic axis is less likely to appear in the beam due to the narrow beam width, but may produce a longer track as it moves along the beam. After weighting, each single-fish echo along a track corresponded to one observation at a given aspect-angle. For example, as demonstrated by Fig. 3, the first fish track consists of 6 echoes and its swimming angle is 90°, then the weighting gives 6 observations at the 90°-angle, whereas the second fish track consists of 23 echoes and it swam at approximately 0°, so we get 23 observations at the 0°-angle for analysis. The number of observations is called weighted *N* in Table 1.

For comparison of aspect–frequency distributions, the one-way ANOVA, with the Poisson distribution and identity-link function, was used (program STATISTICA 6.0, module of Generalized Linear/Nonlinear Models). Likelihood Type 3 test was chosen. In addition, Bonferroni's correction was used to adjust the significance levels of the individual comparisons.

3. Results

3.1. Data processed with the conventional SED

In 2005, we performed acoustic observations of fish orientation at fixed locations along the longitudinal axis of the Římov reservoir. The total number of records processed was 1713 fish tracks (Tributary 901, Upper 285, Middle 228, Dam 299) detected by the conventional SED (Table 1). For the description of fish orientation, we calculated the horizontal aspect of the fish according to Eq. (1). Basic descriptive statistics of the fish aspects are summarized in Table 1 and their frequency distributions are shown in Fig. 4. Random fish orientation should be apparent from these results: means/medians will only approach 45° if there is an equal probability of detection of fish in all aspects. Our measured values of means were within the range 63.2–73.7° (Table 1). No apparent trend of fish orientation from the tributary to the dam was seen in the frequency distributions of fish aspects (Fig. 4), but statistical comparisons of the frequency distributions between the sites were significantly different (Table 2). These differences were caused by the large number of observations, which made the analysis sensitive even to very small changes in the distributions. At all sites, fish appeared to move predominantly in near-perpendicular directions with respect to the beam axis, i.e. side-aspects (90°) of the fish prevailed over other angles and head–tail aspects were only a tiny proportion. These results indicated that fish primarily swim along the longitudinal axis of the reservoir. The absence of any trend did not support the idea of different fish orientations between the lacustrine and riverine zones.

Results from year 2005 data revealed that many fish tracks with steeper slopes, seen in the original amplitude echograms, were not displayed in the SED echograms; seemingly, the sloped tracks were rejected by the conventional SED whose settings were too strict for such fish tracks.

3.2. Data analyzed by the cross-filter detector CFD

In 2006, we decided to reprocess part of the data set from the sites Tributary and Upper using the cross-filter detector (CFD). Furthermore, we performed the criss-cross-beaming experiment in order to better prove the random orientation of fish in the lacustrine zone of the Římov reservoir. If no direction predominates, then the distributions of fish orientation for perpendicular and parallel beaming will be similar, with their means or medians ideally about 45°. These data were also processed by CFD.

In total, 6537 fish tracks were processed from the sites $Trib_{CF}$ (910), $Upper_{CF}$ (2278), C_{TRANS} (2318), and C_{PARA} (1031). The cross-

Table 1
Descriptive statistics of horizontal aspects (in degrees) of fish from the SED processed records in 2005 and the CFD processed record at Tributary and Upper sites of Římov Reservoir, and the criss-cross-beaming acoustic experiment in 2006.

Year	Site	No. of tracks	Weighted, *N*	Mean	Median	Variance	Standard deviation	Standard error of mean
2005	Tributary	901	24,843	63.2	69.9	511.8	22.6	0.14
	Upper	285	4,312	73.7	79.3	290.5	17.0	0.26
	Middle	228	4,539	63.7	75.1	699.2	26.4	0.39
	Dam	299	4,271	67.0	75.8	543.9	23.3	0.36
2006	$Trib_{CF}$	910	17,448	63.4	71.6	583.7	24.2	0.18
	$Upper_{CF}$	2,278	33,605	66.4	73.5	491.7	22.2	0.12
	C_{TRANS}	2,318	46,739	55.3	60.1	693.1	26.3	0.12
	C_{PARA}	1,031	25,074	52.5	57.4	777.9	27.9	0.18

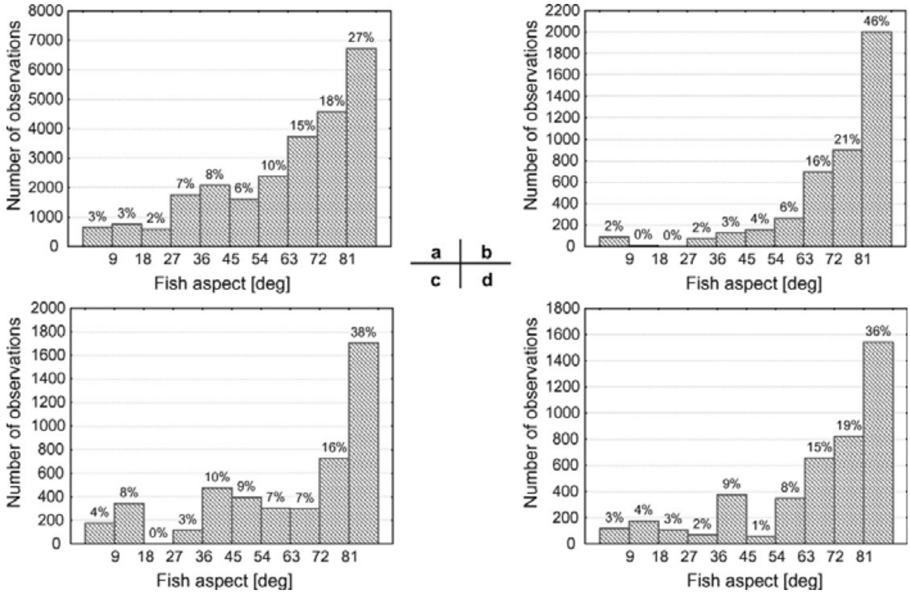

Fig. 4. Aspect–frequency histograms of SED-detected tracks of fish in (a) Tributary, (b) Upper, (c) Middle, and (d) Dam regions of the Římov reservoir.

filter detector found 8-times more tracks from the same record at $Trib_{CF}$ and $Upper_{CF}$ than did the single-echo detector. The mean aspects of CFD-processed tracks are generally lower than those of SED tracks (Table 1). In the aspect statistics of the cross-filtered data (Table 1), the difference between the lacustrine and riverine zones was more apparent than in the previous results. The means and medians differed considerably between the tributary $Trib_{CF,}$ together with the upper part of the reservoir ($Upper_{CF}$), and the lacustrine zone represented by C_{TRANS} and C_{PARA}. The means of $Trib_{CF}$ and $Upper_{CF}$ were 63.4° and 66.4°, respectively, while the means of C_{TRANS} (55.3°) and C_{PARA} (52.5°) were closer to the ideal value of 45°. The medians of $Trib_{CF}$ and $Upper_{CF}$ were 71.6° and 73.5°, respectively, whereas the medians of C_{TRANS} and C_{PARA} were 60.1° and 57.4°, respectively. The aspect–frequency histograms for each site are illustrated in Fig. 5 and their comparison is given in Table 2. Significant differences were found between all sites due to the high number of observations, which made the analysis sensitive even to very small differences between the distributions. $Trib_{CF}$ was characterized by a high proportion of side-aspects (32%, 81–90°) with a sharply declining trend down to head- and tail-aspects (Fig. 5a). This shows that most fish in the riverine zone were presenting predominantly side-aspects to the acoustic beam. A fairly similar pattern of declining distribution was noticed at the Upper site (Fig. 5b), also with a high proportion of side-aspects (32%).

Regarding random fish orientation in the lacustrine zone, the frequency distributions of C_{TRANS} and C_{PARA} were clearly similar (Fig. 5c and d). However, they were different from the uniform distribution (equal probability of all aspects), which could be expected in a randomly distributed fish population. Both C_{TRANS} and C_{PARA} showed similar shapes with a slightly higher proportion of side- and near-side-aspects (20–21% in the category 81–90°, and 14–16% in the category 72–80°) but with approximately the same level of occurrence between angles 0° and 72°. Considering that the side-aspect of the fish recorded in C_{TRANS} corresponds to the head–tail aspect of those recorded in C_{PARA}, and vice versa, then fish moving side-on to the transducer are more frequently detected and thereby overestimated.

Table 2
Comparisons of aspect–frequency distributions of fish between individual sites in Římov Reservoir from SED- and CFD-processed tracks. Significant results according to Bonferroni's correction are in bold.

Year	Comparison between two sites	Degrees of freedom	Log-likelihood	Bonferroni's correction of significance level	*p*
2005	Tributary × Upper	1	5,734,410	0.017	**0.00000**
	Tributary × Middle	1	5,617,501	0.017	**0.00022**
	Tributar × Dam	1	5,602,736	0.017	**0.00000**
	Upper × Middle	1	1,837,655	0.017	**0.00000**
	Upper × Dam	1	1,824,214	0.017	**0.00000**
	Middle × Dam	1	1,704,814	0.017	**0.00000**
2006	$Trib_{CF}$ × $Upper_{CF}$	1	9,919,415	0.017	**0.00000**
	$Trib_{CF}$ × C_{TRANS}	1	10,630,170	0.017	**0.00000**
	$Trib_{CF}$ × C_{PARA}	1	6,982,133	0.017	**0.00000**
	$Upper_{CF}$ × C_{TRANS}	1	13,948,572	0.017	**0.00000**
	$Upper_{CF}$ × C_{PARA}	1	10,300,705	0.017	**0.00000**
	C_{TRANS} × C_{PARA}	1	11,040,008	0.017	**0.00000**

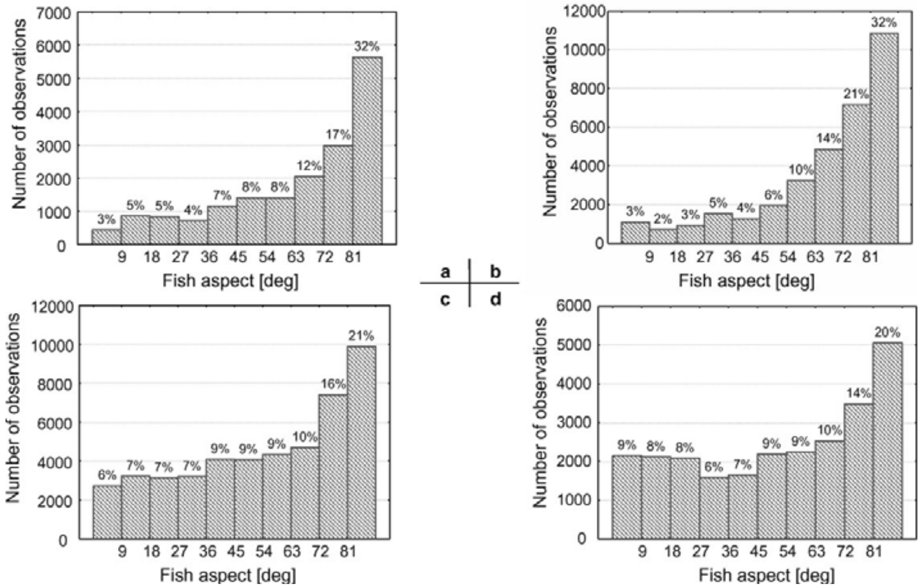

Fig. 5. Aspect–frequency histograms from CFD-detected tracks of fish in the Římov reservoir: (a) Trib_{CF}, (b) Upper_{CF}, (c) C_{TRANS}, and (d) C_{PARA}.

4. Discussion

The measurement of fish orientation is a challenge. For this purpose we can use either optical techniques that are more direct (Huse and Ona, 1996), or acoustic methods that involve assumed scattering models, analysis of broadband acoustic echoes and echo-trace analysis (e.g. Foote and Traynor, 1988; Stanton et al., 2003). In this work we used fish tracking where the body orientation angle is equated with swimming angle (Furusawa and Miyanohana, 1990; Ona, 2001). However, detecting fish acoustically, by single-echo detection and tracking, can be difficult in some environments due to low signal-to-noise ratios and missing detections of echoes in fish tracks (Balk and Lindem, 2000). Using the conventional single-echo detector (SED), scarcely any difference was found between the aspect–frequency distributions along the longitudinal profile of the Římov reservoir. According to distributions of fish aspects, side-aspects would be strongly dominant in all parts of the reservoir. The results confirmed better detection of targets with lower signal (non side aspects) by the cross-filter detector as predicted by Balk and Lindem (2000).

Interpretation of the results is complicated by the fact that all the aspect–frequency distributions are significantly different from each other (Table 2). Weighting by the number of observations along the fish track (Fig. 3) gave a very large amount of data and, consequently, unusually high power to the comparative tests. With thousands of observations the distributions are immediately significantly different, even if the deviations between frequency distributions are unimportant in practice. The conclusion that all the aspect distributions are different, as suggested by this statistical analysis, is unlikely to be helpful. It is rather more useful to look at the similarities in distribution shapes and values of the average aspects. In this respect, we can clearly see that the data from the tributary and upper parts of the reservoir differ from both lacustrine observations (fish in the uppermost parts of the reservoir have very different aspect distributions with more observations corresponding to movement along the longitudinal axis of the reservoir, Fig. 5a and b × c and d). On the other hand, aspect–frequency distributions in the lacustrine part (Fig. 5c and d) are mirror images of each other, suggesting that fish movement patterns in those areas are similar.

We encountered some difficulties with the use of horizontal aspect as an indicator of fish orientation. Both in transverse and parallel beaming, the most frequently recorded fish displayed the side- or near-side-aspect. If all fish were recorded, such a result from the criss-cross-beaming experiment is not credible (except in the unlikely event that the fish changed their swimming direction during the day). The most obvious explanation is the possibility that some targets could not be detected in less reflective aspects, even with CFD. This could happen with smaller fish at sloping aspects (Kubečka, 1996; Kieser et al., 2000). Another possible explanation may be pauses in fish swimming, which would be interpreted as side-aspects due to the much higher estimation precision of ΔR compared to ΔX (Fig. 2, the ΔX component has greater variation due to the jitter in signal phase which can falsely indicate fish swimming laterally). Such pauses are known to occur frequently with changes in swimming direction during "sinusoidal swimming" (Čech and Kubečka, 2002). However, the very small differences between fish aspects in the C_{TRANS} and C_{PARA} observations indicate that there is no predominant direction of fish orientation in the lacustrine zone, and that the assumption of random orientation can be adopted in further studies.

According to our results, fish orientation in canyon-shaped reservoirs is different between the lacustrine and riverine zones (see Fig. 5). In the lacustrine environments of the reservoir, fish appear to move in random directions (Fig. 5c and d) and the assumption of random orientation was confirmed. The fish assemblage of the riverine zone is represented predominantly by side-aspects to the acoustic beam (Fig. 5a) and movements parallel to the main flow (Kubečka, 1996; Kubečka and Duncan, 1998). The assumption of random fish orientation used in acoustic surveys for biomass estimation may not, therefore, be valid in the tributary area of canyon-shaped reservoirs and may lead to TS-overestimated size and biomass in these zones. With the "deconvolution" approach of Kubečka et al., 1994, some side-aspects would be inevitably interpreted as "weaker" aspects and the fish length would be "overcorrected". Consequently, fish sizing and biomass assessment in the tributary area probably needs special consideration. Comparison of the CPUE of different gears (pelagic gillnets, trawls) in the riverine/lacustrine zone could be helpful. Also, acoustic 'cameras' such as the DIDSON (Moursund et al., 2003; Hateley et al., 2006) could be used to determine fish size and the boundaries between random and non-random distributions of fish along the reservoir.

Acknowledgements

This work was supported by the Czech Science Foundation (Projects No. 206/07/1392) and the Grant Agency of the Academy of Science of the Czech Republic (Project No. IAA600117502). The authors would like to thank Helge Balk for help with data cross-filtering and Dr. Małgorzata Godlewska and Dr. Mary Burghis for valuable comments on the manuscript.

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IV

Paper IV

Evaluation of potential bias in observing a fish by a DIDSON acoustic camera

Tušer M, Frouzová J, Balk H, Muška M, Mrkvička T, Kubečka J

(unpublished manuscript)

Evaluation of potential bias in observing fish by a DIDSON acoustic camera

Michal Tušer[1,2], Jaroslava Frouzová[1], Helge Balk[3], Milan Muška[1], Tomáš Mrkvička[1,4], Jan Kubečka[1]

[1] Institute of Hydrobiology, Biology Center of the Academy of Sciences of the Czech Republic, Na Sádkách 7, 370 05 České Budějovice, Czech Republic

[2] Faculty of Science, University of South Bohemia, Branišovská 31, 370 05 České Budějovice, Czech Republic

[3] Department of Physics, University of Oslo, P.O.Box 1048, Blindern, 0316 Oslo, Norway

[4] Faculty of Economics, University of South Bohemia, Studentská 13, 370 05 České Budějovice, Czech Republic

Corresponding author: Jan Kubečka, email: kubecka@hbu.cas.cz

Abstract

Standard acoustic experiments with a fish rotating carousel were conducted to ascertain the dependences of fish detection and their length estimates on fish size, spatial orientation and range from the transducer. Cyprinid fish of known sizes and body orientations were deployed in known positions within a DIDSON high-frequency array of beams. All deployed fish were invariably detected in side aspect. Their lengths were accurate only in the center of the beam array, and were underestimated at the edges of it. In addition, no effect of range was observed. However, when the fish were other than sideways, the detection probability and length estimates strongly declined with diminishing fish size and increasing aspect and distance from the transducer. Moreover, we observed that a wider girth of larger fish can shadow the rest of the body, and dramatically decreased the observed length. We show that the determination of the true fish length is challenging and would not be a trivial task, and we raise the question of where to define fish length along echo intensity of fish. We conclude that including the corrections for length estimates allow DIDSON to obtain more reliable and accurate biological information of fish.

Introduction

Real-time, acoustic-imaging technology has been developing rapidly over the past decades, addressing namely to mechanically scanned or multi-beam systems with a wide variety of frequencies, ranges and resolutions (Simmonds and

MacLennan 2005). To the foreground of all imaging sonars has currently come the dual-frequency identification sonar (DIDSON^{TM}) system, developed originally for the US Department of Defense (Belcher et al. 2001; Belcher et al. 2002).

This sonar is based on the concept of the 'acoustic camera' (Smyth et al. 1963; Jacobs 1965), using principles of multiple beams and scanning to generate an array of visualized points (i.e. pixels). Due to complex beam-forming techniques involving acoustic lenses, the DIDSON technology can create high-resolution digital images, approaching the quality of optical ones, where targets of interest can be positively identified within a biologically meaningful field of view. Operating frequencies are typically 0.7–1.8 MHz, which unfortunately reduces the observable range to a few meters, but this is still substantially better than optical devices can achieve in dark or turbid water. Occupying a niche between fisheries-assessment (conventional) sonars and optical systems, the DIDSON is thus greatly useful where the most detailed imaging is required over short ranges.

Video-like images, nevertheless, may lead users to the idea that a target of interest is represented by true magnitude (size), easily measurable. Yet, users should be aware of that DIDSON images remains acoustic-based and consequently subject to the characteristics of beam arrangement, range, and properties of targets. Regarding riverine research, many studies attempted to verify how reliable fish sizes are particularly in spawning escapement estimates (Baumgartner et al. 2006; Cronkite et al. 2006; Burwen et al. 2007). The advantage of riverine application is that fish predominantly swim aligned with the current (Burwen and Fleischman 1998; Kubečka et al. 2000; Lilja et al. 2000), i.e. perpendicular to the beam array, being measured only in the middle of that array. Moursund et al. (2003) confirmed that the best geometry to obtain high-resolution images of fish and the possibilities of distinguishing fish from other objects is when targets are aligned along the 96-beam plane, as accomplished in spawning migrations. Moreover, migration studies usually examine one-species migratory populations with relatively large sizes detected in strong aspects. In this study, we investigated the performance of DIDSON fish recording in suboptimal conditions when smaller fish could be observed from the less-reflective aspects. The aim was to ascertain how fish detection probability and length measurement in a DIDSON beam array depend on fish size, spatial orientation and range from the transducer. We deployed fish of typical sizes and species occurring in European lakes and reservoirs. The results give guidance whether DIDSON can be used for quantitative studies in multispecies systems.

Materials and Methods

Study site

In the Římov reservoir (Czech Republic), implemented was a standard acoustic experiment with a dual-frequency identification sonar (DIDSON) using a fish rotating carousel. The entire construction of the experiment was mounted on a floating boat garage (Fig.1), which was located above a depth of 7.5 m, directly in the open water of the reservoir. The sonar, which generates a fan-shaped multi-beam array across 14° vertical and a 29° horizontal sector (www.soundmetrics.com), was mounted on a remote-controlled sub-Atlantic pan-and-tilt unit. Both devices, attached to a steel rod, were submerged to a depth of approximately 1.5 m below the surface (from the surface to the point amid of the DIDSON's lens). This arrangement ensured that acoustic recordings were not affected by boundary (surface or bottom or garage floats) interference. Moreover,

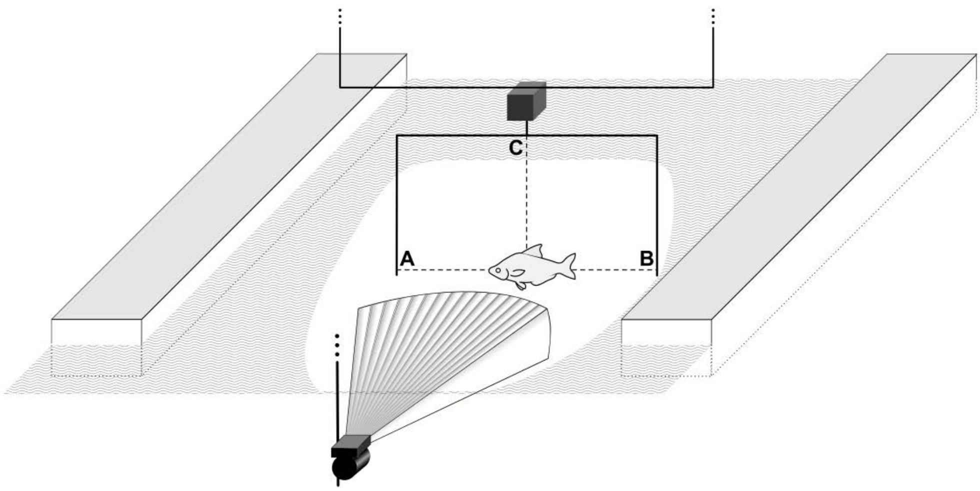

Figure 1. A scheme depicting the construction for the standard acoustic experiment with a fish rotating carousel. Into the carousel's frame, the anesthetized fish was tethered between the lower ends of vertical metal rods (A and B) and to the middle of a horizontal rig (C).

in the experiment period (19th to 23rd June 2007), the daily temperature profile of the water column below the garage was constant (Fig. 2). For acoustic recording,

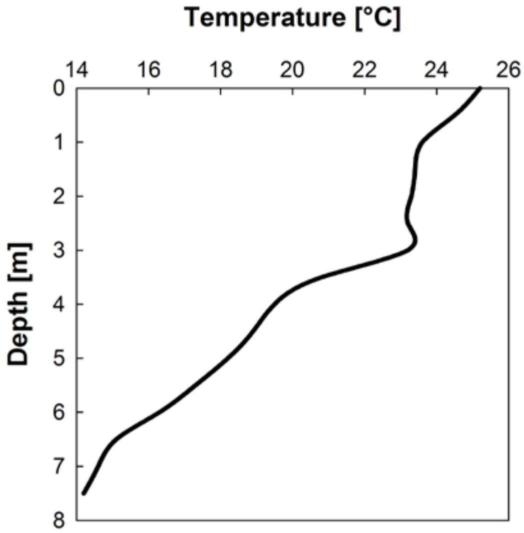

Figure 2. The temperature-depth water profile shown above depicts the temperature layering in the period of the standard acoustic experiment.

the DIDSON was operated in a 1.8 MHz-frequency mode for the highest resolution, in which the array is horizontally divided into 96 elements with a 0.3° horizontal resolution. The image window was set to start 2.92 m in front of the transducer with a 10-m window length, and at a capture rate of 7 frames per second.

Experimental setup

In this study included were six fish from the family Cyprinidae, namely two bream Abramis brama (L.), three roach Rutilus rutilus (L.) and one common carp Cyprinus carpio carpio L., ranging from 10 to 60 cm in total length and weighing from 9 g up to 3.5 kg (Table 1).The fish were captured by electrofishing in a minor tributary of the Římov reservoir. All fish were enclosed in a special live pen directly in the reservoir in order to remain in their natural conditions until they could be deployed.

Directly prior to the experiment, each fish was anesthetized with tricaine mesylate (MS-222), and measured for standard length, total length and weight. Consequently, the anesthetized fish was carefully tethered in the carousel's frame with 0.3-mm fishing lines (also see Frouzová et al. 2005). Briefly, three fishing lines were sewn on to the jaw, tail, and spine of the fish. The head and tail lines were stretched to the lower ends of the frame's vertical metal rods (Fig.1, A and B). The spine line was attached to the middle of the frame's horizontal rig above

Table 1. The fish deployed in the experiment with their measured body parameters. SL = standard length, TL = total length.

Species	SL [mm]	TL [mm]	Weight [g]
bream *Abramis brama*	140	175	49
	250	310	373
carp *Cyprinus carpio*	480	580	3468
roach *Rutilus rutilus*	80	100	9
	118	145	36
	225	270	253

the water (Fig.1, point C). The head, tail and spine lines were slightly stretched to hold the fish in straight, upright position in the water. The frame with the tethered fish was then lowered down into the water and moved into a required distance from the transducer. The fish body was located to a depth of approximately 1.5 m. The distance of the fish was first set to 6.4 m and then to 9.5 m from the transducer. In both ranges, established were two types of design setup.

In experiment 1, the framed fish was positioned sideways to the transducer with its head on the left as seen from the transducer. This position of the fish was held during this setup. The transducer was first tilted to have the fish vertically centered in the DIDSON acoustic field, and second it was panned to left until the fish was no longer visible on the DIDSON images. After a start of recording, the transducer was successively panned from left to right until the echo of the fish disappeared on the other side. Thus, in any location of the ensonified field, the side aspect of the fish was constantly (aligned) perpendicular and in the same range to the transducer, or more precisely to incident linear array. The same routine was performed backwards, from right to left. One round took about one and half minute.

In experiment 2, the transducer’s pan and tilt were trimmed back so that the fish was exactly centered in the middle of the multi-beam array (i.e. horizontally and vertically). This time, the transducer was fixed in this position for the next procedure. The fish was still positioned sideways to the transducer with its head pointing to the left as seen from the transducer. Consequently with a start of recording, the fish was yawed anticlockwise (i.e. rotating along dorso-ventral axis) back to the initial position. One complete turn took 7 minutes, and that was performed twice per fish per range.

After completing these two designs at 6.3-m range, the fish was moved to 9.5-m range from the DIDSON, and all process of both designs was repeated.

Data processing

All acoustic data were processed with Sonar5 Pro post-processing software (Balk and Lindem, University of Oslo). Probability of fish detection was determined as a proportion of positive observations of the fish to all investigated frames in increments of 2.5° off-axis angle and 10° body aspect (i.e. 90-99°, 100-109° and such). Total length and aspect angle of the fish image were manually extracted by deploying an intelligent ruler in DIDSON viewer of Sonar5 Pro. The DIDSON viewer enabled to locate and play only the region of the selected time and range sequence. As a drawing tool, line was used and drawn through a fish image, starting slightly in front of its snout and finishing slightly behind its tail. To find the start and end of fish, the system composed echo intensity along the line with running mean filters for beam size and range (3,3). Consequently, the intelligent ruler searched for minimum and maximum intensity along the drawn line and then measured length according to the selected threshold model (50%). After that, the system was set to advance to the next third frame forth. When fish image was somehow obscured (by signs of the tether or freely swimming fish), the operator skipped that particular frame, and searched for a better fish image in the successive frames. At the edges of the DIDSON's beam array, the fish was subject to processing only when the complete, not partial, fish echo was imaged. The frames that showed signs of the tether or wild freely swimming fish, which occasionally entered the experimental area, were also excluded because the fish image could be somehow obscured. Display threshold and intensity setting were selected in such a way that optimized the contrast of the fish image and background.

For statistical evaluation of acoustic data, we used multiple regressions of Generalized Linear Models in the Mathematica software to assess the error of observed fish length depending on the position within the beam array, body horizontal orientation and distance to the transducer.

Results

Position in the beam array

In the experiment 1, when fish bodies were sideways to the DIDSON transducer, all fish deployed in the study were invariably detected along the 96-beam plane in both ranges (6.3 and 9.5 m). In terms of fish length, we observed similar pattern at all fish used, i.e. the length values were highest in the center and declined to the edges of the beam array (Fig. 3). Relatively, this pattern was least expressed with the largest fish. The error between the observed and true length was modeled in the dependence of off-axis position and range, and was best described by the following quadratic equation:

$$L_{ERROR}\ (\theta, R) = -(0.025 \times \theta^2) + (0.008 \times \theta) - (0.098 \times R) + 1.207 \quad (1)$$

where L_{ERROR} (θ, R) stands for the error of observed fish length in centimeters for given off-axis angle and range from the transducer, θ represents the off-axis angle of DIDSON array in degrees, and R is the distance from the transducer in meters. In the model, only effect of quadratic term significantly accounted for the variability in length error (Table 2). In both ranges, the observed length was slightly overestimated amid of the DIDSON beam array, and underestimated at the edges of the beam array (Fig.4). The decline of the model curve to the edges was slightly sharper in 9.5 meters, but no effect of range was significantly proved (Table 2).

Fish body aspects

In the experiment 2, we focused on dependences of fish body aspect only in the middle of the beam array. The probability of fish detection was strongly dependent upon the fish size and also the distance from the transducer (Fig. 5a). In the closer range, all fish except two smallest ones were successfully detected in all body aspects. Both the smallest, 10-cm and 14.5-cm long, roach failed to be detected in head-or-tail aspects (160-180°, Fig. 5b). The effect of the body aspect was significantly distinct in the 9.5-m range from the transducer. Fish detectability diminished with decreasing size and increasing body aspect to the transducer. The smallest fish, for instance, was no longer detected than in its near-side aspect. In contrast, only the 58-cm long carp retained the full detectability in all body aspects (Fig. 5c).

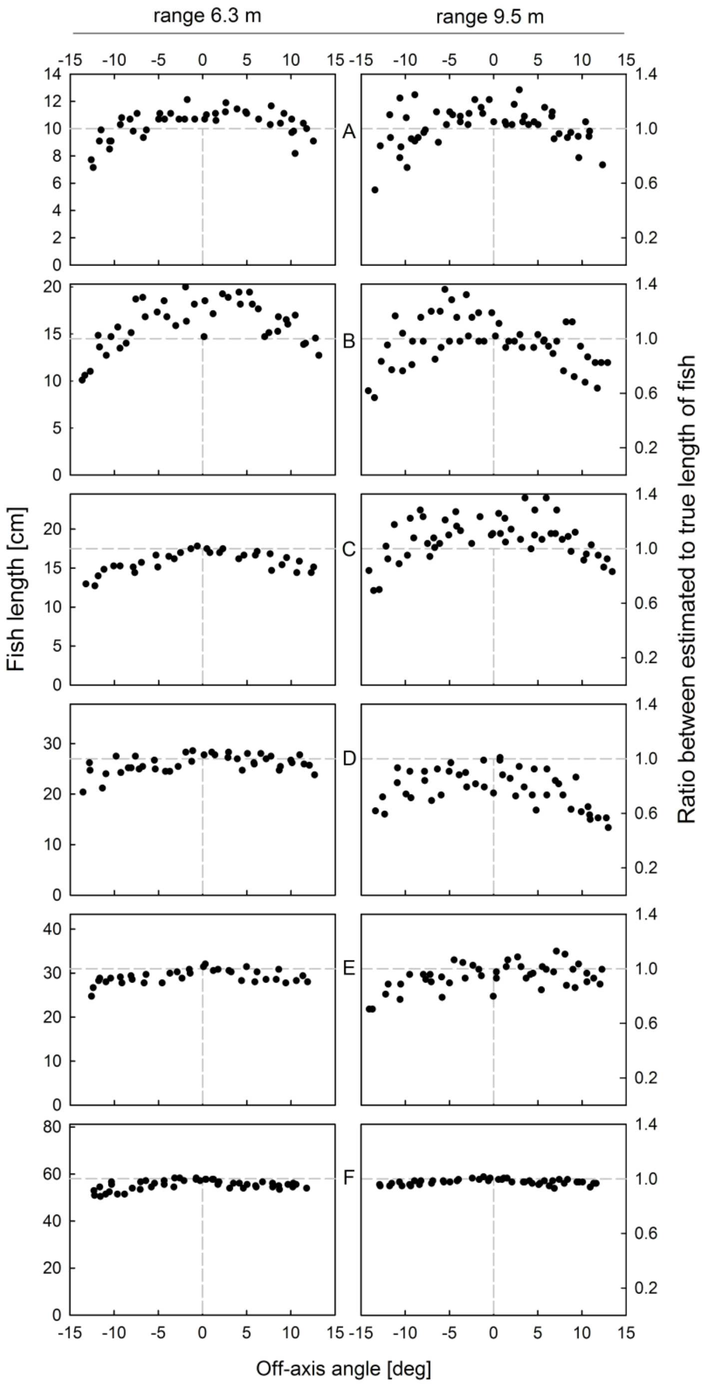

Figure 3. Observed lengths of all fish deployed along all positions in the DIDSON's horizontal plane for two ranges. A horizontal line indicates the true fish size. A vertical line depicts the middle of the DIDSON beam array. A = 10 cm roach, B = 14.5cm

Table 2. Summary table of ANOVA tests for Equation 1 (DF = degrees of freedom, SS = sum of squares, MS = mean square). Significant results are in bold.

	DF	SS	MS	F-Statistic	P-Value
Range	1	9.8	9.8	1.4	0.246
Off-axis angle	1	28.3	28.3	3.9	0.049
Off-axis angle^2	1	894.8	894.8	123.1	**6.86E-26**
Error	534	3880.1	7.3		
Total	537	4813.1			

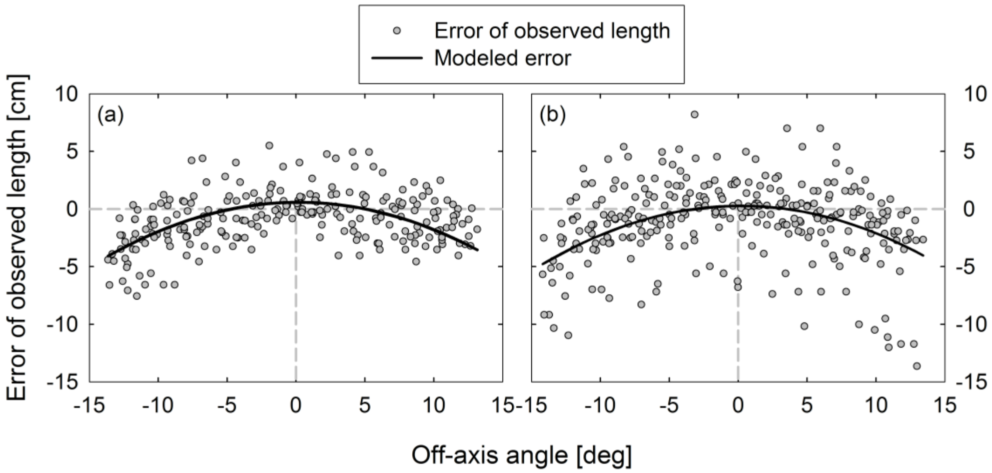

Figure 4. A model for the error of the observed length depending on off-axis angle of DIDSON in (a) 6.3-m range and (b) 9.5-m range.

Also, the observed lengths of the fish had a strong relationship with the actual fish body aspect. With the increase of the body aspect, observed lengths decreased, more markedly at smaller fish sizes and in the further range away from the transducer (Fig. 6). Additionally, the length decline was asymmetrical in larger fish, probably caused by different body dimensions from a fish head to tail. The observed length of the carp, for example, gradually declined to its tail aspect in a "dome-shaped" curve, while towards the head aspect it was more stable until the point where it abruptly declined to half (see E in Fig. 6). A wider girth in the frontal part of the body likely shadowed the thinner caudal part. Furthermore, the 10-cm long roach was not included here. When we started to rotate the fish, the fish images became only a single point (pixel) devoid of apparent prolonged body shape, and consequently disappeared.

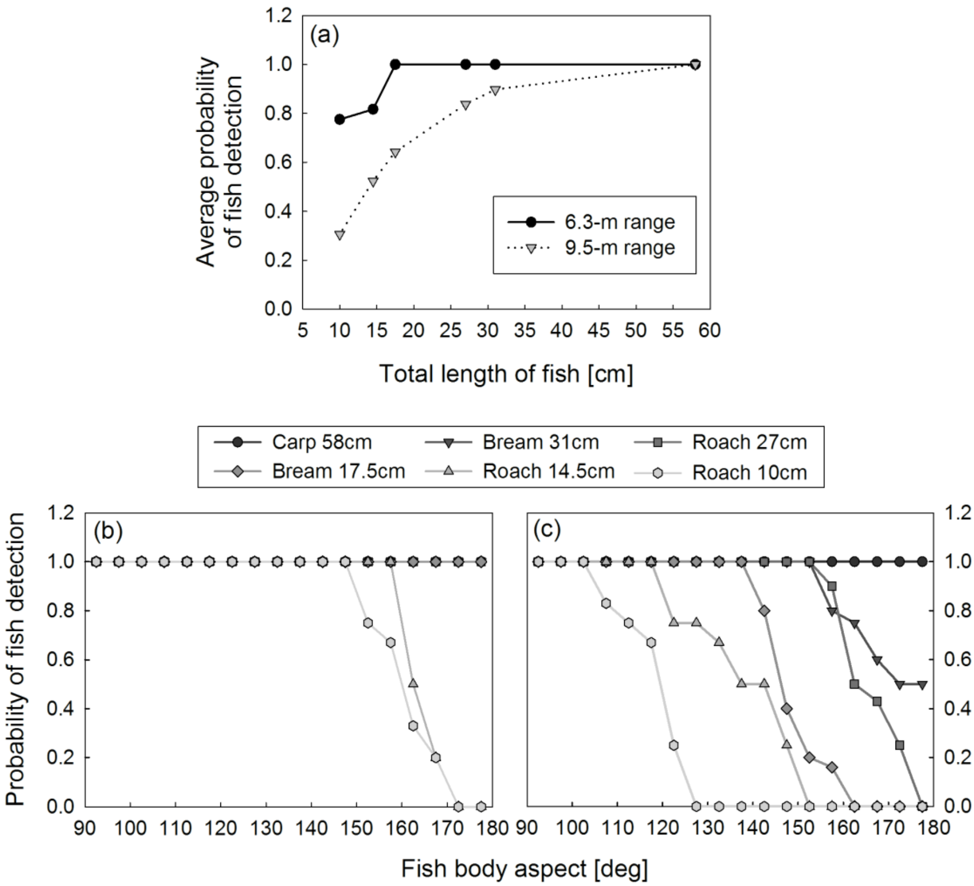

Figure 5. Detection probability of all fish deployed in all body aspects for (a) average for both ranges, (b) 6.3-m range, and (c) 9.5-m range. Data were pooled, i.e. side aspects are represented by 90° and head-or-tail aspects are represented by 180°.

We modeled the error of length estimate in the dependence of fish body aspect and range by the following quadratic function:

$$L_{ERROR}(\alpha,\ R) = -(0.002 \times \alpha^2) + (0.418 \times \alpha) - (1.822 \times R) - 4.449 \quad (2)$$

where L_{ERROR} (α, R) stands for the error of observed fish length in centimeters for given fish aspect and range from the transducer, α represents the body aspect in degrees, and R is the distance from the transducer in meters. For this model, all tested effects were significantly accounted for the variability to the data (Table 3). In the model, the observed lengths in near-side aspects were overestimated at the 6.3-m range, and slightly underestimated at the 9.5-m range (Fig. 7).

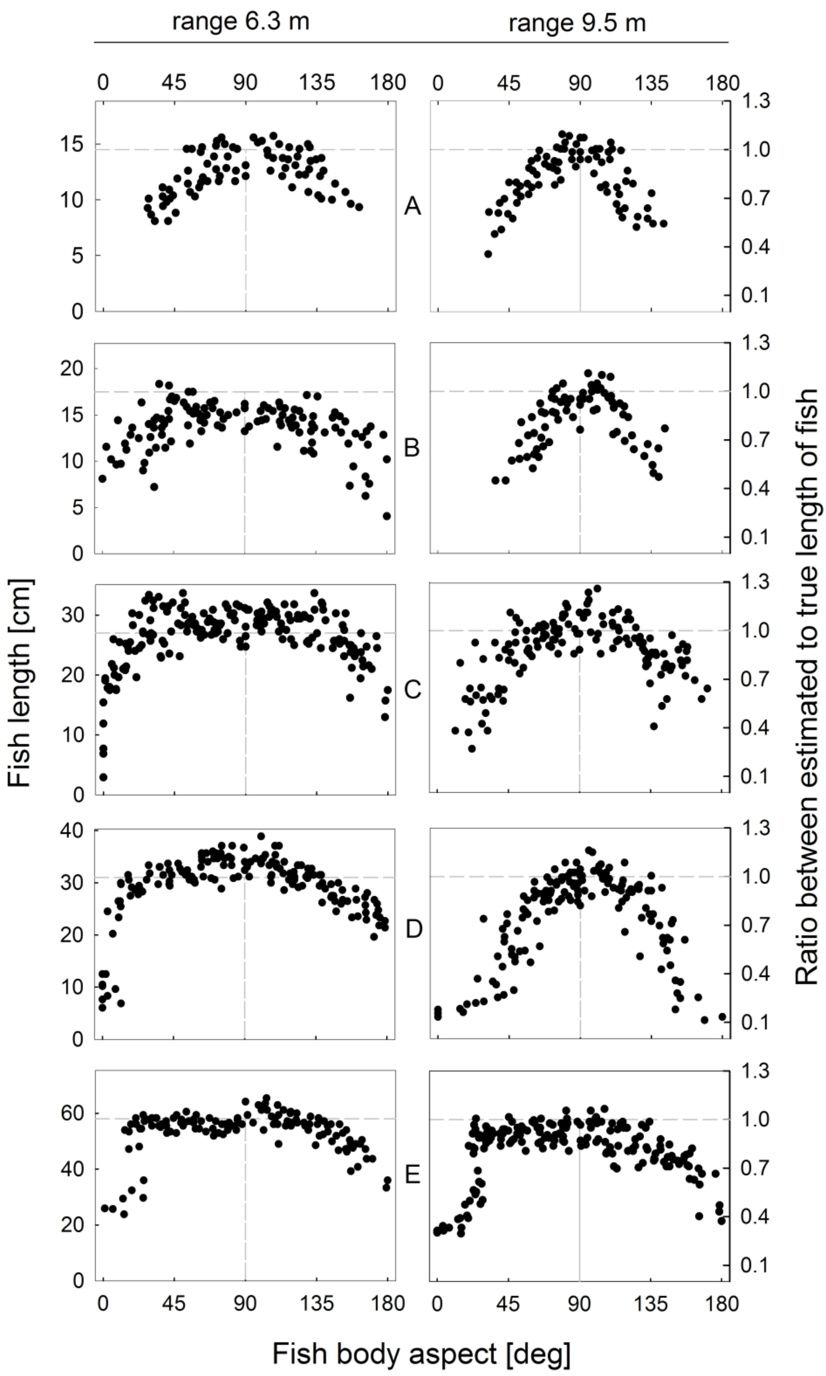

Figure 6. Observed lengths of all the fish deployed in all body aspects for both ranges. A horizontal line indicates the true size of the fish. A vertical line indicates a side aspect of the fish to the transducer. A = 14.5cm roach, B = 17.5 cm bream, C

Table 3. Summary table of ANOVA tests for Equation 2 (DF = degrees of freedom, SS = sum of squares, MS = mean square). Significant results are in bold.

	DF	SS	MS	F-Statistic	P-Value
Range	1	5263.8	5263.8	200.9	**1.45E-42**
Body aspect	1	787.7	787.7	30.1	**5.01E-08**
Body aspect^2	1	29 084.0	29 084.0	1109.8	**2.21E-177**
Error	1328	34 801.5	26.2		
Total	1331	69 937.1			

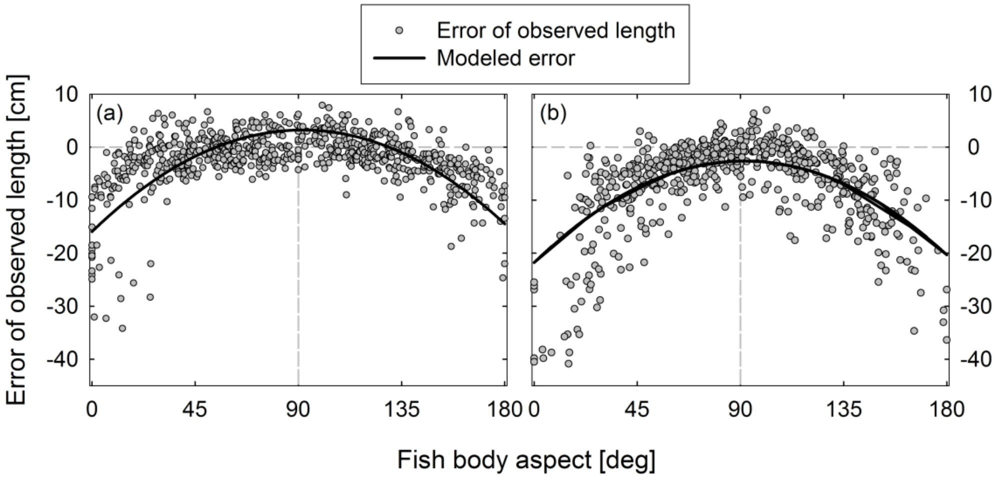

Figure 7. A model for the error of the observed length in all body aspects in (a) 6.3 m range and (b) 9.5-m range.

Discussion

We have shown in this study that the DIDSON sonar was capable to observe all the fish deployed, ranging from 10 to 60 cm in length. The detection and length estimates of the fish, however, markedly depended upon their size, body orientation and range to the transducer.

The detectability of all the fish posed no problem when the fish were sideways to the transducer in any position from the center to edges of the beam array. There can be no doubt that DIDSON possess the best resolution to see the target along 96-beam horizontal plane of its beam array (Moursund et al. 2003). However, the estimate of the fish length diminished to the edges of the beam array. Similarly as Burwen et al. (2010), the error analysis showed that there was no additional effect of range on length estimate. Most likely, the decline of fish length might be caused by lower beam gain intensity or by slightly wider spacing at the edges of the beam array (E. Belcher pers. comm.). Thus, intensity envelope of the same target in these parts will be likely lowered and accordingly shorter.

As shown by the results from the experiment 2, when fish body aspect was altered, the detection probability and observed length of the used fish dramatically declined with diminishing fish size and increasing distance from the transducer. This effect could consist with the decrease of scattered energy and also with declining both the down- and cross-range resolutions of DIDSON are on the decline further away from the transducer (Burwen et al. 2010). Thus, the smaller sizes of targets, the less single beams collide with them, and the worse resolution of the targets is obtained with increasing their body aspects and distance from the transducer. Additionally, we observed an interesting effect that different girth along fish could cause a drastic shortening of the observed length. As a result, it means that a long fish could be easily misinterpreted for a quite smaller fish in these less-reflective aspects. This effect of acoustic shadowing would be obviously matter of larger-sized fish and likely species-dependent.

Furthermore, we encountered another problem in determining fish length. Although we used 0.3 mm thick fishing lines to tether the fish, we experienced that those fishing lines were visible in some cases, usually at some angle. At low signals in some cases, it was difficult to resolve the echoes from the tether and fish. As a result, these echoes from the tether might have been implemented into the fish echo and unintentionally elongated it without a chance to distinguish where the actual echo of the fish commences or terminates. This raises the important question of where to define fish length along the intensity envelope of the fish echo. The length measurement here was based on echo intensity of fish, firmly set to 50% between minimum and maximum. In this study, it seemed to be appropriate threshold to obtain good results in estimating length. Especially at small-bodied fish, which echo intensity is lower to noise, the difference between a terminal pixel of fish outline and the surrounding noise might be small, and this may lead to the misinterpretation of the actual beginning and termination of the fish image. Additionally, signal-to-noise ratio might be also affected by manual fine-tuning setting of threshold and intensity for a better user-defined visual contrast, i.e. altering minimum and maximum level for the resultant echo envelope of the fish. For defining the true length of small-sized fish, advanced filtering of the DIDSON data would be helpful to enhance the signal-to-noise ratio, such as the cross-filter analysis (Balk et al. 2009).

The current DIDSON with its capabilities and functionalities for both data handling and processing cannot be quantitatively used for detection and sizing of fish smaller than 20 cm from variable aspects. As weaker signals are not detected, both detection probability and sizing accuracy were biased in a similar way. The study shows that there is a need to improve signal-to-noise ratio or the resolution of the systems. At special cases, the relationships from this study can be applied to correct recording biases or to estimate the risks of false observations.

Acknowledgement

This study was financed by the project No. CZ.1.07/2.3.00/20.0204 of the Ministry of Education, Youth and Sport of the Czech Republic, and by the project No. P504/12/1186 of the Grant Agency of the Czech Republic.

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Curriculum Vitae

Michal Tušer, MSc.
Faculty of Science
University of South Bohemia
Branišovská 31
370 05 České Budějovice

Study

2008-present **PhD. student** in Hydrobiology

at Faculty of Biology Sciences, University of South Bohemia, CZ

Thesis: Fish detection by modern sonar systems, supervisor: Prof. Jan Kubečka, PhD.

2004-2007 **MSc. degree** in Ecology

at Faculty of Biology Sciences, University of South Bohemia, CZ

Thesis: Fish orientation along the longitudinal profile of the Římov reservoir, supervisor: Prof. Jan Kubečka, PhD.

2001-2004 **BSc. degree** in Ecology

at Faculty of Biology Sciences, University of South Bohemia, CZ

Thesis: The dead zone in acoustic detection of fish near the bottom of reservoirs, in Czech, supervisor: Prof. Jan Kubečka, PhD.

Employment

2002-present **student assistant worker**

at Institute of Hydrobiology, Academy of Sciences of the Czech Republic, České Budějovice

Publications (selected)

Muška M, **Tušer M**, Frouzová, J, Draštík V, Čech M, Jůza T, Kratochvíl M, Mrkvička T, Peterka J, Prchalová M, Říha M, Vašek M, Kubečka J (2013). To migrate, or not to migrate: partial diel horizontal migration of fish in a temperate freshwater reservoir. Hydrobiologia 707, 17-28

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Grants and Projects:

2012 Hydroacoustic distinguishing between fish and bubbles, and quantification of methane bubble ebullition in freshwater reservoirs of temperate zone. Financial support: Grant Agency of the Czech Republic

2011 Fish parasites beyond the Polar Circle, Polar Ecology Course, University of South Bohemia, Svalbard, Norway

2008 Acoustic studies of behavioural patterns among mesopelagic jellyfish Periphylla periphylla. University i Bergen & University i Oslo, Lurefjorden, Norway

2007 The monitoring of a spawning run of shad (Alosa fallax) on the River Ebro. AQUASON C./San Antonio Claret Barcelona, Spain

Conferences:

2012 Polar Ecology Conference 2012, 30th September - 4th October, České Budějovice, Czech Republic
contribution: Fish parasites beyond the arctic circle: Myxozoa (poster)

2010 Fish Sampling with Active Methods (FSAM), 8th-11th September 2010, České Budějovice, Czech Republic (organizer)

2009 Assessment of aquatic ecosystems Quality Using Acoustics (AQUA), 28th May - 5th June, Polish-Norwegian Research Fund, Poland

2008 DIDSON-based Fish Assessment: Techniques for monitoring migratory fish in rivers, Alaska Chapter of the American Fisheries Society with Alaska Department of Fish and Game, 26th-28th October 2008, Anchorage, Alaska contribution: „Detection and accuracy of length measurement with DIDSON“ (oral presentation) and „Mobile DIDSON application by 90° - Depth determination of fish“ (electronic poster)

2008 Ecosystem Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS), ICES 6th Symposium in Acoustics, 16^{th}-20^{th} June 2008, Bergen, Norway
contribution: „Suitability of DIDSON acoustic camera for quantitative fish stock assessment by mobile surveys: Standard acoustic experiment with a fish rotating carousel“ (oral presentation)

2007 Fish Stock Assessment Methods for Lakes and Reservoirs: Toward the true picture of fish stock, 11^{th}-15^{th} September 2007, České Budějovice, Czech Republic
contribution: „Fish orientation along the longitudinal profile of the Římov reservoir” (oral presentation)

2004 ICES Annual Science Conference, 22^{nd}-25^{th} September 2004, Vigo, Spain (as Czech representative)

michal.tuser@gmail.com

Fish detection with modern sonar systems
Ph.D. Thesis Series, 2013, No. 5

Printed in the Czech Republic by Vlastimil Johanus
Edition of 20 copies

University of South Bohemia in České Budějovice
Faculty of Science
Branišovská 31
CZ-37005 České Budějovice, Czech Republic

Phone: +420 387 772 244
www.prf.jcu.cz, e-mail: sekret@prf.jcu.cz