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Water bodies in Europe: Integrative Systems to assess Ecological status and Recovery

DELIVERABLE

Deliverable 3.4-3: Guidelines for standardisation of hydroacoustic methods

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PP	Restricted to other programme participants (including the Commission Services)	
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Content

Non-technical summary

The use of transmitted underwater sound to survey fish populations (known effectively interchangeably as hydroacoustics, echo sounding or sonar) has a long and extensive record of successful application, particularly in the marine environment where most of its major developments have historically taken place. In recent decades, technological developments, including the miniaturisation of electronic components and rapidly increasing computing power, have facilitated the production of hydroacoustic systems which can be readily deployed from small vessels on fresh waters. The present document gives an introduction to this still developing field and provides a set of guidelines specifically for the application of hydroacoustics to the investigation of fish populations in European standing freshwater bodies. As such it will help to produce hydroacoustic surveys which are compatible with current best practice, well reported and will facilitate the future valid comparison of hydroacoustic datasets for lakes and reservoirs from across Europe. In addition to explaining the basic principles of hydroacoustics and reviewing appropriate hardware and software currently available, guidance is also given on pre-survey planning (general considerations, design of survey route, sound transmission and recording parameters), survey and data acquisition (immediate pre-survey activities, survey itself, immediate post-survey activities), post-survey data analysis (general considerations, choice of analysis method, echo counting, trace counting, echo integration, further processing of analysis results), and finally reporting and data archiving.

1. Introduction

The use of transmitted underwater sound to investigate fish populations has a long and extensive record of successful application, particularly in the marine environment where most of its major developments have taken place. Simmonds and MacLennan (2005) provide an authoritative history of this well studied but still rapidly evolving field, which in the freshwater environment is now most commonly referred to as hydroacoustics, although the terms echo sounding and sonar (originally an acronym for SOund Navigation And Ranging) are still used, effectively interchangeably, to some extent. The very efficient transmission of sound in water, particularly when compared with that of light, makes this remote-sensing technique highly effective in most aquatic ecosystems and under many environmental conditions. As a result, it provides a valuable complement to capture-based sampling techniques.

The first scientific experiments using what would now be called hydroacoustics to detect fish were made by Kimura (1929) using large (individual length 40 to 50 cm) sea bream (*Pagrosomus major*) held in a pond and insonified with continuous sound at a frequency 200 kHz. The following decade brought the first hydroacoustic studies of fish in their natural environment, with Sund (1935) recording the vertical distribution of cod (*Gadus morhua*) in the Lofoten area of Norway. Commercial development of the technique quickly followed and found an obvious application within the sea fishing industries of Europe and elsewhere. The arrival of the Second World War and the associated need for surface vessels to increase their abilities to detect submarines provided further impetus and hydroacoustic systems rapidly became more powerful and sophisticated. However, these systems were still relatively large and relatively very expensive. With very few exceptions, their scientific use was largely restricted to marine investigations where large vessels and large budgets were available and where scientific advances have been nurtured and standardised by the International Council for the Exploration of the Sea and other international bodies (Fernandes *et al.* 2002).

Remarkably, it was not until the 1970s that technological developments, including the miniaturisation of electronic components and rapidly increasing computing power, facilitated the production of hydroacoustic systems which could be readily deployed from small vessels on lakes, reservoirs and rivers (Brandt 1996). Even so, few hydroacoustic studies of fish were carried out on fresh waters until the mid 1980s, when the advent of early personal computers produced breakthroughs in the ability to digitise data, analytical ability and lower system costs and was followed by an explosion in the numbers of such studies (e.g. Thorne 1983; Burczynski and Johnson 1986; Jurvelius and Auvinen 1989). Freshwater hydroacoustics as a field has been periodically reviewed in subsequent years, including the production of guidelines to varying degrees of detail. Notable articles in this context include those of Brandt (1996), Maxwell (2007), Taylor and Maxwell (2007), Beauchamp *et al.* (2009), Parker-Stetter *et al.* (2009), CEN (2009) and Rudstam *et al.* (submitted).

Standardised guidance is now available on the conditions under which hydroacoustics is an appropriate technique for surveying fish populations in fresh waters in both North America (Bonar *et al.* 2009) and Europe (CEN 2006), with additional perspective on the subject given by Kubecka *et al.* (2009). However, all but one of the above hydroacoustic guidelines (i.e. Brandt 1996; Maxwell 2007; Taylor and Maxwell 2007; Beauchamp *et al.* 2009; Parker-Stetter *et al.* 2009; Rudstam *et al.* submitted) specifically consider application to fresh waters in North America, including the exceptional water bodies of the Great Lakes, and the sole document specific to Europe is that of CEN (2009) which addresses mobile hydroacoustics in both standing and running fresh waters. However, it should be noted that CEN (2009) is only a stage within the formal CEN standardisation process and so a full CEN standard for hydroacoustics in Europe has not yet been completed.

The aim of the present document is to provide a set of guidelines specifically for the application of hydroacoustics to the investigation of fish populations in European standing freshwater bodies, i.e. lakes and reservoirs. It is written for an audience with no or little previous knowledge of hydroacoustics. As such, it is not written with the high technical detail of guidelines for surveys of the Great Lakes given in over 38,000 words by Parker-Stetter *et al.* (2009), nor does it have the broad habitat coverage of mobile hydroacoustics on both standing and running fresh waters as given by CEN (2009). It will, however, give an introduction to this still developing field (Kubečka *et al.* 2009) and help to produce hydroacoustic surveys which are compatible with current best practice, are well reported and will facilitate the future valid comparison of hydroacoustic datasets for lakes and reservoirs from across Europe. Note that although hydroacoustics can also be used to study zooplankton, macrophytes and the bottom substrate (Godlewska *et al.* 2004), such applications are beyond the scope of the present guidelines and so are not considered further here.

2. Hydroacoustic background

2.1 Basic principles

The basic principles behind the use of hydroacoustics for the investigation of fish populations are relatively simple. Essentially, an instrument called an echo sounder is used to transmit a pulse of sound into the water column where it spreads much like the pattern of light spreading from a hand torch. The sound travels at a speed of approximately 1500 m s^{-1}, with its exact speed in fresh waters depending primarily on temperature. The sound may be directed vertically or horizontally and effectively insonifies a cone of water with each pulse (Figure 1). When this wave meets an object (usually referred to as a target) of density different to that of the water, it is reflected, again spreading like light from a hand torch, and a component of this reflected sound reaches the echo sounder where it is recorded as an echo (further details of subsequent analyses of such echoes are considered in Section 6). For each pulse of sound, the echo sounder records the time taken for the echo to return (which using the speed of sound can be readily converted to target distance), its strength and, in most systems currently in use (so-called split-beam systems, see Section 3.1), its direction relative to the echo sounder. A modern echo sounder is usually composed of three basic components, i.e. a surface unit which essentially generates electrical instructions for the production of sound, a laptop computer which controls the surface unit, records data, and provides real-time information in the form of an echogram (Figure 2) and display of other data, and an underwater component called a transducer which converts the electrical instructions into a sound wave and then detects returning echoes and converts them back into an electrical signal which is then further processed by the system. In addition, a Global Positioning System (GPS) unit is usually connected to the echo sounder to record location information. Further details of the hardware and software of echo sounders are considered in Section 3. On lakes and reservoirs, hydroacoustic data are usually collected effectively continuously from a boat moving along a number of contiguous or spaced pre-planned transects. The data then require substantial post-survey processing in order to produce information on fish abundance, distribution and other features. There are three main methods for such analysis, i.e. echo counting, trace counting and echo integration, each with relative strengths and weaknesses and which will be considered in detail in Section 6. These basic principles encompass a large degree of technical complexity at all steps of the hydroacoustic process. Fortunately, knowledge of all this detail is not essential for the successful application of the technique, but the practitioner should be at least aware of the following complexities and limitations.

2.2. Underwater sound and its propagation

The frequency of the sound used varies considerably but in most freshwater applications it typically ranges between 70 and 420 kHz with some specialised so-called multi-beam (see Section 3.1) systems using much higher frequency sound of up to 1.8 MHz. In most systems, this frequency is fixed by properties of the hardware and so it is rarely variable in the field, although the simultaneous deployment of more than one transducer (so-called multiplexing) can overcome this limitation to some extent. Higher sound frequencies generally give better detection of targets, but they also penetrate through water less effectively than lower frequencies although this only becomes a practical limitation in very deep lakes with a water depth in excess of 100 m. The shape (circular or elliptical) and width (or angle, typically between 6 and 12° for a circular beam and typically approximately 2 by 10° for an elliptical beam) of the sound beam

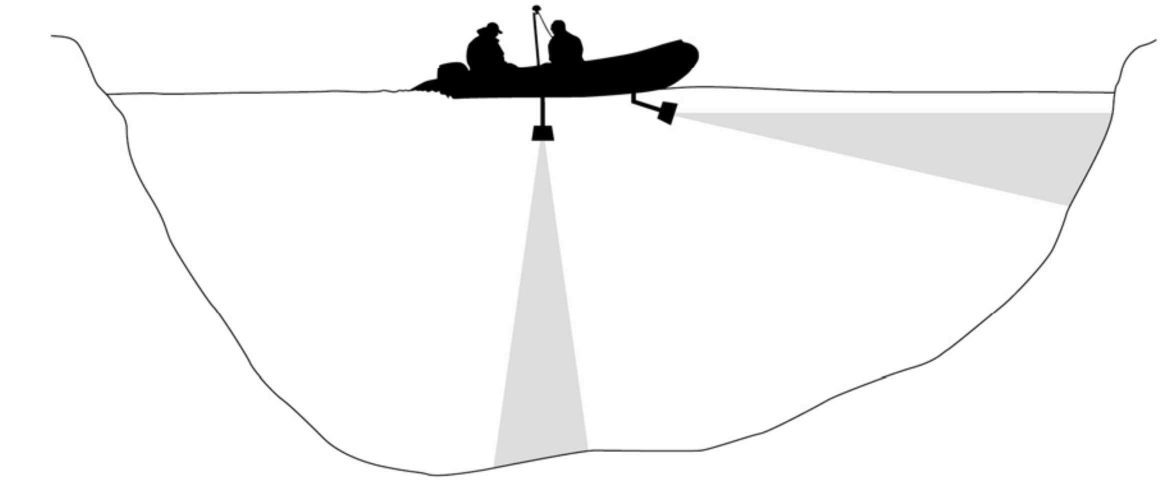

Figure 1: Vertically and horizontally orientated transducers as deployed in a hydroacoustic survey of a lake or reservoir. Sound beams are shown as shaded triangles, although in reality they each approximate to a cone much like the pattern of light spreading from a hand torch.

is also a function of hardware and cannot be altered, although post-survey data analysis can be constrained to echoes within various parts of the beam. In contrast, the duration (or length) and rate (or interval between) each pulse of sound can be readily varied and typical values used in freshwater studies are 0.1 to 0.6 ms and 0.1 to 10.0 pulses s^{-1}, respectively, with different combinations having different advantages and disadvantages. It is particularly important to appreciate that decisions must be made on specific settings for all of these values before a survey begins and that they cannot be altered in any post-survey data analysis.

Description of the quantification of the passage of sound to and from a target is a very technical process and is beyond the scope of these guidelines. An excellent account of this issue is given by Parker-Stetter *et al.* (2009) with detailed reference to the so-called sonar equation, which is summarised here qualitatively as

Size of echo = Signal transmitted – loss on transmission + size of target – loss on return

The full sonar equation also allows for any loss due to the target being off the main axis of the hydroacoustic beam. In the present context, the size of the target is determined by its acoustic reflectivity which is frequently referred to as its target strength (TS) and is measured in decibels (dB). Note that the decibel is a logarithmic unit and is relative to a specified reference level.

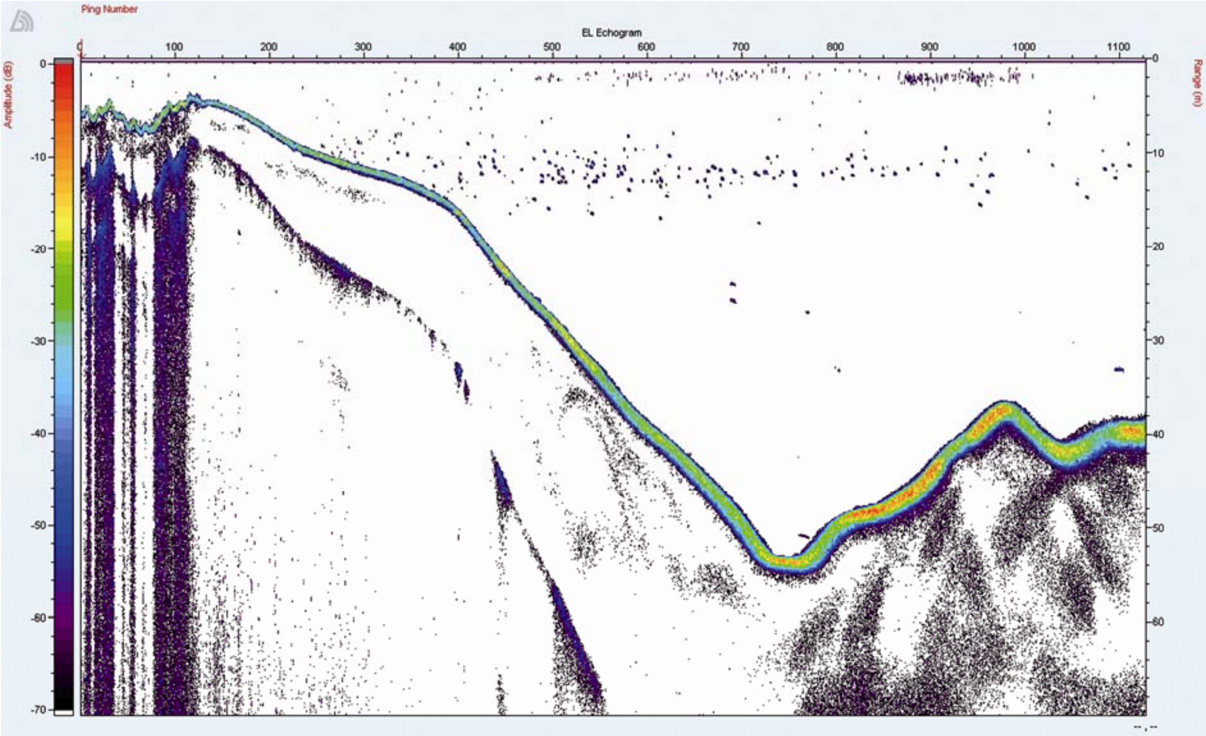

Figure 2: An example echogram produced along part of one transect during a night-time vertical survey of a deep lake. The horizontal axis represents time elapsed (equivalent to horizontal displacement in a mobile survey) while the vertical axis, labelled on the right of the figure, represents range from the transducer (effectively water depth in a vertical survey) running here from 0 m at the top of the figure to 70 m at its bottom. The thick predominantly green line is the bottom echo, with individual fish represented by small blue marks clustered mainly at a depth of 8 to 14 m. Marks below the bottom line are artefacts of no direct relevance to fish surveys. Colours of the bottom and fish echoes are indicative of their strength in dB, with a key running down the left of the figure. Produced using BioSonics Visual Acquisition 6.0 software.

Thus, a -3 dB difference between two values of TS implies a 50% reduction. To some extent, the TS of a given target is also a function of the sound frequency being used (Guillard *et al.* 2004; Godlewska *et al.*, 2009) and so this factor must also be taken into account. Again, it is stressed that this is a highly technical area and Parker-Stetter *et al.* (2009) may be consulted for a more detailed account beyond the following essential summary.

The journey of the sound wave to and from the target is essentially one of a two-way spreading, although a further complication exists in that the outward and inward sound beams do not have an abrupt edge. Modern transducer designs focus the sound primarily along an axis running perpendicularly to the transducer, but so-called side-lobes of sound inevitably exist away from the main axis and may cause complications under certain circumstances. In addition to the spreading effect, a small part of the sound energy is lost as heat during both journeys. These factors combine to result in the fact that the strength of an echo received from a target is a function not only of the acoustic properties of the target itself, but also of its distance from the transducer. In addition, echo strength is also influenced by the target's position in the cross-section of the sound beam. This effect can be taken into account in echo processing, but the accuracy of this procedure decreases with increasing distance of the target from the axis. Consequently, in applications where a very accurate measurement of target strength is needed only echoes originating from targets within the central part of the sound beam may be valid. Constraining consideration to such echoes is readily achievable in post-survey data analysis. The accurate determination of target strength for individual fish also requires that only echoes originating from single individuals, and not compound echoes arising from two or more fish in close proximity, are taken into analysis. Again, a number of echo features can be exploited to identify such single echoes in post-survey data analysis procedure usually termed single echo detection (SED).

2.3 Acoustic properties of underwater targets

The acoustic properties of the target itself are basically driven by its density difference from the surrounding water which means that a larger fish will tend to produce a stronger echo than a smaller fish. Dynamic ranges are extremely high in modern echo sounders (typically running at least from less than -90 dB to -20 dB) and so there is no practical limitation on the ranges of target strength that can be detected in freshwater applications, although again there are some complications. For fish species which possess a swim bladder, which includes most species likely to be encountered in European fresh waters, this organ is the main source of reflected sound. However, some sound is also reflected by other parts of the body and the strength of the resulting echo is also dependent on the orientation of the fish (Frouzova and Kubečka 2004; Frouzova *et al.* 2005). Given that the swim bladder is typically horizontally elongated in shape, this means that, for example, an individual fish swimming horizontally and insonified from above will produce a stronger echo than if it was swimming vertically. As most fish spend most of their time in a horizontal orientation, this means that hydroacoustic surveys using a vertical beam of sound will tend to produce relatively robust measurements of target strength and so approximate individual sizes can be reliably inferred from target strengths. However, if such horizontally-orientated fish are insonified with a horizontal beam of sound, then they are much more likely to be hit at a range of incident angles and so the target strengths of their echoes will show much more variation. In practice, this means that it is difficult to determine individual sizes of fish using horizontal hydroacoustic surveys in lakes and reservoirs.

2.4 Some inherent limitations of hydroacoustics

Echoes are also produced by targets other than fish. Echoes from the lake or reservoir bottom are typically very strong and readily identified in either real-time or post-survey data processing. In most situations, echoes from macrophytes or other targets projecting from the bottom are also easily distinguishable, although they can compromise surveys if they are sufficiently abundant.

Echoes from other targets within the water column itself can be more problematical, particularly if they are abundant and/or strong. In lakes and reservoirs, plankton is the most frequent source of such unwanted echoes, although they are usually of low target strength and can usually be eliminated during post-survey data processing. In some water bodies, gas bubbles rising from the bottom sediment may also be a significant complication (Rustadbakken *et al.* 2010). The magnitude of the difference between echoes originating from fish and such ‘unwanted’ echoes originating from plankton or other non-fish sources within the water column is termed the signal to noise ratio (SNR). A high SNR is always desirable for post-survey data analysis and many echo sounder parameters may be adjusted to maximise it, but in some field situations SNR is inherently low and unavoidably limits the kinds of analyses which can be carried out.

The use of hydroacoustics as a technique for surveying fish populations in lakes and reservoirs must also take into account two so-called blind zones. Firstly, in the immediate vicinity of the transducer termed the near field the sound intensity is unpredictable and so echoes detected here are unreliable in terms of fish surveying. In addition, the volume of water insonified in this region before the beam has spread out is very small and the transducer face is itself typically deployed at least 0.5 m below the water surface. These factors combine to produce an effective upper blind zone in the immediate vicinity of the transducer, the size of which depends to some extent on sound frequency but is typically between 1 and 2 m in extent. Secondly, the echoes of any fish in close association with the lake or reservoir bottom may be indistinguishable from those of such larger targets. In practice, this produces a lower blind zone of typically 0.5 to 1 m in extent. Lake or reservoir areas with particularly steep bottom gradients may have a wider lower blind zone due to the side-lobes of the acoustic beam hitting the rising bottom.

2.5 Further reading

The above account still remains a great over-simplification of both the theory and practical application of sound transmission in water for surveying purposes. Almost all of the aspects mentioned are either considerably more complex in theory, in reality, or in both. Fortunately, they are also very well understood, although in parts not without a good understanding of the fundamental physics of sound and a fair mathematical capacity. A particularly detailed but accessible account of this complexity is given from a marine perspective by Simmonds and MacLennan (2005), with a less detailed but highly readable freshwater view given by Parker-Stetter *et al.* (2009). Both of these articles are strongly recommended as essential background reading for researchers intending to lead hydroacoustic surveys for fish, although knowledge and understanding of their details are certainly not required for support staff and others conducting and to some extent analysing the results of such surveys.

3. Equipment hardware, software and training

3.1 Hardware

As mentioned above, modern hydroacoustic systems are much smaller, more rugged and thus far more portable and reliable than those in use a few decades ago and this development has been fundamental to their increased use on fresh waters. In terms of equipment suitable for deployment on lakes and reservoirs, the European market is dominated by BioSonics (BioSonics Inc., U.S.A. www.biosonicsinc.com), HTI (Hydroacoustic Technology Inc., U.S.A. www.htisonar.com) and Simrad (Simrad Kongsberg Maritime AS, Norway. www.simrad.com). All three companies have been active in the hydroacoustic manufacturing and research fields for many years, during which time equipment has evolved from the original single-beam systems (which cannot directly determine the location of a target across the sound beam), through a generation of dual-beam systems (which can only directly determine the radial location of a target across the sound beam), to the current generation of split-beam systems (which can directly determine the full location of a target across the sound beam). While single-beam systems can still be used for fish surveys in some situations, they are significantly out-performed by the two later classes of systems. Furthermore, the most recent and most sophisticated class of split-beam systems has a number of distinct advantages and so is strongly recommended for use in all fish investigations in lakes and reservoirs. Finally, there is another very different family of multi-beam systems operating at very high sound frequencies. However, these systems have limited applications to surveys in lakes and reservoirs and so will not be considered further here.

Systems made by BioSonics, HTI and Simrad all offer options for sound frequencies over the range typically used in freshwater applications, transducers suited for vertical and horizontal applications, provision for direct inputs of location data (essential for some types of hydroacoustic data analysis and highly desirable for all) from a GPS unit, are of similar physical size and weight, and can be powered from a 12 volt battery or from the in-board power systems of larger survey vessels. Some differences do exist in capabilities and performances, but these are highly technical beyond the scope of these guidelines and are subject to frequent change as modifications and new models are developed. The websites of all three manufacturers provide further technical details of available models and system configurations and should be consulted for up-to-date information. Transducer orientation sensors, transducer rotators and other miscellaneous hardware components are also available but are not fundamentally essential for most applications. A calibration sphere for periodic field checks of system performance should also be acquired as part of any hydroacoustic system. The hydroacoustic system should also be periodically serviced and factory calibrated in accordance with the manufacturer's recommendations.

Finally, hydroacoustic surveys typically produce several hundred megabytes of data and so, although not strictly part of the hydroacoustic system, a substantial and robust data archiving system is essential. It is also recommended that post-survey analyses (see Section 6) are carried out on copies of the original data files.

3.2 Software

BioSonics, HTI and Simrad all provide proprietary software for use on a standard or ruggedised laptop computer to control the echo sounder during surveys and for other associated tasks in the field. Specialised software is also essential for post-survey data analysis. Again, all three manufacturers provide analysis software of varying complexity as part of their systems and their websites can be consulted for details. Data certainly can be and are analysed using only such software, but many researchers also use analysis software produced by third parties. In addition to more sophisticated and often faster analytical capabilities, such third party software can read the propriety data files produced by hardware from the different manufacturers. This is a major advantage for collaboration between researchers using different hardware systems and is an approach long-adopted by the marine hydroacoustics research community, where international collaborations have been commonplace for many years. Many members of the marine community have standardised on Echoview produced by Myriax (Myriax Software Pty Ltd, Australia. www.myriax.com), which was initially developed for large-scale marine applications but is now also used by some members of the freshwater community. Alternatively, Sonar5-Pro produced by Lindem Data Acquisition (Lindem Data Acquisition, Norway. www.fys.uio.no/~hbalk/sonar4_5/index.htm) was originally developed for use with data collected from lakes, reservoirs and rivers and in Europe at least is becoming established as the *de facto* standard for data analysis.

3.3 Training

It is highly desirable and arguably essential that researchers intending to lead hydroacoustic surveys are provided with some level of training. BioSonics, HTI and Simrad all periodically offer multi-day training courses covering the general principles of hydroacoustics and the specific hardware and software components of their systems. Similarly, Lindem Data Acquisition and Myriax also periodically run training events including courses and workshops. Although the internet facilitates tremendous distance learning and technical support, there is no substitute for focussed, hands-on training events. Once a project leader is trained, he or she can then pass on in-house appropriate levels of training to support staff and others conducting and to some extent analysing the results of surveys.

4. Pre-survey planning

4.1 General considerations

As with any scientific investigation, the first step in planning a hydroacoustic survey of fish in a lake or a reservoir should be to define its objectives. In many cases these will be given at least in general terms by outside agencies, but even in such situations they are likely to need further refinement in order to be able to guide the many subsequent strategic and tactical technical decisions which will have to be made. The objectives of applications of hydroacoustics to fish populations in lakes and reservoirs are usually concerned with their abundance or spatial distribution, although other features such as their size structure may also be under investigation.

The next essential step is to gather as much background information as possible. In many instances there may have been previous hydroacoustic investigations at the study site, although these may have been made using a different echo sounder to that currently available. Nevertheless, their technical details and results are extremely valuable in determining the appropriate approach and parameter settings for the planned survey. At the other extreme, there may be a complete absence of relevant background information and in such circumstances a preliminary survey is highly desirable, although in practice it may be impossible for various reasons. Most situations will fall between these two extremes, with some degree of background information available.

An essential prerequisite is a map of the study site, preferably digital and preferably with depth contours. The depth of the study site is a major determinant of whether the hydroacoustic survey should use a sound beam orientated vertically, horizontally, or two beams orientated in both directions. Vertical hydroacoustic surveys have by far the longest history of application and continue to be the most common of the three approaches. They are generally more robust in terms of both data collection and subsequent data analysis and so, where the upper blind zone does not present a major limitation (Knudsen and Sægrov 2002; Djemali *et al.* 2009), they are generally the preferred option. Horizontal surveys are extremely sensitive to survey vessel roll and pitch. Although a rotator can help to counter this problem to some extent, the resulting data have some inherent limitations in terms of determining target strength. In addition, as demonstrated by Gangl and Whaley (2004), horizontal surveys are also strongly influenced by wind conditions. Surveys of each orientation can be performed with circular or elliptical transducers, but the former type is usually employed in vertical studies and the latter type is used in horizontal applications with the ellipse aligned parallel to the water surface.

Even if depth contours are available they should be treated with caution in case they are inaccurate or, in the case of a reservoir, water levels are lower at the time of the planned survey. In their absence, maximum depth is available for most water bodies and can be used to set the maximum recording range in the planned survey, which should be set to maximum depth plus a margin of safety of several metres. For reasons discussed earlier, echoes recorded within the first few metres from the transducer are of little practical use and so a minimum recording range of 1 or 2 m is also frequently used. However, high data storage capacities of modern hydroacoustic systems are such that there is little cost to recording data up to the transducer face itself. Such information may be useful when diagnosing echo sounder malfunctions and so is recorded by some researchers.

Temperature and oxygen profiles of the water body are also useful background information. Strong thermal stratification may alter the propagation of sound significantly, particularly during horizontal surveys, while marked oxygen depletion at depth may impact the vertical distribution of fish.

Information should also be collected on biological features of the study site. Knowledge of the fish species present and their ecology is invaluable in determining the most effective timing of the planned survey and the most appropriate target strength – fish length relationship to be used in post-survey data processing. Such information on the fish community should ideally come from historic or contemporary scientific sampling, but information from fishery sources is also useful. In addition to fish species present, it is also useful to have information on their local spatial distributions and movements. The timing of the planned survey should be such so as to avoid any periods when fish aggregate in dense groups, such as during spawning or in some species during the winter, concentrate close to the lake or reservoir bottom, move to very shallow littoral habitats, or when some component of their populations has temporarily migrated completely out of the water body. The complex field of fish spatial distribution and movements, with a particular focus on implications for hydroacoustic studies, is usefully reviewed by Lucas *et al.* (2002). In particular, although some species can be effectively surveyed during the day, particularly in deep lakes, many species form dense shoals during daylight which can be difficult to quantify. In general, hydroacoustic surveys are usually most effective at night when individuals are more dispersed and less associated with the bottom or other physical structure (Vondracek and Degan, 1995). Hydroacoustic surveys are best avoided at times of rapid changes in light levels such as dusk and dawn, or times of unusual lighting conditions such as the full moon on a clear night. Seasonal patterns in fish abundance also occur, with their numbers changing as a function of summer-time recruitment and winter-time mortality (Winfield *et al.*, 2007). If the distribution and movements of fish in the water body to be surveyed are not well known, an appropriate approach is to conduct both day and night hydroacoustic surveys at some time within the summer months when fish are likely to be most dispersed.

Background information should also be sought on non-fish biological aspects of the study site. The abundance of plankton, particularly *Chaoborus* larvae (Knudsen *et al.*, 2006), may generate substantial unwanted echoes and thus lower the SNR and influence the most appropriate sound frequency to be used. If substantial plankton echoes are expected, if possible a sound frequency towards the lower end of the available range such as 70 kHz should be used. Knowledge of local macrophyte distribution is also important because if sufficiently abundant it can compromise hydroacoustic surveys of fish, although this is usually only a significant problem for horizontal surveys in shallow water areas.

4.2 Survey route

Many designs of survey routes, each typically comprising a number of individual transects, have been used in hydroacoustic investigations on lakes and reservoirs and their relative advantages and disadvantages are usefully reviewed by Yule (2000), Taylor *et al.* (2005), Guillard and Verges (2007) and Parker-Stetter *et al.* (2009). Two forms have been used with particular frequency, i.e. systematic parallel and zig-zag (Figure 3). The systematic parallel design has some statistical advantages, while the near-continuous collection of data allowed by the zig-zag design is very efficient but its subsequent analysis must beware of over-sampling in the region of the ends and starts of successive transects. The ziz-zag design also has the practical advantages of minimising the time that the survey vessel is in shallow inshore water, with its attendant dangers (particularly at poorly known study sites at night), and of being the only feasible design in very narrow riverine reservoirs. Note that whatever survey route is planned, it may subsequently have to be altered slightly in the field to accommodate unexpected areas of very shallow water, extensive growths of macrophytes, or even islands.

The sampling effort required in a particular hydroacoustic survey in terms of the length of the survey route is dependent on a number of factors, including the physical complexity of the study area, the variation in population density of the fish, and the level of precision required by the study (Aglen, 1983). At least one of these factors is unknown at the start of the survey and so thorough and robust guidance on appropriate survey lengths cannot be given in advance. However, a useful measure of hydroacoustic sampling effort is the degree of coverage which is defined as the survey length (in km) divided by the square root of survey area (in km^2) and as a guide this should be at least 3.0 and preferably as high as 6.0. While in theory the degree of coverage can be increased simply by adding more transects to the survey design to increase survey length, in practice this aspect of sampling effort is usually constrained by changing environmental conditions and by logistical factors (Simmonds and MacLennan, 2005), which on fresh waters may include battery life, available survey time, survey vessel speed and operator fatigue. While battery life can be effectively extended simply by carrying spare batteries or even using a generator if the survey vessel can carry one, survey vessel speed is usually limited to less than 10 km h^{-1} and in many cases will be significantly lower than this for various reasons.

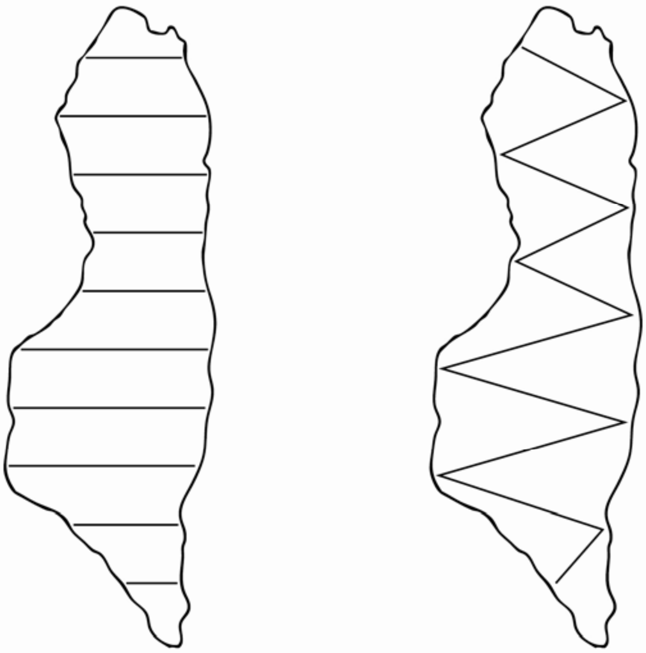

Figure 3: Diagrammatic examples of systematic parallel (left) and zig-zag (right) designs for a hydroacoustic survey in a lake or reservoir. In each case, the survey is composed of 10 individual transects. In the systematic parallel survey, data recording is stopped as the survey vessel moves along the inshore area between transects (not shown).

On lakes and reservoirs, depending on the survey vessel and environmental conditions a speed of between 6 and 8 km h^{-1} is often considered to be appropriate. Operator fatigue is a particularly significant issue when working from a small open survey vessel during night surveys. In practice, this means that hydroacoustic surveys on lakes and reservoirs are usually limited to less than 3 h of active survey time. If a water body is of such size that an acceptable degree of coverage cannot be achieved in one survey session, then consideration should be given to completing the survey over several consecutive days or nights provided that environmental conditions remain consistent.

Once a survey route has been designed, it should be transferred to a GPS unit, possibly independent of the unit used to input location data into the echo sounder, to facilitate subsequent navigation during the survey.

4.3 Sound transmission and recording parameters

Based on the background information assembled as described above, settings must be decided upon for sound transmission and recording parameters. On lakes and reservoirs, pulse duration settings from 0.1 to 0.6 ms are appropriate and a value of 0.3 or 0.4 ms may be considered as a suitable default. For example, using a 70 kHz system Godlewska *et al.* (2011) demonstrated that there is no effect of variations in the pulse duration on estimates of fish densities and size distributions, although a long pulse length (i.e. greater than 1.0 ms) should be avoided when fish density is high. Similarly, appropriate pulse rates may vary from 0.1 to 10.0 pulses s^{-1}. However, maximum depth of the water body may constrain the feasible pulse rate because of the danger of a too high value resulting in the appearance of a false bottom echo within the water column. In water columns of up to 50 m in depth a rate of 5 pulses s^{-1} is a suitable default value, but beyond this a lower pulse rate should be explored. While maximum depth may in theory impose some constraint on options for these parameters, in practice this is not a significant issue for all but the deepest lakes in Europe. As implied above, the aim of any alterations to these default settings should be to increase SNR as discussed in Section 5.1. In practice, this can only be carried out on the water and so, if they are explored, adjustments should ideally be made in a preliminary survey or in a short test run immediately before the survey itself.

Decisions must also be made concerning the data to be recorded during the survey. These essentially cover the range from the transducer and strength of the echoes. If data storage space is a concern, then a range of from 2 m from the transducer face to 3 m beyond the maximum depth (or in horizontal work the distance at which SNR becomes too high for any analysis) is usually appropriate. If storage space is not a limitation, then a recording range of from the transducer face to 3 m beyond the maximum depth (or in horizontal work the distance at which SNR becomes too high for any analysis) should be used. If there is any doubt concerning the maximum depth of the water body, then the recording range should be extended appropriately. The only cost to recording data beyond the maximum depth is the call on data storage space. With respect to echo strength, if storage space is limited a recording threshold of -70 dB would be appropriate, but if it is effectively unlimited a level of -90 dB or even lower can be used. Again, the only cost to recording such data is the call on data storage space. Note that a higher analysis threshold may always be set in post-survey analysis, but of course not a lower one.

Some echo sounders offer a variable power level with respect to the volume of the transmitted sound. Excess power is usually only a problem in certain shallow water situations and so, unless there is good reason to deviate, the manufacturer's recommended setting or advice should be used as a default value.

4.4 Associated activities

In addition to the specifically hydroacoustic preparations described above, simple general logistical issues such as charging all batteries, packing equipment for safe transport and checking data storage space should also be undertaken. Appropriate safety activities should also be completed, including a final check on the weather forecast immediately before the survey and, for night surveys in particular, arranging a call-in time and emergency procedure with an onshore colleague.

5. Survey and data acquisition

5.1 Immediate pre-survey activities

On arrival, the hydroacoustic system should be assembled and installed on the survey vessel (Figure 4). Particular attention must be given to the transducer mounting to ensure that it is robust. In a vertical survey, the transducer should be mounted so that sound is projected as near vertically as possible, bearing in mind that survey vessel pitch and roll may change depending on its speed and wind conditions. Transducer alignment is even more critical for horizontal surveys and the use of a rotator is strongly recommended for such activities. All transducers are susceptible to damage if operated in air and so great care should be taken not to transmit sound before the transducer is underwater.

Water temperature should be taken and entered into the hydroacoustic system. Although this should ideally be a depth-weighted average, if this is impossible to obtain then a near-surface water temperature should avoid the uppermost 1 m of the water column. Sound transmission and recording parameters should then be set, ideally followed by a field target test (sometimes known as a field calibration) using the manufacturer’s recommended protocol and a manufacturer-supplied or manufacturer-recommended calibration sphere. However, a field target test does require very calm wind conditions and may not always be possible. Field target tests can, of course, also be performed outside of survey events.

Finally, a short test run of a few minutes should be performed with all systems, i.e. hydroacoustic and navigational, operational. At this stage, particular attention should be paid to transducer alignment, watching for any movements in its mounting. In this context, if in a vertical survey most fish traces (see Section 6.4) on the echogram are not horizontal but are inclined diagonally, this is indicative of a transducer mounting which is not truly vertical and which should be corrected. SNR should also be assessed by examining the echogram being produced by the system. On some echo sounders, background noise may be checked by stopping pulse transmission and putting the machine into a passive listening mode with the display threshold set to the system’s lowest available level. If excessive background noise is found, it may be reduced by running a metal cable from the system into the water. If it persists

Figure 4: A hydroacoustic system assembled and installed on a small survey vessel in preparation for a night-time survey of a lake. The system's grey surface unit can be seen in the middle of the vessel, with an open ruggedised laptop on top of it and a blue 12 volt battery to its stern. The system's transducer hangs over the vessel's port side at the lower end of a pole topped by a GPS unit and which is lowered prior to survey in order to place the transducer's face approximately 0.5 m below the water level.

at unacceptable levels, the effects of changes to sound transmission parameters, particularly a longer pulse duration, should be explored. Unwanted echoes from air cavitation from the survey vessel or its propellor(s), or generated by another nearby echo sounder, should also be looked for at this time.

5.2 Survey

If all of the above pre-survey activities have been completed as described, the survey itself should be a very straightforward procedure. Data recording should be started and stopped in accordance with the hydroacoustic system's operating instructions. As a safeguard against potential data loss, it is recommended that individual transects are recorded as individual data files, rather than combining them into one, potentially extremely large, data file for the entire survey. Although hydroacoustic systems can automatically name data files uniquely and appropriately, the use of a field log book to record this and associated information is strongly recommended. Weather conditions, moon phase (on a clear night survey) and any unusual events, such as the need to repeat a transect due to sailing off course, should also be recorded. Most importantly, as the survey progresses the operator of the hydroacoustic system should monitor it to ensure that it continues to operate as instructed, that problems with false bottom echoes do not develop in specific parts of the water body, and that GPS data continue to be received. The transducer mounting should also be watched, or at least periodically inspected, for any movement.

5.3 Immediate post-survey activities

After the hydroacoustic system has been shut down in accordance with the manufacturer's instructions, it should be disassembled and packed for transport. It is strongly recommended that collected data are copied from the controlling laptop's hard drive to a second storage device while still in the field. On return to the laboratory, the entire system should be checked for any signs of wear or damage, paying particular attention to the transducer and cable connections, before being stored away from extreme temperature fluctuations. At the same time, the collected data should be copied to safe storage on a backed-up and archived storage system.

6. Post-survey data analysis

6.1 Pre-analysis preparations

Before analysis can proceed to give information on fish abundance and other features, hydroacoustic data must be subjected to a number of pre-analysis procedures and in addition a number of decisions must be made concerning the analysis itself.

The first step should always be to conduct some form of quality assurance check. This should include the examination, if available, of the field target test data to ensure that the hydroacoustic system performed within specification during the survey. Then, whether or not a field target test was possible, a thorough visual inspection should be made of echograms of all collected data files. In addition to giving a visual double-check that the system continued to operate properly throughout the survey, which should have also been checked in real-time in the field by the continuous viewing of the echogram as data were collected, such examination will also reveal the general level of SNR and identify any specific areas of the data files with complications. The latter may include, for example, areas with entrained bubbles from the washes of other vessels or distinct echoes produced by passage over objects such as anchor chains. Such sources of unwanted echoes should be identified and removed from subsequent data processing, following the specific procedures of the analysis software.

The range limit to the data to be analysed should then be determined. For vertical surveys, this is usually the lake or reservoir bottom for which all analysis softwares include a routine for its detection. This procedure usually involves the detection of a very strong echo typical of the bottom, qualified by matching one or more additional identifying criteria. The bottom echo is then subsequently excluded from the analysis, although in other procedures beyond the scope of these guidelines the nature of the bottom echo can be analysed to reveal aspects of the physical nature of the bottom. The bottom is thus identified automatically by the software, although such recognition should still always be inspected visually and corrected manually if appropriate. Particular caution should be exercised in areas of steep bottom gradients, where side-lobes of the acoustic beam may cause complications, and in areas with very dense fish aggregations which may be wrongly identified by the software as the lake or reservoir bottom. For horizontal surveys, the limit to range is either the far side of the lake or reservoir or, more usually, the distance at which SNR declines to unusable levels. Consequently, it is usually set to a fixed range after initial data examination. For combined vertical-horizontal surveys, the range of the horizontal beam is usually fixed in order to cover the near-surface area not insonified or only poorly insonified by the vertical beam.

Data analysis is also usually structured spatially in terms of the covered range being broken into contiguous range strata, the most appropriate number of which depends in a complex manner on the distribution of the fish and on their abundance. An appropriate default approach is usually to make such strata each of thickness 1 m, although a lower resolution may be appropriate if fish are scarce and the water column is very deep. Finally, consideration must also be given to the horizontal resolution of data analysis. Just as each transect may be broken into vertical strata, it can also be broken into horizontal segments. Thus, the unit of survey analysis is not necessarily each whole transect, but potentially some part of it. This entity has been defined as the elementary distance sampling unit (EDSU) and has been given extensive consideration in both the marine world (Simmonds and MacLennan 2005) and in lakes and reservoirs (CEN, 2009). Ideally it should be determined after a thorough statistical examination of the collected hydroacoustic data, although on a pragmatic level most surveys of lakes and reservoirs, which may involve relatively short transects of only a few 100 m in length, continue to use the transect as the unit of horizontal resolution.

Once the data to be analysed have been defined spatially, an analysis threshold must be defined. This can be identical to the recording threshold, although it is more usually higher depending on the size of fish of interest and on SNR of the environment. With respect to determining the appropriate analysis to use in the context of the fish size of interest, guidance can be taken from the many equations which have been published relating fish size, usually length, to their target strength. Examples of such relationships for a range of lake and reservoir fish taxa are given in Tables 1 and 2 for fish insonified vertically and horizontally, respectively. Note that these relationships are to some extent species-specific. However, unless only one species is present in the study site, in most surveys the fish detected will be a mixture of species and so the more generic relationships given in these two tables are usually best used. Whatever the fish size of interest, the choice of analysis threshold is also strongly influenced by SNR. As discussed earlier, this issue may in turn be greatly influenced by environmental factors, such as plankton abundance, over which the surveyor has no control. In extreme cases, this may mean that echoes from small fish cannot be isolated from echoes from other sources such as plankton and so they are lost from the analysis. Determination of the lowest valid analysis threshold is a complex process and has to balance conflicting issues. Parker-Stetter *et al.* (2009) and CEN (2009) both give useful and highly technical guidance in this area.

Table 1: Examples of published target strength (TS, in decibels) and total length (TL, in centimetres or millimetres) relationships for a range of fish taxa insonified vertically by different sound frequencies (f) in dorsal aspect.

Relationship	Fish taxon	Total length range and units	Sound frequency (kHz)	Reference
TS = 19.1*log (TL)-0.9*log(f)-62	Mixture of species	1.5 to 100 cm	Various	Love (1971)
TS = 19.39*log (TL)-62.63	Mixture of species	10 to 39 cm	70	Borisenko *et al.* (1989)
TS = 20.63*log (TL)-65.11	*Coregonus lavaretus*	20 to 39 cm	70	Borisenko *et al.* (1989)
TS = 31.88*log (TL)-76.3	*Perca fluviatilis*	18 to 36 cm	70	Borisenko *et al.* (1989)
TS = 21.2*log (TL)-62.87	*Rutilus rutilus*	13.5 to 25.4 cm	70	Borisenko *et al.* (1989)
TS = 21.15*log (TL)-84.95	Mixture of species	72 to 690 mm	120	Frouzova *et al.* (2005)
TS = 25.5*log (TL)-70.9	*Coregonus albula*	3 to 20 cm	120	Mehner (2006)
TS = 24.4*log (TL)-89.44	*Salmo trutta*	72 to 259 mm	120	Frouzova *et al.* (2005)
TS = 20.79*log (TL)-86.41	*Perca fluviatilis*	10 to 41 mm	120	Frouzova & Kubecka (2004)
TS = 33.11*log (TL)-110.68	*Perca fluviatilis*	101 to 290 mm	120	Frouzova *et al.* (2005)
TS = 18.11*log (TL)-77.96	*Rutilus rutilus*	117 to 305 mm	120	Frouzova *et al.* (2005)
TS = 14.371*log (TL)-77.15	*Perca fluviatilis*	12 to 41 mm	420	Frouzova & Kubecka (2004)

Finally, the identification and measurement of echoes originating from single fish, as opposed to compound echoes which are produced by more than one individual or an individual in close proximity to some other object, is now an important part of hydroacoustic data analyses. Analysis softwares have sophisticated algorithms for SED based on a number of echo parameters including strength, shape and location in the acoustic beam, with appropriate settings also being strongly influenced by SNR of the environment. Again, Parker-Stetter *et al.* (2009) and CEN (2009) both give useful and highly technical guidance in this area.

Table 2: Examples of published target strength (TS, in decibels) and total length (TL, in centimetres or millimetres) relationships for a range of fish taxa insonified horizontally by different sound frequencies (f) in side aspect.

Relationship	Fish taxon	Total length range and units	Sound frequency (kHz)	Reference
TS = 24.71*log (TL)-89.63	Mixture of species	72 to 710 mm	120	Frouzova *et al.* (2005)
TS = 17.25*log (TL)-75.48	*Salmo trutta*	72 to 259 mm	120	Frouzova *et al.* (2005)
TS = 18.34*log (TL)-80.82	*Perca fluviatilis*	12 to 14 mm	120	Frouzova & Kubecka (2004)
TS = 24.98*log (TL)-88.98	*Perca fluviatilis*	101 to 290 mm	120	Frouzova *et al.* (2005)
TS = 33.55*log (TL)-107.51	*Rutilus rutilus*	117 to 305 mm	120	Frouzova *et al.* (2005)
TS = 23.90*log (TL)-87.30	Mixture of species	52 to 528 mm	200	Kubecka & Duncan (1998)
TS = 39.7*log (TL)-90.3	*Coregonus lavaretus*	34.5 to 54 cm	200	Lilja *et al.* (2000)
TS = 28.9*log (TL)-77.8	*Salmo trutta*	29 to 63 cm	200	Lilja *et al.* (2000)
TS = 23.49*log (TL)-85.60	*Perca fluviatilis*	55 to 274 mm	200	Kubecka & Duncan (1998)
TS = 27.72*log (TL)-95.29	*Rutilus rutilus*	52 to 253 mm	200	Kubecka & Duncan (1998)
TS = 27.49*log (TL)-96.16	Mixture of species	52 to 528 mm	420	Kubecka & Duncan (1998)
TS = 27.48*log (TL)-98.60	*Oncorhynchus mykiss*	125 to 443 mm	420	Kubecka & Duncan (1998)
TS = 19.88*log (TL)-85.88	*Perca fluviatilis*	7 to 14 mm	420	Frouzova & Kubecka (2004)
TS = 31.01*log (TL)-102.49	*Perca fluviatilis*	55 to 274 mm	420	Kubecka & Duncan (1998)
TS = 30.29*log (TL)-101.25	*Rutilus rutilus*	52 to 253 mm	420	Kubecka & Duncan (1998)

6.2 Choice of analysis method

Once the pre-analysis preparations have been completed, a decision on the most appropriate analysis method must be made between echo counting, trace counting and echo integration, although data can of course be analysed and reanalysed in more than one of these ways. Which method is most appropriate to the data collected in a particular survey depends on a number of factors including fish abundance, SNR, SED quality and GPS availability. Method choice is a highly complex decision, but essentially echo counting is appropriate only when GPS information is absent, fish are at low abundance and thus single echoes dominate, trace counting is relatively robust in low SNR but is compromised by high levels of compound echoes, and echo integration can be used at all fish abundances including when echoes originating from more than one fish dominate. Detailed technical guidance on selecting the most appropriate analysis method is given by CEN (2009). All three methods are capable of giving an areal or volumetric measure of fish population density in terms of numbers or biomass. Common units for areal estimates are individuals ha^{-1} or kg ha^{-1}, while for volumetric estimates they are individuals m^{-3} or g m^{-3}.

6.3 Echo counting

Echo counting simply counts the number of single echoes detected during the survey and converts this number into a measure of fish population density by dividing by the volume of water insonified, which is itself a simple function of beam shape and the number of pulses transmitted. As noted above, this method is greatly compromised by significant numbers of multiple echoes and so can only be used in lakes and reservoirs with low fish abundance. As data analysis software has become more sophisticated, echo counting has now been effectively replaced by trace counting and echo integration. However, it does still offer a limited option for analysis if GPS information is unavailable.

6.4 Trace counting

Trace (also known in some cases as track) counting involves the detailed spatio-temporal analysis of echoes in order to identify and delineate those originating from individual fish insonified a number of times in rapid succession. Such trace assembly, which is usually based on single echoes, is governed by sophisticated algorithms specific to the analysis software being used and involves a number of variable parameters, although in most circumstances in lakes and reservoirs its results tend to be robust to minor or medium changes in their values. Assembled traces are then counted and scaled with respect to the volume of water insonified to produce an estimate of fish population density. The appropriate calculation of the volume of water surveyed when this method of analysis is employed is more complicated than that used in echo counting or echo integration (see Section 6.5) and requires GPS data (or at least manually-calculated sailed distance). Like echo counting, this approach may be compromised by high levels of compound echoes. Advanced analytical procedures such as cross-filtering (Balk *et al.* 2005) enable this approach to be used in environments with low SNR, although this may require substantial effort in determining appropriate analysis parameters.

6.5 Echo integration

Echo integration (also known technically more accurately if less intuitively as sv/ts scaling) is a very robust method and works by dividing the average reflection from all fish (the volume backscattering coefficient, s_v) by the average echo intensity from individual fish (the backscattering cross-section, σ_{bs}). The latter value must be derived from single echoes or, preferably, from tracks constructed from a number of single echoes (see Section 6.4). In the complete absence or at least relative scarcity of single echoes, the latter of which may be assessed using the so-called Sawada Index (Sawada *et al.* 1993), appropriate target strength information can be manually entered into the analysis if appropriate values can be robustly assumed or can be calculated (using literature relationships such as those given in Tables 1 and 2) from physical size measurements of fish sampled biologically during the survey. Although such simultaneous biological sampling is frequently used in the marine environment, in lakes and rivers target strength is more usually estimated from the hydroacoustic data.

6.6 Further processing of analysis results

Once data analysis has been completed for each layer and EDSU of the survey, the resulting measures of fish abundance and other features must be combined. For vertical surveys, this may be a simple process of adding up areal estimates or averaging volumetric estimates, although discontinuous vertical distributions introduce further statistical complications. For horizontal surveys, areal estimates should be avoided because the cross-section of the sound beam is not identical to the area of the beam parallel to the water surface. For combined vertical and horizontal surveys the process is even more complicated, although the usual procedure is to use results from the horizontal beam to substitute for the upper blind zone of the vertical beam. A clear example of this procedure is given by Gangl and Whaley (2004).

The calculation of hydroacoustic survey summary statistics as average fish abundance with some measure of confidence limits should take into account two important factors. Firstly, hydroacoustic data are collected not as point samples but as effectively continuous data along transects. As discussed above, this introduces the option of breaking a single transect into smaller horizontal segments before analysis. However, such procedures should be aware of the statistical dangers of spatial auto-correlation as discussed for lake fish hydroacoustic data by Vondracek and Degan (1995). In particular, spatial auto-correlation is a potential problem with respect to variability between transects or segments (whether expressed as standard deviation, standard error or confidence limits) and thus associated statistical tests, but it is not an issue for the calculation of average values. Secondly, the horizontal and vertical distributions of fish in lakes and reservoirs are usually very heterogenous and even in the open water at night they can still display a considerable degree of patchiness (Schael *et al.* 1995). Following a detailed analysis of such data, Baroudy and Elliott (1993) concluded that geometric means were more appropriate than arithmetic means while Taylor *et al.* (2005) and Guillard and Vergés (2007) found that arithmetic and spatially-structured geostatistical approaches gave similar average abundance estimates, but the latter more sophisticated analysis gave a higher precision. The potential complexity of fish spatial distribution patterns is such that Taylor and Maxwell (2007) recommend that exploratory data analysis should be undertaken to determine the most appropriate statistical approach, although if there is no indication of spatial autocorrelation in the transect data sets then a more simple arithmetic approach can be employed.

Finally, although not strictly a part of hydroacoustic data analysis, in multi-species lakes and reservoirs hydroacoustic results can only be apportioned to specific fish species by using data from simultaneous or at least contemporary biological sampling techniques. While in theory such biological data can be acquired from fish capture techniques as diverse as angling, seine nets and trawl nets, in practice gill nets have proven to be particularly useful as demonstrated by Yule (2000), Cyterski *et al.* (2003) and Winfield *et al.* (2009).

7. Reporting and data archiving

7.1 Reporting

Reports of hydroacoustic surveys should be produced to the normal standards and conventions of scientific reporting. CEN (2009) gives extensive recommendations on the level of detail which should be documented. In particular, it is critically important that the analytical steps between the raw data files and the final estimates of fish abundance or other objectives of the study are rigorously described in unambiguous detail.

7.2 Data archiving

As noted above, hydroacoustic surveys typically produce several hundred megabytes of data and so a substantial and robust data archiving system is essential. The safe storage of such data is essential not only in order to allow analyses to be repeated with contemporary software using variations in analytical parameters, but also to allow them to be revisited with future developments in analytical software which may allow their analysis in new ways. In addition, unless read into dedicated playback or analysis software which can be cumbersome when large volumes of files are being managed, raw data files are largely uninformative other than perhaps the date and time of their collection being incorporated into the file name. Consequently, archived raw data files should be accompanied by metadata files. The latter can be as simple as spreadsheets, or as complex as a relational database or geographic information system.

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