Development of hydroacoustic methods for fish detection in shallow water

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Thesis for the degree of
Doctor Scientiarum

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UNIVERSITY OF OSLO, NORWAY
2001
To the fish!

It is an established custom to dedicate a scientific work to someone. "To my wife", "to my sons" or "to my father" are commonly seen. However, this work has been something I have done because I wanted to do it. Many people, both friends and particularly the family have been suffering and supporting me during the work. If dedicating the work would help them, I would have dedicated it to all involved people. However, I feel that doing so in this occasion will be false. None of my family or friends will benefit by a dedication. So why not thank them with all my heart and dedicate the work to those who might benefit from it: The fish.
Preface and acknowledgements

This Dr. Scient. study was carried out during the years 1997-2001. The study was initiated shortly after my M.Sc. thesis "Digitalisation of sonar" with Torfinn Lindem as my supervisor. After having finished the M.Sc. thesis the question arose; what to do next? Taking a job in the industry as a programmer or as a designer of electronics seemed to be the most obvious. The idea of not spending many hours every spring preparing for exams sounded tempting at that time. Had it not been for the advice and persuasion from two persons, I probably would be sitting at some office desk today. Instead I have had the opportunity to take a look into the world of hydroacoustic science, meeting and discussing physical problems with other scientists, participating in interesting fieldworks, and doing experiments many places around the world. For this, I would like to thank Torfinn Lindem for persuading me to embark upon this study, for providing funds, and for all help throughout the study. I will also thank my live-in Gry V. Haraldsson for persuading me to take the study and for her support through these four years of hard work. She has also assisted in the fieldwork at Tana and Hidra.

Fieldwork has been of great importance for this study and without the help of a number of institutions and persons, this fieldwork would have been difficult or even impossible to carry out.

Simrad AS with their staff has been of great help with theoretical support and advice, providing equipment and practical support for the fieldwork in the River Tana and on the ice of Lake Semsvann. In particular, I will like to thank Erik Stenersen, Frank R. Knudsen, Haakon Solli, Helge Bodholt, Raymond Brede, and Rolf Nielsen for their assistance.

The fieldwork in the River Tana was also supported by the Finnish Fish and Game Research Institute (RKTL), the County governor in Finnmark represented by Kjell Moen, and the River Tana Salmon Fishing Rights Owner Association represented by Jon Viktor Aslaksen.
RKTL, represented by Jaakko Erkinaro and the staff from RKTL’s research station in the border village Utsjoki, 50 km from the Polmak site, assisted with manpower and equipment. Matti Kylmäaho assisted in building the camp and with diving. Jorma Kuusela helped repairing broken computers and analysing data. Two students from RKTL lived in the camp and assisted with the daily work. These were Jani Lehtinen in 1998, and Antti Tuomaala in 1999. Arne Rollstad from the local police office, provided the Norwegian caravans for equipment and accommodation. Ole A. Nilsen was responsible for setting up the guiding net in 1998. As the closest neighbour to the camp, he also helped whenever we needed extra assistance. Seppo Sottinen and Finn Are Varsi were responsible for setting up the guiding nets in 1999.

The fieldwork in Rimov in the summer of 2000 could not have taken place without the support from Jan Kubecka and his Institute: the Hydrobiological Institute, Academy of science of the Czech Republic, Ceske Budejovice. Kubecka and the Institute provided equipment and accommodation during the one-week survey. Kubecka also assisted and gave advice during the work. I also thank Jarka Frouzova from the Hydrobiological Institute for her assistance during this survey.

The first fieldwork at the River Tornionjoki in northern Finland 1997 was made possible by RKTL, represented by Atso Romakkianemi. I am grateful for what I learned from Atso Romakkianemi and his team during the stay. Raymond Brede from Simrad AS participated in this fieldwork, and I thank him for his support.

The fieldwork on the ice of Lake Semsvann in 1998 and 1999 was carried out in co-operation with Frank R. Knudsen from Simrad AS. In 1999 Martin Cech from the Hydrobiological Institute in Ceske Budejovice assisted. The 2000 fieldwork was carried out with assistance from Jørgen Døvle from the University of Oslo.

Developing computer programs for analysing sonar data has been an important part of the study. This would have been difficult without help from Simrad and HTI. At Simrad, Haakon Solli has given invaluable help. From Hydroacoustic Technology Inc. (HTI), Patrick A. Nealson has been most helpful providing necessary information.

For many interesting and helpful discussions about programming and programming techniques I would like to thank Olav Mork and Jørgen Døvle from our sonar lab at the University of Oslo.

In addition to the sonar data recorded by our own echo sounder, data have been received from other scientists as well. These data have played an important part in the
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development of the analysis methods, and I thank Nathalie Gaudreau (Ca), Dan Yule (US),
Jan Kubecka (Cz), Atso Romakkianemi (Fi), Juha Jurvelius (Fi), Pia Romare (Se), Simrad
and HTI for their contributions.

Writing English has been difficult, and much time has been spent on studying the
English language. An advice from the referees was that I should let an English person read
trough the manuscript. This advice has been followed and I want to thank Patricia
Kongshavn, Alex Reed, David Wormal, and Richard Fears for their help correcting the
language in the papers. I also want to thank Trygve Reenskaug, Rune Gangeskar and my
father, Hartmut Balk, who have been of great help proof-reading the thesis.

I am very grateful to all these persons and institutions for their assistance and
support. Even more people should have been mentioned, and I apologise for not being able
to mention everyone.

Blindern 08.03.2001

Helge Balk
ABSTRACT

Management of salmon stocks from various regions is of great importance. Optimal management can only be achieved with knowledge of the size and the changes in the stocks. Hence, monitoring methods are important. In marine fisheries, split-beam echo sounders are frequently applied to monitor fish. In recent years this hydroacoustic fish detection method has been applied in many rivers. Aligning one or a few transducers horizontally provides a simple way to monitor major parts of a river's cross section.

However, the horizontal shallow water application introduces new problems related to the acquisition, analysis, and interpretation of the sonar data. Fieldwork has been carried out in lakes and rivers, and a systematic analysis of these problems has been made. From the experience and the studies of the recorded material, new methods have been developed. Signal processing based on image analysis and classification theory is introduced, and promising results have been achieved.
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1 List of papers

I. Implementing and testing multiple-target trackers on split-beam sonar data recorded in lakes. Aquat. Living Resour. (In press)

II. Evaluation of the hydroacoustic fish counting method based on single echo detection and tracking in shallow rivers. (To be submitted)

III. Why single echo detectors tend to reject echoes from fish in shallow water. (Abstract accepted by Can. Jour. Fish. Aquat. Soc.)


VI. Application of linear discriminant function analysis to the classification of echo-tracks detected by split-beam sonar in shallow rivers. Aquat. Living Resour. (In Press)

VII. Discrepancy between expected and measured sound field in shallow waters (To be submitted. Pending on more data.)

VIII. Influence from water current on hydroacoustic measurements. (To be submitted. Pending on more data.)

Proceedings:


2 Glossary

Various terms are applied by different sonar equipment manufactures. While the Norwegian company Simrad AS uses the names depth, along-ship, and athwart-ship when they describe the position of an object in the sound beam, the American company Hydroacoustic Technology Inc (HTI) uses the terminology range, x, and y to describe the same. When Simrad refers to an echogram, they normally refer to the total echo-signal presented in a time-range diagram. This is the signal from the sonar's amplitude detector. To HTI, an echogram normally means the output from the single echo detector. The linguistic differences relate to the main usage of the equipment and it is somewhat historical. Simrad started early producing downward-looking single-beam applications for boats presenting the amplitude-based echo-signal on paper echograms. Later advancing to split-beam sonar and computer screens, they continued presenting the amplitude signal. Naming the spatial co-ordinates relative to the boat and the sea as references was natural.

HTI has basically focused on presenting the signal from the single echo detector and on horizontal river applications. Then the application of a more traditional co-ordinate system is appropriate.

In order to avoid confusion, we have chosen to use the terminology range (r), athwart-ship (Ath), and along-ship (Alo) when discussing the spherical co-ordinates and z, x, y when converting to Cartesian co-ordinates. (r ->z, Ath->x, Alo->y). In horizontal river applications, where the transducer is placed with the main elliptical axis horizontally, Ath or x will refer to the up or down stream direction while Alo or y will describe vertical positions. This is demonstrated in Figure 1.

The single echo detector will frequently be abbreviated SED. Whenever it is important to distinguish whether an echogram has been produced by the Single Echo Detector or by the Amplitude detector, the prefix SED or Amp will be added. Single echo detection involves a set of parameters. For most of these parameters, Simrad’s EY500 terminology will be used. On exception is the parameter Max. Gain Comp. Throughout the thesis, this parameter will be denoted Max. Beam Comp.

Another convenient abbreviation that will be used is the sonar data analysis method STM, referring to the single echo detection and tracking method.
3 Introduction

Through the years of 1960 to 1990, the catch of Atlantic Salmon (Salmo Salar L.) in the high seas fluctuated between 6000 and 12000 tonnes. Through the 1990s, the catch has decreased considerably to the present level of the 3000 tonnes (Jacobsen, 2000). Overfishing, influences from escaped fish from fish farms, destruction of hatching areas, manmade obstacles in the rivers, and the spreading of parasites like Gyrodactilus Salaris and salmon lice are elements that effect the salmon stocks (NOU, 1999:9). Exact knowledge of the development in the stocks does not exist. After some years with low catches in many Norwegian rivers, last year (2000) was a good season. Independent of the actual situation, management of the resources is important. Optimal management cannot be achieved without knowledge of the size and the changes in the stocks. Enumerating fish is a difficult task, and development of monitoring systems is therefore important.

For salmons returning to the same river after one to five years, the river is a natural monitoring place. Various monitoring techniques have been developed. Catch data, mechanical counters, conductivity, and optical counters to mention some. Even visual
counting of migrating fish from towers on the side of the river has been applied (Enzenhofer et al., 1998). Catch data can be highly inaccurate and especially not suited for monitoring a threatened fish stock, while visual counting is extremely labour intensive.

Mechanical, conductivity and optical counters have limited range, which limit their usage to small creeks or places where the salmons can be led through narrow passages. With large rivers, it is not normally possible to guide the salmon close to a counter. Guiding constructions might interfere with boat traffic, be too expensive, or interfere with environmental concerns. In such situations hydroacoustic fish detection methods provides an interesting alternative. Transducers with narrow opening angle can be horizontally placed on the river bottom. Hence, major parts of a shallow river cross-section area can be monitored without encroachments on the environment.

Hydroacoustic methods have been applied in ocean fisheries and fisheries research for decades and are well established. Different types of sonar and echo sounders are commercially available, ranging from simple monastic fish finders to large multiple beams and multiple frequency sonars. A single beam system can detect echoes from a fish, but the size can only be determined by indirect statistical methods (Lindem, 1981). To obtain direct estimates of the size of the fish, the off-axis distance or position is needed. This can be detected with two or more beams. Dual-beam systems apply a narrow beam surrounded by a wide beam. Off-axis distances are detected by comparing the echo-signal from the two beams. Split-beam systems compare the echo from four receiver elements placed in a quadrant. The phase difference is used to calculate the target’s actual position. Larger sonar systems with many transducer elements can also be used to detect fish. The sector scanner consists of an array of elements. The centre element transmits a pulse, forming a wide beam. The signals from the receiver elements are processed to form thin sectors. Large water volumes can be scanned, but targets can be positioned only in two dimensions. To be able to cover large water volumes and at the same time be able to detect targets in all three dimensions, omni-sonars can be applied. An omni-sonar transmits sound in thin
conical shells that are scanned by the receiving beam. Omni-directionality is obtained by steering the transmission in different directions.

In recent years, many experiments with echo sounders have been carried out in rivers. Ransom and Johnston (1998) reports experiments that have been carried out in more than 14 different rivers. Some examples are the River Tornionjoki and the River Simojoki in Finland, the River Spey in Scotland, the River Wye in Wales, the River Fraser in Canada, and the River Kenai and the River Wood in Alaska. In most of these surveys, one or a few narrow beamed dual or split-beam echo sounders have been mounted horizontally at the river bottom. At a suited site, this application provides good river cross-section coverage. Size, position, direction, and speed of the passing fish can be monitored with the split-beam technique. In the remainder of this text, the “hydroacoustic fish detection method” refers to the split-beam method as described in chapter 9.1.


The need for fish-stock assessment in shallow rivers, and the problems related to side-looking sonar in such environments have inspired this Ph.D. study. In situ experiments have been carried out with downward and side-looking split-beam sonars in lakes and rivers. Data from our own experiments and data recorded by other scientists have been studied. Improving the hydroacoustic split-beam method in shallow rivers has not been a simple task and we have not found all the answers. Some problems have been solved, while new problems have been discovered.
We have found it fruitful to separate the hydroacoustic fish detection method into three main areas or elements. These are a) data acquisition, b) data analysis and c) interpretation. Definition of "the hydroacoustic fish detection method" and the meaning of the three elements are described in chapter 9.1. The separation will be used throughout the text, and problems and solutions will be discussed in this context.

4 Objectives and aims

The aim of the study has been to improve hydroacoustic fish monitoring methods based on side-looking split-beam sonar in shallow rivers. The split-beam sonar was selected due to its simplicity, price and weight, and because it is commonly applied in river monitoring projects. Scientific echo sounders equipped with split-beam transducers are commercially available from companies like BioSonics, HTI, and Simrad. Small size and low power consumption makes it possible to transport the system off-road to selected sites. Split-beam transducers with low opening angle and low side-lobes are available for different frequencies. The 120 kHz split-beam transducers that we have applied in our experiments are fairly small in size and easy to mount in a river. The frequency and the narrow opening angle fit well in shallow water.

Improving the method has been the main aim. Hence, our first challenge was to study the method and find where to focus our attention. During our first fieldwork in the River Tornionjoki Finland in the summer of 1997, it became clear that we had to focus on programming and data analysis.

5 Materials and methods

The study has been carried out by alternately performing fieldwork and by analysis of the recorded material. From this we have learned about the method and we have been able to improve the method further. Experiments on ice have been carried out in order to compare the sound beam in open water and close to boundaries. Experiments in a tank have been carried out in order to perform controlled experiments of phenomena like the influence from surface waves, rain, rattling stones and water current. In long term projects, the problems involved in monitoring fish have been experienced.
Early in the study, a Simrad EY500 scientific split-beam echo sounder equipped with a 120 kHz, 4x10 deg. transducer (ES120-4) was bought. The sounder has proved to be robust and easy to handle in the field. With the low side-lobes and the narrow opening angles, the transducer has been well suited for placement in shallow water. One important feature with this echo sounder is its ability to store the sampled echo-signals directly from the phase and the amplitude detectors (sample angle, sample power, and echo telegram), in addition to the output from the single echo detector (trace-telegram). This has been crucial on many occasions and has enabled us to study the data and to develop new analysis methods in a far better way than if only the processed single echo detections had been available.

Fieldwork has been carried out in the River Tornionjoki in Finland the spring of 1997, in the sea outside the Norwegian island Hidra summer 1997, in the River Tana in the summers of 1997, 1998 and 1999, on the ice of Lake Semsvann winter 1998, 1999 and 2000, in the River Lysaker in 1998 and 1999, and in a pond at Rimov in the Czech Republic summer 2000. The fieldwork is further described in chapter 9.3.

During our first fieldwork, it became clear that lack of suitable software and automatic analysis methods was a major problem. Hence, our first task became to develop software giving us the opportunity to effectively look into the different aspects of the sonar data. The work with the post analysis program Sonar5 was initiated. This work has continued throughout the study, and the program has been our main "working horse". Having access to the source code of a program capable of reading and presenting sonar data was found very convenient. New ideas and methods have been tested, by simply implementing them directly into the source code. Whenever we needed to extract any type of data in any format or to perform multiple calculations and to generate statistics, extraction methods were implemented in the code as well. Thereby, Sonar5 has created most of the figures and tables in our papers. The program is described in chapter 9.2. Borland's Delphi compiler version 3 has been used for the programming. Delphi is a graphical program development tool based on the computer language Turbo-Pascal. (Miller et al., 1997). In addition to the programming tools, Statgraphics PLUS 4.0 from
Material and methods

Statistical Graphics Corp. and Microsoft Excel 97 SR-1 have been applied for statistics, Paintshop Pro v 4.14 for graphical work, while Microsoft Word 97 SR-1 has been the main text editor.

Sonar data from other scientists have been received and applied in the study in addition to the data recorded by our on EY500. This has provided a wide basis for the study. Converters in the Sonar5 have ensured access to data recorded by echo sounders from different manufacturers. A library of sonar files demonstrating various phenomena has been accumulated. This collection is available on CD and through our Internet web page.

6 Problem definition

Obtaining abundance estimates of migrating fish with the application of hydroacoustic fish detection methods in a shallow river is at least in theory straightforward. One or a few transducers are placed horizontally in the river, and fish passing the beam will be registered. The size distribution can be extracted from the amount of reflected energy. The swimming speed and direction can be detected from succeeding echoes in tracks from individual fish. Seasonal and diurnal migration statistics can be found from the registered time of fish passages. This is the theory.

When a split-beam transducer is placed horizontally in a river, several problems occur. These are problems related to the propagation of sound in the turbulent water and to disturbances from the nearby surface and/or bottom. Fish migrating in schools, multiple species, and unwanted targets like drifting debris are other phenomena adding to the list of problems. From our experiments, we have seen that time dependent changes in the environment like changes in the water current, water level, wind, and rain can influence on the sample volume, the fish behaviour, and the noise level. This makes it difficult to interpret the recorded data. Figure 2 and Figure 3 demonstrates the differences between these
environments with photos and echograms respectively. It is easy to see that the river environment offers challenges not seen in the vertical recording.

**Figure 2. Recording sites. Pictures from a deep calm lake (left) and from a rough running river (right).**

**Figure 3. Illustrating the differences between downward and side-looking sonar recordings. Left: Vertically recorded echogram from a lake. All echoes are believed to originate from fish. Right: Horizontally recorded echogram. Only a few of these echoes might origin from fish.**

### 6.1 Problems related to the data acquisition

Data acquisition embraces tasks like equipment selection, site selection, placing the equipment in the water, aiming the transducer, selecting the correct sonar parameters, providing power, and data storage capacity etc. Providing shelter from rain and wind, and security from criminal damage are also important. Working in a river can be both difficult and dangerous. Mounting a transducer so that it will stay steady without vibration and without changing position, pan or tilt over a period of time is important, but not a simple task. Even small vibrations can induce large errors in the angular measurements. The
streaming water makes beam mapping with standard targets difficult. How should the target be mounted in the current in order to stay fixed at the wanted position?

The amount of data produced during a season of sonar recording can cause problems. In order to get good time coverage, one wants the system to run continuously. If the survey lasts for months or years, tremendous amount of data has to be handled.

Data recording involves not only recording of sonar data, but also log-writing and measurements of additional data, not recorded by the echo sounder. Transducer placement, bottom profile, water current, and water level are examples of such data. Wind and rain are other parameters that influence the sonar recording. Events like special weather phenomena or human activity on the site can be important to note in a survey log. Taking care of all the environment information so that it can be correlated with the recorded sonar data can be difficult. However, all information important to the later analysis and interpretation should be noted.

### 6.2 Problems related to the data analysis

Sonar data analysis is the process of extracting information from the recorded data. (Chapter 7.2 and 9.1.2) The two most common analysis methods are (i) the biomass estimation method based on echo integration, and (ii) the single fish detection method based on single echo detection (SED) and tracking (Figure 10). Echo integration is applied whenever the target density is higher than the resolution of the system, such as in the estimation of fish schools in ocean fisheries. Echo integration is well described in most books about hydroacoustics, e.g., *(MacLennan and Simmonds, 1992)*.

The single echo detection and tracking method (STM) can be applied when the density of the targets are lower than the system’s range and time resolution. This is determined by parameters like the transmitted pulse-length and the ping and sample rate. Low fish density is often seen in rivers and during nights in open waters. STM is probably the most common analysis method in rivers today.

The STM method was tested and found to work well in vertical open-water applications with high signal to noise ratio (SNR) and low fish density *(paper I)*. Echoes from single fishes were well detected by the SED, while the bottom detection algorithm removed bottom echoes. With few noise-based echo detections surrounding the tracks, tracking and counting was possible.
Testing the STM method on data from shallow rivers characterised with low SNR gave a different result (paper II). With the sonar beam aligned close to the bottom and/or the surface, disturbing echoes were received from waves on the surface and rocks. The bottom detection algorithm could not remove these echoes, and they made fish detection and tracking difficult. Drifting debris and air-bubbles from nearby rapids and passing boats were other elements generating disturbing echoes.

Changed transducer alignment influences the recording by redefining the sonar's co-ordinate system. While fish are free to move horizontally in the water, vertical movements involve pressure compensation and are therefore avoided if possible. With vertical sonar applications, this means that fish tracks tends to stay fairly constant in range. Combined with the sonar's high accuracy in the range domain, this means that predicting the next echo position is usually quite simple. With horizontally aligned sonar's, this is no longer the case. The fish's swimming pattern introduces higher position uncertainty in the range domain. This reduces the possibility of correct prediction of the fish's next echo position, and tracking becomes less reliable.

Another observation in data from rivers was that the SED tended to reject echoes from passing fish. The reason for this was investigated in paper III. It was found that the characteristics of the returned echo-pulse from the side aspect of a fish in a river were different from the dorsal echo-pulses from fish in lakes. This was caused by elongation of the echo-pulse, multiple peaks, increased fluctuations in the angular estimates and frequent detection of echoes at high off-axis positions. In many cases, echoes from debris, stochastic variations in the background reverberation and echoes from surface and bottom were better detected than the fish-echoes. Tracking fish in situations with few fish-echo detections surrounded with numerous unwanted echoes was found extremely difficult. Under such circumstances, manual tracking becomes time consuming and subjective, while automatic tracking algorithms produce high overestimates by splitting tracks from fish and by generating fish tracks from noise.
Estimating the fish size from the returned echo intensity was found to be a problem. Fish detected in the River Tana were occasionally observed with target strengths up to +5 dB. This represents an acoustic cross-section area of 40 m², which certainly must be wrong. Reasons for this can be found in interference phenomena adding energy from other targets like bottom echoes, problems with nearfield effects, or avoidance of spherical spreading in the shallow river. In open water hydroacoustic, spherical spreading models the transmission loss. With spherical spreading, the echo intensity is damped by R⁻⁴. The sonar's TVG compensates this. In shallow water spherical spreading might be replaced partly by cylindrical spreading (Medwin and Clay, 1998 p115). Then size estimates based on the R⁻⁴ model will be incorrect.

The transducer nearfield is a function of wavelength and frequency. A reflecting fish also has a nearfield and it is possible that the nearfield can be an explanation for some of the errors observed in the size and position estimates (Dawson et al., 2000).

The fish aspect can cause problems. The amount of reflected energy from a passing fish will vary with the aspect of the fish. This has been investigated by Love (1977) and later by Kubecka and Duncan (1996). Love mounted different fish in a carousel and measured the backscatter from all aspects. Head and tail aspect gave the lowest reflection. Kubecka found that a cos³ function could be applied to describe the relationship between TS and the aspect angle. One advantage with river acoustics is that up-stream migrating fish tends to swim straight against the water current. Hence, a transducer can be mounted so that it mainly irradiates the passing fish normal to the side aspect.

It is a question whether the actual swimming motion of the fish can influence the echo intensity. It is natural to think that the reflection properties change when the fish body bends against or away from the transducer. Foote (1985) has done a theoretical study of the influence from the swimming motion in the dorsal aspect. His conclusion was that the swimming motion did not significantly affect the dorsal target strength. Whether this is the same with the side aspect is not known.
The sonar is not well suited for differentiating between fish species (Lilja et al., 2000). When two or more species migrate in a river, other methods have to be applied in order to separate them. Video and catch data can be used. Another problem occurs if there are local species habituating the site. These species can cause a steady rate of detection. From the hydroacoustic counting project in the River Tornionjoki (Romakkianemi et al., 2000), pike was seen as a problem. In the River Tana, small schools of whitefish and a few pikes were observed at the site. The sonar's ability to differentiate between species has been investigated by various authors. Scalabrin et al. (1996) and Cadrin and Friedland (1999) have investigated methods for differentiating species in mono-static fish schools while single fish differentiation has been investigated by Vray et al. (1990). Only partial success has been reported. No good method exists for hydroacoustic species differentiation in rivers.

6.3 Problems related to the interpretation of the data

Having detected a number of fish in the recorded data does not mean that all fish passing the site have been detected. The observations have to be interpreted. It is normally not possible to cover the complete river cross-section, and it is difficult to run the sonar 24 hours a day. A commonly applied interpreting method is based on calculations of the total cross-section area and the covered cross-section area. Assuming equal fish distribution enables extrapolation by multiplying the observed number with the coverage factor. This is often referred as the area expansion method. The assumption that fish are equally distributed in the river is probably wrong. It is natural to think that fish might follow special bottom structures, seek deep parts, or avoid special current and bottom conditions. Gaudet (1990) describes a way to solve this problem by dividing the river cross-section into strata.

The geometry of the sonar beam can cause bias in the estimation of fish size. At short range, the narrow beam allows only a few echoes from a passing fish to be detected. At longer range, the beam is wider and more echoes can be observed. With low signal to noise ratio, strong echoes will have a higher detection probability than weak echoes. This will bias the mean value calculated from a passing fish, and also introduce bias in the resulting fish size distribution (Degnbol and Lewy, 1990).
During the two-year fieldwork in the River Tana it was observed that moving the transducer further out or closer to the riverside also moved the range distribution of the detected targets. Most of the fish tracks were always detected in a layer 25 to 35 m from the transducer. The explanation can be related to the phenomenon described by Degnbol and Lewy, indicating a range dependency in the detection probability $P(r)$. It is impossible to estimate the total number of fish from the observations without knowing the $P(r)$ function.

There is another dependency in the detection probability function that is equally important. That is the dependency of time, $P(t)$. From the River Spey in Scotland, variation in counter efficiency through the season has been reported (Laugthon and Good 1999). Similar phenomena have been observed during the fieldwork in the River Tana. There can be many reasons for this time dependency. Most of these are related to the SNR. The early spring flooding reduces the SNR. The proportion of the river cross-section area covered by the beam is reduced as well, when the water level increases. Wind and rain, and the amount of debris and silt can change during a long-term monitoring project. Even the river bottom profile might change due to erosion. In the River Tana fish were seen to alter their migration paths during the season. Knowledge of the detection probability function $P(r,t)$ is essential for correct interpretation of the observed fish.

A special sound phenomenon was observed during the fieldwork in the River Tana and later in a shallow pond in Rimov (Czech Republic). When the water level sank below a certain level, major deviance between the expected and the measured sound fields was observed (Paper VII). The vertical phase estimates were corrupted and the sample volume was drastically increased. Increased river cross-section coverage can increase the number of detected fish, but with lost control of the sample volume, interpretation becomes difficult. Corrupted vertical angular estimates reduce the ability to determine the target strength.

## 7 Summary of results

The results from this study are the *Sonar5* post-processing program, the new analysis methods, the entitled problems that remains to be solved and the conclusions about whether the hydroacoustic fish detection method can be applied in rivers like the River Tana.
7.1 Results concerning the data acquisition

Data acquisition is not only a question about recording sonar data. Selecting the best suited transducer, selecting and preparing the site, placing and positioning the equipment, recording arbitrary data like weather and water, bottom profiles and events influencing the recording, and tuning the sonar's parameters are all important tasks. Without knowledge about the transducer placement and the site, an echogram becomes meaningless. During a hydroacoustic fieldwork, vast amounts of information are available. Recording this information and associating it with the actual sonar data is important. In a long-term monitoring project, positioning the sonar in the same position as in the previous years can be difficult, but important in order to gain comparable results.

For the fieldwork in the River Tana, two tripods with remote controlled rotors were developed at the University of Oslo. In order to associate arbitrary information with the sonar recordings, the Sonar5 program was equipped with tools for writing a field log, a remote sonar controller, and features for relating and presenting text and digital images together with the recorded echograms. A survey calculator was implemented to assist the operator determining parameters like the beam thickness at certain ranges, sound speed, range resolutions etc. In order to place the equipment correctly in the river, a site descriptor program was developed. This program assists the operator to describe the site, the placement of the equipment, and the actual position of targets in the sonar beam in relation to the river.

Tools for measuring and displaying water current and bottom profile have also been implemented. The direction and strength of the current is an important factor to determine whether a track originates from a migrating fish or not.

Information about the bottom profile is important in order to apply area expansion when interpreting the analysis result. Being able to display tracks relative to the river and not only relative to the transducer, can be crucial in order to see that the system works correctly.
The weather at the site in the River Tana was monitored by a Hugher weather station. This station measured the pressure, rain, wind, temperature, and humidity. Light was seen as a parameter with greater importance to the salmon run than the humidity, thus the station was modified to measure lux instead. A program for converting the weather data into diurnal statistics, that could be compared with the diurnal migration statistic, was made.

7.2 Results concerning the data analysis

As already stated, the analysis of the sonar data is concerned with one thing. That is to detect fish in the recorded data. The analysis is not concerned with the total amount of fish that has passed the site, only in the amount that can be observed in the recorded material. The outcome of the analysis is typically a total number of fish, diurnal or seasonal migration, size distributions etc. It is important to be aware that without an appropriate interpretation, these statistics are nearly meaningless.

A common hydroacoustic monitoring method is the single echo detection and tracking method (STM). Single echo detectors are implemented in many commercially available echo sounders like the Simrad EY500 and the HTI's model 240-243. Manual or automatic tracking-algorithms designed for analysis of the output from the SED are found in HTI's post-processing program Trackman, in Simrad's EP500, and others.

It was natural to start the study by testing this analysis method. Methods for visualising all aspects of the recorded sonar data and for manual tracking were implemented in the Sonar5. So were methods for manual and automatic tracking. Automatic tracking techniques applied in radar technology Blackman (1998) were studied, and an automatic self-adjusting tracking system was designed. This is described and tested on sonar data recorded in vertically open water applications in paper I. The main conclusion from this work was that:
The STM method was capable of detecting fish in vertical sonar applications. The STM was then tested in rivers (paper II) by analysing and comparing data recorded in four rivers and three lakes. Problems related to the STM were also presented at the 21st Scandinavian Symposium on Physics Acoustics Ustaøset 2-4 February 1998 (Proceeding I). The conclusion was that the STM did not work well with data recorded in shallow rivers. The SED was frequently seen to reject echoes from fish, and detect variations in the background reverberation as single echoes. Missing detections of fish combined with numerous unwanted detections were seen to "fool" the tracker. This resulted in overestimates of fish in the order of up to 1:100. Fish tracks were split, overlooked, or mixed with noise. Pure noise-based tracks could take on similarities with tracks from passing fish and thereby be detected in the SED. An important observation in this study was the importance of the Amp-echogram. This echogram was found to contain information that helped in the interpretation of the data. This was information that was lost in the SED process, such as the shape of the detected echoes, echoes not accepted by the SED, and the background reverberation. Phenomena like boat wakes could look like passing fish schools on the SED-echogram. Studying the Amp-echogram seldom left any doubt about the origin of the echoes. The following list summarises the most important results.

- The STM was not well suited for detecting fish-echoes in shallow rivers.
- Noise echoes combined with missing echoes in tracks from fish made tracking difficult.
- The sonar data contains important information lost by the SED.
- Noise, missing fish-echoes, and multiple-targets result in high overestimates.

The work indicated that the SED was the main problem. Hence, our next move was to test this detector. A sample data analyser was implemented in the Sonar5 program, and echoes from fish recorded in lakes and rivers were analysed and compared. The analyser is described in chapter 0. Experiments were also carried out to test the influence from the water current, rain, wind, and rattling rocks on the river bottom. The results are presented in paper III, and in paper VIII. The main conclusions were that:
• Echoes from fish took on similarities with multiple echoes and were rejected by most of the criteria applied by traditional single echo detectors.

• Noise-based echoes frequently shown similarity with echoes from fish detected in vertical applications.

Based on the experience and the conclusions from these works, we could focus on the development of new analysis methods for rivers. Three methods have been developed. First, an improved SED was constructed. The SED applied in commercially available sonar equipment like the Simrad's EY500 and the HTI's model 243 have been optimised on accuracy in the TS estimate. Accuracy is achieved by removing suspicious single echoes according to the applied SED-criteria. This is described in the introduction of paper IV in the paragraph "Traditional single echo detection".

Instead of optimising high accuracy in the TS, we focused optimising detection probability. The idea was that if a higher percentage of the echoes from a fish could be detected, this would improve the tracking abilities. A solution based on two-dimensional filtering combined with pulse-length detection was found to accept more echoes from passing fish, and at the same time reduce the number of unwanted noise-based echoes. The necessary accuracy in the TS estimates could be gained at a later stage in the process after the tracks had been detected. This work is presented in paper IV, and the main conclusion was that:

• SED based on two-dimensional filtering and pulse-length detection improved the detection probability and reduced the noise.

A different way to improve the detection of fish and to remove echoes from unwanted targets was found by applying image analysis. With image analysis, it was possible to extract more of the information available in the sonar signal than with the traditional STM. The application of image analysis on sonar data from rivers was first presented at the 22nd Scandinavian Symposium on Physics Acoustics at Ustaoset (Norway)
February 1999 (Proceeding II), and later at the Shallow Water Fisheries Conference (SWFC) in Seattle September 1999. The work was finally presented in paper V. Background material and software implementation is described in chapter 9.2.2. The main conclusions from this work were that:

- Image analysis could improve the detection of fish in data characterised by low signal to noise ratio.
- Image analysis could extract descriptive features suited to identify origin of the detected tracks.

An important problem related to river acoustics is the existence of multiple-targets. Not only fish, but debris, rocks on the bottom, air-bubbles, and reflections from surface and from passing boats could result in tracks, and thereby in erroneous fish monitoring results. Automatic classification systems were seen as a solution to this. Various classification methods were studied, and a method based on linear discriminant function analysis was found suitable. This was implemented in Sonar5, and tested on data from rivers. The method was found capable of reducing the troublesome overestimates from automatic tracing by up to 93%. The method was tested on tracks generated by the traditional STM. It remains to test the method on tracks generated by image analysis. We believe that even better results can then be achieved. Background material and the description of the implementation in Sonar5 is found in chapter 9.2.3. The application of linear discriminant function analysis and test results is presented in paper VI. The main conclusion here was that:

- Linear discriminant analysis improved the fish detection accuracy substantially.

With this, we have demonstrated that analysis of sonar data can be improved in three different ways, a) by optimising the single echo detector, b) by applying image analysis and c) by applying classification. The methods solve problems related to different stages in the fish detection process, and can be combined in a chain as demonstrated in Figure 4. Image analysis detects regions on the Amp-echogram with high probability of containing tracks from one or a few passing targets. It extracts valuable numerical
descriptions of features from these regions as well. Hence, it is natural to start the analysis by the image analysis. Next step is to apply the new single echo detector and tracker to the regions detected by the image analysis. If the regions contain echoes from more than one passing target, this can be detected. More features can be extracted from the tracked single echo detections like velocity. The classification algorithm can now use all the extracted features to recognise fish and reject unwanted tracks from objects like debris and bottom. A second SED can be added to the chain to mark echoes with low probability of being influenced by interference from other targets. Later, at the stage of producing statistics, the marked echoes can give a better basis for estimating the fish size than applying all the detected echoes.

![Image analysis → New SED → Tracking → Classification → SED → Fish tracks]

Figure 4. Sonar data analysis method based on the developed techniques.

7.3 Results concerned with the interpretation of the data

Without being able to interpret the results from the data analysis, the results will be more or less meaningless. Detecting a number of fish in the recorded data tells that it at least have been that many fish passing the beam. This information can of course be important. However, without knowledge about the sample volume, the uncovered part of the river cross-section area, and the sonar's efficiency, this number cannot be applied in estimates of the actual fish stock. Further, if there are unknown variations in the river cross-section area or in the sonar's detection efficiency, the obtained estimate is difficult to apply in long term studies of changes in a fish-stock. The interpretation process is shown in Figure 5.
7.3.1 Area expansion and stratification

Interpretation by means of spatial extrapolation and stratification is common. The ratio between the covered and the total part of the river cross-section can be calculated, and the observed number of fish can be extrapolated according to this ratio. If uneven distribution of fish is assumed, the river cross-section can be stratified, and the extrapolation applied by taking into account the fish density in each stratum. This is demonstrated in Figure 6.

During the fieldwork in the River Tana, substantial deviation between the expected and the measured sound fields was observed. It seemed as when the water level sank to a certain level, the sound-beam normally measured to have a 4 deg. opening angle, suddenly started to fill most of the river cross-section. The observation was made in the River Tana in 1998 and 1999. In 2000, similar observations were made in a shallow pond in Rimov (Cz). In Rimov different transducers were tested. Indications that the phenomenon depended on alignment and opening angle were seen. The observations are reported in paper VII. We have not been able to explain these observations. More measurements have
to be taken before we can draw definite conclusions. However, if the phenomenon really exists, the changes in the river cross-section coverage make area expansion difficult.

Based on the assumption that the phenomenon exists, the problem can be solved in different ways. The phenomenon can be avoided by avoiding shallow areas, and it might be possible to suppress the phenomenon by proper choice of transducer opening angle and transducer alignment. A different approach can be to constantly monitor the behaviour of the sound field. Then data recorded under the influence of the phenomenon can be interpreted differently from other data. Being able to control the phenomena is definitively tempting and would enable us to cover the total river cross-section from the surface to the bottom.

Figure 6 Area expansion and stratification. Covered and uncovered area can be calculated from the geometry and placement of the beam and from the bottom profile. Stratification can be applied by estimating the fish density $\delta$ in each of the drawn squares.

7.3.2 Time expansion

Running a long-term fish monitor project continuously is not a simple task, and halts in the data recording are bound to occur. In the River Tana the recording had to be stopped when the transducers needed to be repositioned and when data had to be transferred from the recording computers to larger storage. The transfer had to be done each day and halted the recording for about 20 minutes. Accidental power and equipment failure also occurred. In surveys where time multiplexing is used, time expansion is also important.

The acoustic noise level will change during a long term monitoring project in a river. The noise level sets restrictions on the smallest fish that can be detected. To be able to compare results from different periods, it is important to apply a constant threshold. The threshold might be obtained from the highest observed noise level, but this level might be
so high that only a few large fish are detected. If this high level occurs only in shorter periods, it can be desirable to lower the threshold and apply time expansion to the periods with higher noise level. This is demonstrated in Figure 7.

\[\text{Figure 7. Time expansion can be applied to cover periods with too high noise level and periods with halt in the recording.}\]

### 7.3.3 Variations in the detection probability

Variations in the efficiency can be expressed as a spatial and temporal detection probability function $P(r, A \text{lo}, t)$, where $r$ is the range, $A \text{lo}$ represents the vertical position, and $t$ the time. The horizontal position, $A\text{th}$, is of low importance in this context. The detection probability function is controlled by the sensitivity pattern of the beam and by temporal changes in signal to noise ratio. Diurnal and seasonal changes in the signal to noise ratio exist in a river, due to influence from the weather.

We do not believe that full knowledge of the variation in $P()$ can be gained in a river application. Hence, reducing the influence of the $P()$ is important. From the monitoring in the River Tana it was seen that the most effective part of the beam was the region from 18 to 30 m. Most of the fish were detected in this region. Moving the transducer further out or closer to the riverside did not influence this, and it is natural to conclude that this is related to the spatial part of the transducers detection probability. Forcing the fish to pass the sonar in this region will reduce the effect of the $P(r)$. Nets and ropes can be used to guide the fish into this region.

In the River Tana, a guiding net was used to prevent fish from passing behind or close to the transducer. Underwater cameras verified that the fish did not turn into the shore and behind transducers as soon as they had passed the net. However, due to the water depth and the strong current, we did not manage to build nets that could shelter the beam as
far out as 18 m. This might be solved with other net constructions as described in chapter 9.3.3 - 9.3.2.

On the east riverside in the River Tana, a trench in the river bottom allowed fish to pass sheltered from the beam. As an experiment, an orange coloured rope was stretched 50 cm above the bottom in the trench. The rope formed an artificial bottom for the sound beam. Underwater video recordings indicated that fish actually preferred to pass above the rope and not under it. This could provide a way to reduce the effect of the P(Alo), and to improve the area coverage ratio.

7.3.4 Determining the fish size distribution

Interpreting the actual fish size from the observed target strength (TS) was found to be difficult. The intensity of an echo from a fish depends on the size, the aspect angle, and the actual specie. Love (1977), Kubecka (1994), and Kubecka and Duncan (1998) have investigated this. A method based on Kubecka and Duncan's result was implemented in Sonar5 and tested. The method estimates the target strength and the aspect from tracked fish-echoes, and combines the estimates with data from "fish in carousel" measurements. The aspect was estimated by linear regression of the x, z positions of tracked echoes, while target strength was calculated by averaging the echoes’ acoustic size determined from the individual echoes. Implementation in Sonar5 is described in chapter 9.2.5.

Applying the method on tracks detected in the River Tana resulted in unrealistic fish size distributions. Estimating the aspect angle from detected fish-echoes with linear regression gave erroneous results when the targets did not pass in straight lines. Hence, methods based on smoothing should be tested.

Another difficulty involved in converting TS to real fish size was the influence from interference phenomena. The received echo is a sum of contributions from other nearby fishes, from multiple echo sound paths generated by reflections via the surface and the bottom, and from the general background reverberation level. In vertical applications with low reverberation level, this is normally not a problem. However, in rivers unwanted signal contributions can bee seen to increase the intensity of some fish-echoes dramatically. When the target strength of a fish track is calculated by converting from TS to acoustic cross-section and back, the strongest echo will influence most. When converting back to logarithmic values, it is often seen that mean and maximum TS are approximately the same. There is a long ongoing debate whether the averaging of TS
should be done in the logarithmic or the linear domain (Lilja et al., 2000). Averaging in a non-linear domain is certainly not mathematically correct, and other methods should be tested. Avoiding extreme values and estimating the size by algorithms like the median, sigma, or the $k$-nearest neighbours (KNN) should be tested.

Calibration based on reference targets or by measuring and compensating for the background reverberation level can be other ways to improve the accuracy in the TS estimates. Further research is needed in order to find suited methods for estimating TS and fish size in rivers.

### 7.3.5 Continuous monitoring the sound field

In rivers where recording conditions vary with time, continuous mapping the sound field seems to be a solution. Placing known targets in, under, and above the sound beam in the river during operation can do this. Knowledge of the acoustic size and the positions of these targets will enable us to detect variations in the sensitivity, spherical spreading, and deviation from the expected beam. This information can be used to correct the target strength from detected fish and to estimate the river cross-section coverage if the sound field should deviate from the expected field. Figure 5 demonstrates the usage of reference targets in the interpretation procedure.

Placing targets in a river is, however, a nontrivial task, and the targets might influence on the fish behaviour. It remains to carry out experiments with this method.

### 7.3.6 Practical improvements

Interpretation of sonar data obtained in shallow rivers involves a lot of considerations and calculations. Assistance from computer programs can be of great help. A good sonar post-processing program should be able to assist the operator in all the interpretation stages demonstrated in Figure 5, such as area expansion, stratification and time expansion, determine track aspects, and estimate fish size distributions based on aspects and carousel measurements. The program should be able to determine the spatial and temporal variations in the noise level, and from this, estimate fish size thresholds in long-term monitoring projects. The program should also be able to convert the detected track positions from transducer co-ordinates to river co-ordinates, and to present the results relative to the river profile as diurnal and seasonal statistics.
8 Conclusions and perspectives

Hydroacoustic fish stock assessment in shallow rivers has been recognised as far more difficult than similar vertical assessment in lakes. However, after having studied the method, we are convinced that the technique in many cases can provide a good alternative, or be a good supplement to traditional methods like catch statistics.

A major problem has been to obtain and separate fish tracks from noise in the recorded data. The analysis methods developed during this study have proven capable of reducing this problem. It has been demonstrated that the image analysis method and the new single echo detector managed to suppress noise and increase fish detection probability compared to existing methods. It has also been demonstrated that the suggested classification method could identify tracks from migrating fish.

Interpretation of the results from the data analysis has been recognised as difficult due to the observed variations in the sonar's efficiency. Hence, it is important to reduce these variations, and methods for doing so have been discussed.

The discrepancy between expected and measured sound fields in the River Tana is interesting. It is important to find out whether the phenomenon really exists, and if so, what causes it, and how to avoid or control it. It is tempting to be able to observe the total river cross-section.

Estimating the fish size distribution from sonar data recorded in the River Tana was difficult. Non-realistic fish sizes were obtained. Interference as well as the described "Tana phenomenon" are believed to be the reasons for this. Ways to overcome the problem have been suggested in the thesis.

The Sonar5 post-processing program developed during the study has proven capable of assisting in all three stages of the hydroacoustic fish detection method; acquisition, analysis, and interpretation. However, further improvements are possible. The number of parameters involved, both in the Sonar5 and in scientific echo sounders in general, is a threat to the method. Studies of methods for reducing, simplifying, and autotuning parameters are needed. Due to the time variation in the sonar's detection efficiency, not only fish-echoes, but also the surrounding noise level should be detected and applied in the interpretation. The volume of calculations involved in operations such as time and area expansion and stratification are overwhelming, and should be left to the software.
9 Topical presentation

9.1 The hydroacoustic fish detection method

In this thesis, the hydroacoustic fish detection method refers to a method based on one or a few split-beam transducers. The transducers can be fixed or moving, and they can be mounted with the acoustic axis downwards or sideways. Further, the "method" refers not only to the acquisition of echo data, but to the total detection process. This also embraces the data analysis and the interpretation of the analysis results. The three elements, acquisition, analysis, and interpretation constitute the method as illustrated in Figure 8. Data acquisition involves tasks like selection of equipment and suitable sites, mounting the equipment, tuning the sonar parameters, and recording the data. Analysis involves detecting the wanted information from the recorded data, while interpretation converts this information into useful statistics.

![Diagram of the three elements involved in the hydroacoustic monitoring method.](image)

Figure 8. The three elements involved in the hydroacoustic monitoring method.

9.1.1 The echo sounder

Active echo sounders generate short bursts (pings) of high frequency sound. These bursts are emitted into the water by the transducer. Between each emission, the echo
sounder switches into receiving mode, the transducer functions as a hydrophone, and the returned echoes are recorded (Figure 9).

In a split-beam echo sounder, the returned sound intensity is measured with four separate elements in the transducer. These elements are arranged in a geometrical pattern so that echo from a target with an off-axis position will reach the different elements with different phase. The four signals are amplified separately, and passed on to a phase detector, and an amplitude detector. In the phase detector, the signals are compared, and the targets’ angular positions are extracted. In the amplitude detector, the four signals are combined, and the modulated amplitude signal detected. The signal is then compensated for transmission loss. Presenting the amplitude signal from subsequent pings as columns in a diagram gives the echogram. Here, the vertical axis represents the distance from the transducer (range) while the horizontal axis represents the time.

The output from the amplitude and phase detectors is also used as input to the single echo detector. This detector applies a set of echo criteria to detect echoes from single targets, and to reject background reverberation and multiple echoes. Accepted echoes are beam pattern compensated according to their off-axis positions in the beam. The single echoes can be plotted in echograms and in two- or three-dimensional position diagrams. To distinguish between the two types of echograms, the prefix Amp and SED are used. Figure 9 demonstrates the main elements in a split-beam system.

The echoes cannot be distinguished when two targets are located in the sound beam so that their echoes reach the transducer without sufficient temporal separation. (Figure 13). The targets will then interfere and cause an error in the size estimate. If these targets have different angular positions, the phase signal will fluctuate and it will not be possible to determine the targets’ positions. This will cause an error in the calculation of the beam compensation factor and again cause errors in the size estimates. Removing multiple echoes removes these sources of errors.

A positive side effect with the single echo detector is its ability to reduce the amount of data that have to be stored during a hydroacoustic survey. Only five numbers are

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1 Amplitude detection, also called envelope detection, can be compared with the processes of detecting the low frequency signal in amplitude modulated radio communication. The targets in the sound beam modulate the high frequency signal emitted by the sonar. The modulation is extracted in the detector while the original carrier is removed.
sufficient to represent a single echo; intensity, time, range and the two angular estimates Alo and Ath. Compared with the originally sampled amplitude and phase signals, this represents a tremendous data reduction.

**Figure 9.** Main elements in a split-beam echo sounder system. With the EY500, sample angle telegrams are obtained at point A, sample power telegram at B, trace telegram at C and Echo telegram at D. Tracking is not part of the EY500 system. TVG = time variable gain, Ch = channels.

9.1.2 Analysing the data

Sonar data analysis is the process of extracting information from the recorded data. Two common methods are the biomass estimation method based on echo integration and the single fish detection method based on single echo detection (SED) and tracking. Echo integration is applied whenever the target density is higher than the resolution of the system, such as estimation of fish schools in ocean fisheries. Echo integration is well described in most books about hydroacoustic, e.g., ([MacLennan and Simmonds, 1992](#)).

9.1.2 - 1 **Single echo detection and tracing**

The single echo detection and tracking method (STM) can be applied when the density of the targets is lower than the system’s rage and time resolution. This is determined by the transmitted pulse-length, the ping and sample rates. Low fish density is
often seen in rivers and during nights in open waters. In river applications, STM is the most common analysis method today.

SED is based on comparing the returned echo-pulse with a set of parameters such as the echo intensity, pulse-length, shape, and the amount of variation in the phase signal. An important side effect of the SED process is the high reduction of data gained especially due to removal of the background reverberation. SED is further described in the introduction of paper IV.

Tracking is the process of detecting traces from targets passing the beam. Depending of the sonar's ping rate, the target's speed, and the beam width, a number of echoes will be received. In order not to count each target more than once, these SED-echoes has to be combined. This is the task for the tracker. Tracking is described in paper I.

*Figure 10. Elements in the STM analysis method. The example shows vertical recorded fish from Lake d’Annecy (Fr). Not all fish seen in the recording (Amp-echogram) have been detected by the SED.*

9.1.3 Interpretation of sonar data

It is a challenge to detect fish in the recorded sonar data. A totally different task is to interpret the meaning of this detection. The sound-beam will only cover a proportion of the total water volume, temporal and spatial variations exist in the sonar's detection efficiency, and it cannot be assumed that the fish are equally distributed. In vertical applications, cruise track planning and volume expansion methods are important (MacLennan and Simmonds, 1992). In river application with fixed transducers, cross-section area expansion and stratification can be applied (Gaudet, 1990).
9.1.4 River applications

In shallow rivers, fixed positioned side-looking transducers are common. The cone shaped beam fits well with a steady declining river bottom, and good river cross-section coverage can be achieved with one or a few transducers. This is demonstrated in Figure 11. Transducers with elliptical beam are popular. Aligning the main elliptical axis horizontally in the direction of the river current increases the number of echoes that can be detected from migrating fish. The narrow vertical opening angle enables placement in shallow water and prevents the beam from hitting the bottom and surface. Transducers with 2x10 and the 4x10 deg. opening angles, and sound frequencies of 120 kHz, 200 kHz and 400 kHz are common. With increasing frequencies, the size of the transducer is reduced. This makes it easier to handle the transducer and to achieve stable mounting in the river current. A drawback is the shorter wavelength, which results in detections of smaller particles and reduces the range.

Ping rate is important. With low ping rate, the probability of detecting a fish with sufficient number of hits decreases and tracking becomes difficult. The highest possible ping rate is physically limited by the decay-time of the background reverberation. If the water is still ringing from the previous sound emission, the next ping will add new energy and increase the reverberation level. This can result in reduced detection probability of small fish. The transmitted power, the range and the nature of the site are factors that influence on the decay of the ringing.

Selection of a well-suited site is important. Three factors should especially be considered: Bottom, noise level, and water current. An ideal bottom is shaped as the lower edge of the sound beam and with the water depth increasing according to the transducers’ opening angle. Rocks or trenches on the bottom reduce the area coverage and enable fish to pass sheltered from the beam. Artificial fish guiding constructions, more transducers or transducers with time controlled aiming can sometimes solve this, but it will complicate the survey.

The background noise level depends on factors like boat traffic, air-bubbles, silt and drifting debris. It is important to avoid sites close to rapids or open parts where wind can generate waves.

The water current is an important factor. A steady laminar current of some strength is ideal. The current will force fish to pass the site with the side aspect towards the transducer and prevent fish from hovering in the beam or inhabit the site.
9.1.5 The sonar equation for point targets

The initial sound intensity that the transducer can produce is called source level (SL). When a sound-pulse is emitted from a point source in open water, the sound will spread out in a spherical way. The intensity will be reduced with the factor of the increasing area of the wave front (geometric damping). The sound-pulse will also interact with the molecules in the water and a portion of the energy will be converted into heat (absorption). Geometrical damping and absorption forms the transmission loss (TL). If the sound hits a target, this target will reflect some of the sound back to the sonar (echo). The intensity of this echo is described as target strength (TS), which relates to the target’s acoustic cross-sectional reflection area, ($\sigma$). On the way back to the transducer, the echo will be damped and absorbed in the same way as the incident sound-pulse. The echo intensity that the transducer experiences on its surface is the echo level (EL). For the sonar to estimate the target's size and position, the echo level has to be converted to electric power.

Like radio and television antennas, modern transducers can focus sound. Focusing is controlled by the transducer’s geometry, the number and placement of the internal transmitter elements, and by weighting the signal to and from these elements (shading) (Urich, 1983 chapter 3.9). The intensity along the acoustic axis relative to an equal, but non-directional transducer is described by the directivity index DI. The beam pattern function $b(\theta, \phi)$ describes the sensitivity in all directions. The beam is strongest along the main axis and becomes weaker with increasing off axis position. This effect has to be compensated to estimate the correct TS.
If the sound hits a layer of water with a different density, such as a school of fish, reflections will occur from all parts of the beam. This is described as reverberation. The intensity of the sound reverberated from a unit volume of water is described as the volume reverberation (Sv). The total amount of reverberation is found by multiplying Sv with the volume of water found at the specific range in the beam. Volume is computed by multiplying the area of the surface covered by the beam with a factor (h). This factor is defined as the distance the sound manages to travel during 1/2 of the transmitted sound-pulse (h= 1/2 * sound speed * transmitted pulse-length).

Two sonar equations can be formed depending on whether single targets or volume reverberation are to be estimated. The echo level in the two cases can be described by:

\[
EL = SL - 2TL_R + TS - b(\theta, \phi) \\
EL = SL - 2TL_R + Sv + V_R \\
V = 10\log(\text{volume}_R)
\]

Here, the upper expression calculates the echo level (EL) from a single fish while the lower expression calculates the EL from a fish school. TL = Transmission Loss, TS = Target Strength, Sv = Volume reverberation. V is the logarithmic volume of the beam at a range R.

9.1.6 Acoustic size

The cross-section area of a target is the portion of the object that is hit by the sound. The acoustic cross-section area (σ) is defined from the ratio between the sound power hitting the target and the power reflected by the target measured at a unit distance. Intensity (I) is defined as power per unit area (Wm⁻²). The power hitting the target can then be expressed as P=I*σ. Assuming spherical spreading of the reflected energy from the target, the reflected power at a distance of one meter can be expressed as P(out)=I(out)*4π. The following equation demonstrates this.
The hydroacoustic method

\[ P_{\text{IN}} = P_{\text{OUT}} \]
\[ I_{\text{IN}} \cdot \sigma = A \cdot I_{\text{OUT}} \]
\[ I_{\text{IN}} \cdot \sigma = 4\pi R^2 \cdot I_{\text{OUT}} \]
\[ \sigma = \frac{I_{\text{OUT}}}{I_{\text{IN}} \cdot 4\pi} \quad : \quad R = 1 \]

Here, \( \sigma \) is the target's acoustic cross-section area. Reflected intensity is measured at a
distance of 1 m from the target, \( A \) is the surface area of the reflected wave front, \( R \) is the
radius from the target to the wave front, \( P \) is power, and \( I \) is the intensity.

Target strength (TS) is the logarithmic expression for the relationship between the
incident and the reflected intensity. TS relates to \( \sigma \) by a factor of \( 4\pi R \) as seen in the
following expression.

\[ TS = 10\log \left( \frac{I_{\text{OUT}}}{I_{\text{IN}}} \right) = 10\log(4\pi \sigma) \quad : \quad R = 1m \]

9.1.7 Relationship between wavelength and acoustic size

Wavelength is the distance between two neighbouring peaks of the wave or two
points on the wave with a phase difference of 360 deg. The frequency and the speed
decide the wavelength of a mechanical wave. The relationship is demonstrated in the
following equation

\[ \lambda = \frac{c}{f} = cT \]

where \( \lambda \) =wavelength, \( c\) = sound speed, \( f\) = frequency, and \( T \) is the period of time or the
time that the wave needs for a 360 deg. phase shift.

In measurement techniques based on waves, wavelength is a limiting factor. Measuring objects being smaller than the probing wavelength can be difficult. Strutt and
Rayleigh (1940) have investigated this. They discovered that when the target’s physical
cross-section area was large compared with the wavelength, the ratio between the physical
and acoustic size was independent of the wavelength. In the opposite case, the acoustic size was highly dependent on the wavelength. The function between the wavelength and the target’s acoustical and physical size is seen in Figure 12. For a spherical target smaller than the wavelength, the acoustic size was found to increase with the sixth power of the physical radius and decrease with the fourth power of the wavelength. Reflection from targets in this region is called Rayleigh scatter.

![Figure 12. Scatter from a spherical target as a function of wavelength and target size. $k$ is the wave number ($k=2\pi/\lambda$), $a$ is the radius of a spherical target and $\sigma$ the acoustic cross-section area.](image)

The acoustic size reaches a maximum when the wave number $k$ multiplied with the radius equals one. This maximum point is important to bear in mind when operating an echo sounder. With a 120 kHz transducer, Rayleigh scatter will occur with targets having a radius smaller than ca. 2 mm. In order to avoid effects from the wavelength, the targets should have a physical radius ten times this size ($a > 2$ cm). This is demonstrated in the following equation

$$ka = \frac{2\pi a}{\lambda} = 1$$

$$\lambda = \frac{c}{f} = \frac{1500 m/s}{120 kHz} = 0.0125 m$$

$$a = \frac{\lambda}{2\pi} = \frac{0.0125 m}{6.28} = 0.00199 m \approx 2 mm$$

where $a = \text{radius}$, $k = \text{wave-number}$, $c = \text{sound-speed}$, $\lambda = \text{wavelength}$, and $f = \text{frequency}$. Resonance might occur until the radius is about 10 times the calculated size.
9.1.8 Transmitted pulse, range resolution and sample frequency

Dependency between the target size and the wavelength has been described. With active digital echo sounders, other dependencies exist. These are the relationships between the transmitted pulse-length ($\tau$), the sample period ($\Delta t$), and the range resolution. The range resolution ($rr$) describes the maximum density of targets along the range axis. If the distance between two targets is shorter than:

$$rr = \frac{c \cdot \tau}{2}$$

where $c =$ sound speed and $\tau =$ transmitted pulse-length, these targets cannot be distinguished. The reason is demonstrated in Figure 13.

![Figure 13. Relations between transmitted pulse-length $\tau$, sound speed $c$, sample frequency $\Delta t$ and target distance $d$. If the target distance $d$ is too small, the two echoes will overlap and form a multiple echo.](image)

If the distance between two targets is less than $rr$, the tail of the echo from the first target will overlap the front of the echo from the second target. Typical echo sounder pulse-lengths are 0.1 to 1.0 ms. With a sound speed of 1500 m/s$^{-1}$, this gives a range resolution of 7.5 and 75 cm, respectively. From this, it seems as if a short pulse is an advantage. With shorter pulses, however, the amount of energy transmitted by the sonar is reduced. There is also a dependency between the needed bandwidth (BW) and the pulse-
length (BW = 2/τ). Pulses in the range from 0.1 to 1.0 ms then result in bandwidths from 20 kHz to 2 kHz. The signal to noise ratio decreases with increasing bandwidth. From this it is clear that finding the optimum pulse-length involves many considerations.

With digital echo sounders, the sample frequency is a factor that sets limitations to the range resolution. With a sample frequency of 10 kHz and a speed of sound of 1500 ms\(^{-1}\), the distance between each sample will be:

\[
rr = \frac{c}{2 \cdot f_S} = \frac{c \cdot Δt}{2} = \frac{1500}{10kHz \cdot 2} = 0.075 \quad \text{: 7.5 cm} \tag{7}
\]

where \(c\) is the speed of sound, \(f_S\) the sample frequency, and \(Δt\) the sample period. The factor 2 originates from the fact that the sound has to travel the distance twice.

According to Nyquist's sampling theorem, the sample frequency has to be twice the highest frequency component obtained in the echo-signal. The signal we are discussing here is not the high frequency sound emitted by the transducer, but the low frequency modulations caused by the targets in the beam. This modulation signal is detected in the sonar's amplitude detector. It is this signal that normally is sampled in (to days) digital echo sounders. The highest frequency in the modulation signal is limited by the transducer's bandwidth. With a 20 kHz bandwidth, the highest modulation frequency component is 20 kHz. This would have demanded a sample frequency of 40 kHz. However, with a pulse-length of 0.1 ms, the range resolution is 7.5 cm and a sample resolution of 3.75 cm or 20 kHz would be sufficient. See Figure 13, Figure 14 and Figure 15.

![Figure 14. Two standard Cu-spheres (23.0 mm, 120 kHz, -40.3 dB) separated by 20 cm along the range axis. 0.1 ms pulse-length and 3 cm sample resolution have been applied.](image)

\[\text{Figure 14. Two standard Cu-spheres (23.0 mm, 120 kHz, -40.3 dB) separated by 20 cm along the range axis. 0.1 ms pulse-length and 3 cm sample resolution have been applied.}\]
Designing an echo sounder with the optimum bandwidth and sample frequency is a problem for the echo sounder constructor. However, choosing the optimal bandwidth and pulse-length often have to be done by the operator in the field depending on the actual monitoring project.

Figure 15. Carrier signal modulated by targets in the beam.

<table>
<thead>
<tr>
<th>Pulse-length</th>
<th>Range resolution</th>
<th># samples in an echo</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short 0.1 ms</td>
<td>7.5 cm</td>
<td>3</td>
<td>20.0 kHz</td>
</tr>
<tr>
<td>Medium 0.3 ms</td>
<td>22.5 cm</td>
<td>11</td>
<td>6.7 kHz</td>
</tr>
<tr>
<td>Long 1.0 ms</td>
<td>75.0 cm</td>
<td>24</td>
<td>2.0 kHz</td>
</tr>
</tbody>
</table>

*Table 1. Relation between pulse-length, range resolution, samples per echo, and bandwidth. In the EY500, sample frequency is adjusted according to the soundspeed, so that each sample cover a range of 3 cm.*
9.2 Programming

Programming has been an important working method throughout the study. Our first fieldwork was carried out in the River Tornionjoki in northern Finland, where we participated in the ongoing Tornionjoki project led by Atso Romakkianemi. The main reason for participating was to learn about river acoustics from the Finnish team and to compare our new Simrad EY500 echo sounder with the HTI equipment. Our transducer was mounted near one of the Finnish transducers so it should cover the same part of the river. Different sound frequencies allowed simultaneous pinging.

Problems occurred when we started to compare the recorded sonar files. Automatic splitting of the files stored on disk resulted in different start times. We could not set up the systems with the same ping rate, and the post analysis programs from HTI (Trackman) and from Simrad (EP500) displayed the data differently. Trackman presented the output from the single echo detector (SED-echogram) in black and white, while EP500 displayed the output from the amplitude detector (Amp-echogram) in colours. Navigation and zooming with large files in the EP500 was slow and limited. All this made it very difficult to locate the same targets in the two sets of data, and we had to abandon the comparisons.

9.2.1 Development of the Sonar5

Based on the experience from the River Tornionjoki, we realised that our first contribution to the hydroacoustic fish detection method in rivers should be to develop new software. The work with the Sonar5 program was initiated.
Borland's Delphi was used for the programming. Delphi has a graphical programming interface (GUI). It operates under Window 98 and produces source code based on the programming language Pascal. It is object orientated and supports modularised programming (Miller et al., 1997).

A general file system utilising data compression and high-speed presentation of sonar data was designed. Converters for Simrad's telegram-based dg-files and HTI's ascii-based raw-files were implemented. A message system broadcast commands and events. With this as a basis, a set of presentation windows was designed to display all aspects of the split-beam echo data. Two and three-dimensional echograms, position diagrams and oscilloscope windows were implemented together with routines for fast navigation, zooming and compression. Various methods for easy access to echo information like range, ping number, recording time and file statistics were added. With this, Sonar5 became a powerful tool that enabled us to study all available aspects of the sonar data.

We soon found that the browser not only provided an easy way to study the recorded data, but that it also provided a nice way to test new ideas. Due to the object orientation, modularization, and messages system, new objects could be defined in separate modules and connected to the existing system. This made the Sonar5 to our main "working horse". New ideas and analysis methods were tested by designing new modules and by linking them into the code. The existing code provided easy access to the data and to different presentations of the results. A few examples of methods tested in this way are the
automatic multiple-target tracker, the new single echo detector, the classification unit, and the image analysis system. The following list shows some of the methods and tools we have implemented in the Sonar5 program.

- Echograms: Amp and SED-echograms with zooming and compression options, two- and three-dimensional Amp-echogram and free choice of colour scale resolution and thresholds.
- Image analysis with echogram enhancement filters, segmentation, and feature extraction.
- Tracking: Manual tracking of SED-echoes, automatic multiple-target tracking of SED-echoes, automatic track parameter detection, tracking by image analysis, track storing, editing and generation of track statistics.
- Single echo detector specially designed for situations with low signal to noise ratio.
- Sample data analyser for studying high-resolution power and angle data.
- Position diagrams for graphical presentation of echoes and tracks. Water current and bottom profiles can be displayed together with the tracks.
- Classification based on absolute demands, linear discriminant functions, and sum scores.
- Oscilloscopes.
- TS to fish size estimation methods based on aspect angle and fish in carousel measurements.
- Communicator unit for controlling the EY500.
- Digital photo and text description options, tools for connecting and presenting digital photos and text descriptions with the sonar data, including a text editor and a separate photo browser program.
- Beam calculator and site calculator. The beam calculator calculates and displays the beam graphically from the Bessel function. The site calculator calculates parameters needed during a survey, such as the sound speed, the absorption coefficient, and the beam thickness at chosen ranges.
- Peak echo detection and Fourier analysis.
- Water current measuring and presentation tools.
• Bottom profile storage and presentation tools.
• Field-log writing tools.
• Site descriptor program to assist the operator mapping the site.
• Tools for extracting data to other programs.
• TVG: 20log(R), 40log(R), user chosen, and passive mode options.

9.2.1 - 1 Object orientation, modularization and messages

To allow smooth operation and future updates, Sonar5 has been designed as a message-based, modularised and object-orientated program. New methods can be implemented simply by writing a new module and linking it into the system. The new module can be set-up to receive and transmit messages and the existing system will then work with the new module without any further changes. The system is designed as a “parent-child” program with the main Sonar5 object as the parent. This is the visual background window that is seen when the program is started. Child windows like echograms and position diagrams are opened and closed on demand from the parent window. The objects are related in a hierarchical structure as demonstrated in Figure 17. A top object, Tform, contains basic methods needed by all visual windows, while the TSonTop contains basic sonar methods. Objects deeper down in the hierarchy inherits these methods. Active windows are referenced in an element list maintained by the parent window. If the operator opens a new echogram or oscilloscope, this will be added to the element list. The list is used to keep track of the activity in the program and for delivering messages. An example of a message is when the operator draws a square around some echoes on the echogram. This generates an analysis message containing a description of the selected region. The message is broadcast and received by objects like the oscilloscope, the tracker, the sample analyser, and the 3D-echogram. Each of these objects will react independently and start to analyse the region defined in the message. The tracker will combine the echoes. If the resulting track is accepted according to the tracer's parameters, a fish track message will be generated. This message will in turn be broadcast to all objects that might be interested, such as the position diagrams and the classification unit. Even the echogram that generated the initial message will receive the fish track message and display what the tracker found within the selected region.
9.2.1 - 2 File format

Sonar5's file-format is binary. A file starts with a technical description of the file containing the number of pings, followed by recording and environmental descriptions like transducer type and gain, survey and transect description, water current, bottom profile, etc. Names on a digital photo and a text description file are also stored in this first block. The remaining part of the file contains the data from each ping. Two types of data can be stored. They are the output from sonar's amplitude detector and from the single echo detector. Data from each ping starts with a header containing pointers to the next and previous ping followed by the number of single echo detections and compression information. Only echoes above the operator-selected threshold are stored. The number formats are selected to give optimal compression and fast data access. Depth is stored with 12 bit numbers, while TS is stored with 11 bits. TS is coded with a 10 bit colour index, which enables the system to look up the colour directly in a table. The short format results in high compression, while the lookup process results in fast echogram presentations without the need for any calculations. The extra 11th bit in the TS value carries information about whether a single echo should be visible to the analysis and on the SED-echogram. Noise echoes can then be hidden temporally without being deleted.

9.2.2 Implementing image analysis

When testing the traditional sonar data analysis method (STM) on data from rivers, we discovered the importance of the Amp-echogram. On the SED-echogram, single echoes
from fish were often buried in noise or missing, or it was difficult to see whether the echo originated from fish or from other targets. On the Amp-echogram noise was less disturbing, fish-echoes rejected by the SED could often be seen, and the background reverberation level surrounding an echo could add valuable information about the origin of echoes. It was clear that the SED removed important information and that this information could improve the detection as well as the classification of targets. We found image analysis to be an interesting way of extracting this information. The application of image analysis in detection of single fish is described in paper V.

Elements from image analysis were implemented in Sonar5 in the form of a command language. It was necessary to test large selection of methods. With a command language altering parameters, implementing new methods and testing different command combinations was facilitated.

The interface between the operator and Sonar5’s image analysis was implemented as a new page in the already existing tracker window. This new dialog page was designed with a memo box for entering commands, another memo box for describing filter coefficients, a checkbox to control whether the total file or just the visible part of the echogram should be analysed, and buttons for start and stop. The page is seen in Figure 21. The Amp-echogram window is used for input and for presenting the results. Results can also be written to file.

Image analysis is a relatively new expertise developed along with the development of the computer. A typical image analysis system consists of four main steps. These are image enhancement, segmentation, shape analysis, and classification. (Pratt, 1991 and Niblack, 1986).

Image enhancement involves filtering. Low-pass filters can remove high frequency noise while high-pass filters can be applied to enhance edges. Many types of filters exist like convolution-based finite impulse response (FIR), infinite impulse response (IIR) windowing by masks, and algorithm-based filters. Other types of filters are based on transformation to the frequency domain by e.g., Fourier analysis. Transformation into the frequency domain enables filtering with sampled versions of analogue filters (Roberts and Mullis, 1987).

Segmentation is the process of classifying pixels in an image. Classification criteria can be found in features connected with each pixel such as colour or intensity. Different segmentation methods are available. The most common methods are the threshold and the
edge detection method. With the edge detection method, edges from the objects are detected with high-pass filters and linked together into complete closed perimeters. Threshold techniques separate pixels into classes according to one or more thresholds. Both edge detection and threshold techniques were tested on echograms. Threshold was found to be best suited to separate background and foreground in the tested data sets.

Shape analysis is applied to obtain numerical descriptions of the segmented regions. These estimates can be used for further identification of the different segments. Features like perimeter length, area, elongation, centre of gravity, and topography can be calculated.

9.2.2 - 1 Implementation of filter techniques based on convolution

A picture can be expressed mathematically by the two-dimensional shift integral. This integral integrates the product between the image function F and a delta Girac function:

$$F(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi, \eta) \cdot \delta(x - \xi, y - \eta) d\xi d\eta$$  \hspace{1cm} (8)

If the operation we want to apply to the image is a linear operator, the result of the transformation G can be described by:

$$G(x, y) = O\{F(x, y)\}$$  \hspace{1cm} (9)

Replacing the function F by the ideal image shift integral and realising that the operation on F(x,y) is independent of the integrating variables, we can move the operation into the integral and write:

$$G(x, y) = O\{ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi, \eta) \cdot \delta(x - \xi, y - \eta) d\xi d\eta \}$$  \hspace{1cm} (10)

$$G(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi, \eta) \cdot O\{\delta(x - \xi, y - \eta)\} d\xi d\eta$$

The definition of a linear operator's impulse response can be can be written:
\[ H(x,y;\xi,\eta) \equiv O(\delta(x-\xi,y-\eta)) \quad (11) \]

If the operator is substituted by this impulse response, we can recognise the additive super position integral:

\[ G(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi,\eta) \cdot H(x,y;\xi,\eta) \, d\xi \, d\eta \quad (12) \]

Under the condition that the super position integral is space invariant meaning that the following condition:

\[ H(x,y;\xi,\eta) = H(x-\xi,y-\eta) \quad (13) \]

is fulfilled, the super position integral can be rewritten as a convolution integral.

\[ G(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\xi,\eta) \cdot H(x-\xi,y-\eta) \, d\xi \, d\eta \]
\[ G(x,y) = F(x,y) \otimes H(x,y) \quad (14) \]

The following sampled and truncated version of this convolution integral is suited for implementation in computers. In *Sonar5*, function \( F \) represents the echogram while function \( H \) represents the filter operation that is applied to the echogram:

\[ Q(m_1,m_2) = \sum_{n_1} \sum_{n_2} F(n_1,n_2) \cdot H(m_1-n_1+1,m_2-n_2) \quad (15) \]

In practice, a filter matrix is defined with a set of coefficients. This matrix is often called a window. The window is placed in the top left corner of the echogram. The sum of all products between coincident coefficients in the window and the echogram is calculated. This sum is used as the output pixel in the resulting echogram. The window is then moved one pixel-row downward, and the process will be repeated until all pixels in the first echogram column (ping) has been treated. The window is then moved to the second column’s top position. The process continues until all echogram pixels or samples have
been treated. The idea is illustrated in Figure 18. The result of applying a 3x3 mean filter is demonstrated in Figure 19.

Figure 18. The echogram represents the input function $F(x,y)$ while $H(x,y)$ represents the impulse response matrix enlarged for readability. In practice, this $H(x,y)$ covers 3x3 sample units or pixels in the input image at each position.

Figure 19. Output echogram $G(x,y)=F(x,y) \otimes H(x,y)$. $F$ is the echogram seen in Figure 18 and $H$ is a 3x3 lowpass mean filter.

Selection of filter size and filter coefficients is important. While one set of coefficients will result in a low-pass filter, a different set can result in a high-pass filter. Examples of low-pass filters are the mean and the pyramid filters, while examples of high-pass filters are the Prewitt, Gradient and Laplace filters. Four filter examples are shown in Figure 20. The coefficients of the mean and pyramid filter should be divided with appropriate factors so that the total sum of the coefficients is 1.
In *Sonar5*, the operator can define a filter in the filter memo box by simply typing the filter name followed by the coefficients row by row. The filter can then be called from the command window with the command "filter" followed by the name. See Figure 21.

### 9.2.2 - 2 Algorithm-based filters

Convolution of impulse response filters is not the only way to implement a digital filter. Algorithm-based and mask-based filters are other possibilities. Examples of algorithm-based filters are the median, sigma and $K$NN filters. Examples of mask filters are the hit-add and the hit-remove filters. A window is moved over the entire picture. At each position, the window defines a local region. The mask or the algorithm reads the pixels in this region and produces an output value before the window is moved to the next position.

With a median filter, the locally selected pixels are sorted and the median is selected as the output value. With the $K$NN filter ($k$-nearest neighbours), the differences between the window's centre pixel and the other pixel values are calculated. The pixels with the $k$-smallest differences to the centre pixel are detected, and their mean value is used as output. $K = 6$ is typical for a window with the dimension 3x3. $K$NN, Median, Mode and sigma filter algorithms are implemented in *Sonar5*. Descriptions can be found in most books about image analysis, e.g., *(Niblack, 1986)*.

### 9.2.2 - 3 Masks and morphological filters

With mask filters, a masking matrix is defined. This mask is moved over the entire echogram image, looking for occurrences fitting the mask. If the image fits the mask at a
position, an operation will be carried out at that position. The centre pixel or the recognised pattern can be changed in shape (morphological) or changed in intensity. In Sonar5, two mask filters are implemented. They are the hit-remove and the hit-add. The operator defines the recognising patterns in the filter memo box and calls the masks by their names from the command window.

### 9.2.2 - 4 Segmentation

Segmentation means to separate classes of pixels in the image. Many techniques are described in the literature (Pratt, 1991 and Niblack, 1986). We have experimented with edge based and threshold based techniques and found that threshold based techniques were best suited due to the high intensity fluctuations on the echograms. An adaptive method based on measurements of the background reverberation level surrounding the fish has been invented for this purpose. This method has been patented and cannot be fully described here. In Sonar5, this adaptive threshold technique is called from the command window with the command "Segmentation".

Segmentation can involve more than the application of a threshold. Morphological operations like growing and shrinking can improve the segmentation by filling gaps and cracks in the detected regions. Another important operation is the morphological size filter that removes detected regions with short and long perimeters. Applied to echograms from rivers, this was found capable of removing regions containing high intensity noise pulses and echoes from stationary objects like stones. In Sonar5, the commands Grow, Shrink and Perimeterfilter are available.

### 9.2.2 - 5 Tracking by image analysis

Image analysis can be applied as the first stage in a hydroacoustic fish detection system as shown in Figure 4. Echograms recorded in shallow rivers can be split into three main classes of echoes. These are echoes from passing targets, stones, and scattered noise. The three classes look fundamentally different and it is therefore possible to differentiate between them in an image analysis system. Low-pass filters can suppress most of the scattered noise. Segmentation can differentiate between echoes from stationary targets and passing targets. Fish will typically be found in the class of passing targets together with drifting non-fish targets like debris. With knowledge of the current direction and by aiming the transducer some degrees upstream or downstream, it is possible to detect even the
direction and speed of the passing targets with image analysis. However, with the angular estimates from the split-beam system available, movement can be detected in better ways.

In situations with low signal to noise ratio there will always be a probability of missed detections and it cannot be guaranteed that the regions detected by the analysis contains passing targets only. Similar to scattered noise echoes, boat wakes and bottom reflections will occur. A detected region can also contain echoes from more than one passing fish. What we can guarantee is that the probability of containing echoes from a passing target has increased in these detected regions. The remaining task is then to increase the probability further and to separate tracks if a region represents more than one track.

One way to do this is to apply single echo detection, tracking, and classification algorithms. Because we are now dealing with small parts of the original echogram, and because the detected regions have high probability of containing passing targets, we can apply SED and tracking methods that are less restrictive than if the original echogram had been analysed. What we actually want is to investigate whether a region contains none, one or a few series of peaks related to none, one, or a few passing targets. The new single echo detector described in paper IV or a simple peak detector can do this. If these detections or peaks form none, one or a few lines, they can be tested with a simple tracker. Line fitting is another way to investigate the regions.

From the detected tracks, additional track features can be calculated and the result passed on to the classification algorithm.

In Sonar5, the described analysis can be set up in the tracker’s image command editor. A set of image analysis commands is first written. The analysis result is stored in memory and can be displayed on the echogram window. The image analysis commands are followed by a tracking command. Given this command, the program calculates the detected region’s perimeter length, area, and duration/range ratio. For each region, an analysis message containing the extracted features and the position of the extracted region is generated. This message is similar to the message that the user would generate by drawing a square around the same region on the echogram. The difference is that the described area is not square, but exactly fitted to the detected region. The extracted numerical features describing the region are added to the message, and the message is sent to the tracker only. The tracker looks up available single echo detections within the described region and tries to combine these into tracks. If any tracks are found, fish track
messages will be broadcast as usual. When received by the classification unit, the tracks will be accepted as fish and stored in a fish-basket or rejected as unwanted noise and stored in the wastebasket. A minimal set of commands to do this is:

- (a) Load, (b) Mean 3 5, (c) Segmentation, (d) Tracking 20 500

The parameters 3 5 for the mean filter determines the filter's dimension. The tracking command parameters 20 500, causes the system to skip regions with perimeter-length shorter than 20 and longer than 500 sample-units. A perimeter shorter than 20 indicate noise while a perimeter longer than 500 indicate time stationary targets like stones. The applied parameter values are given as examples only, and must be tested with the actual data. Because they relate to sample units, they will depend on the ping and sample resolution. A complex set of analysis commands is seen in the left part of Figure 21.

Figure 21. Implementation of Sonar5's image analysis command window (left) and parts of the MTT tracker (right).
9.2.3 Classification

The first part of this paragraph describes classification and classification methods. It was written as a pre-study for paper VI and gives a brief overview of the topic. The second part describes the implementation in Sonar5.

Automatic fish tracking in sonar data recorded in shallow rivers tends to produce a large number of tracks. Most of these tracks will originate from background noise, bottom reflections and drifting objects. Only a small percentage might originate from fish. This is demonstrated in paper II. When a person tracks fish manually, he or she actually performs two processes, tracking and classification. Cluster of echoes are combined and studied in a position diagram. This is tracking. If the operator believes that a track originated from a fish, it is stored and counted. If not, the track is deleted. This is classification. An automatic tracking algorithm does the first part by combining clusters of echoes originating from one and the same object, but the tracker does not classify the tracks.

In order to enumerate fish correct in rivers, it is necessary to sort out the non-fish tracks from the automatic tracking results. This can be done manually by evaluating each track. The operator is relieved of the job of combining the tracks. With a fish/non-fish track rate of up to 1:100, as found in paper II, this sorting can still be time consuming. It is therefore tempting to leave the job to an automatic classification algorithm.

Figure 22. Examples of three typical echo phenomena seen in a shallow river: a) track from fish or drifting debris, b) reflection from bottom, c) noise echoes from waves on the surface. The upper row displays single echo detections in position diagrams. The lower row displays the echo intensity in Amp-echograms.
Classification is the process of grouping echo objects according to some common criteria. In sonar data, objects can be defined in different ways. The tracks formed by single echo detection and tracking gives one sort of object. Other types of echo objects are the regions detected by image analysis of Amp-echograms and single echo-pulses detected from individual pings (Figure 23). Classes can be fish species, fish-schools, and stones on the bottom of a river or other objects and phenomena producing echoes. Figure 22 illustrates three classes frequently observed in rivers. Background theory on classification is found in books about multivariate statistical methods and involves topics like cluster, factor, principal component, discriminant and canonical correlation analysis (Richard and Dean 1986).

Species classification based on echo-signals from fish schools is well known from the literature such as Lu and Lee (1995) and Scalabrin et al. (1996). Species classification based on vertically recorded echo-signals from single fish has been investigated by Vray et al. (1990). Little have been written about classification of tracks detected in shallow rivers, however. In the referenced articles, it is always "believed" that the echoes originate from fish, and the question is to identify the fish species. In rivers it cannot be assumed that these echo objects represent fish.

Classification can be divided into supervised or unsupervised methods (Niblack, 1986). With unsupervised methods, an algorithm analyses the tracks and sort them into separate classes based on similarities in the track variables. With this method, the operator has to identify the classes afterwards. Unsupervised methods are frequently referred to as cluster analysis (Tryon, 1939). Various clustering algorithms exist, such as joining tree clustering, block clustering, k-means clustering and nearest neighbour clustering. Unsupervised methods will not be discussed further.
With supervised methods, the operator supervises the process by selecting a training set containing objects from each possible class. Examples of classes can be tracks from fish swimming towards the current, debris, and stones. This forms the training set. From the training set the algorithm "learns" what each class looks like. Unclassified objects detected outside the training set are compared with objects in the training set and classified according to detected similarities in variables. Examples of supervised methods are linear discriminant function analysis, Bayes classification and neural network. Linear discriminant methods transform the input data to obtain maximum separation between the objects in the different classes. Bayes classification is based on conditional probabilities, while linear networks simulate the neurones and synapses in the brain.

The use of features is common for all classification methods. A feature is a statistical variable that describes the objects so that they can be sorted into the different classes. Wine can be classified as white or read by measuring the colour. The colour is a statistical variable because each bottle of wine can take on random variations from dark read to near transparent. One can expect that the colour will separate the wine correctly into the two main classes, but it is often impossible to find a single feature that separates the classes so well. Additional features can then be defined and evaluated. This is demonstrated in Figure 24. Here, it is clear that no decision rule can be made that separates the classes based on either the feature $x_1$ or the feature $x_2$. By studying the joint distribution $f(x_1,x_2)$, however, it is possible to separate the classes as the stippled line indicates. Another important aspect seen in this figure is that it might be possible to rotate or transform the realisations of the features so that a simple decision rule can be applied. This is what linear discriminant function analysis does.

![Figure 24. Upper part: Scatter plot for observations from two classes described by two features $x_1$ and $x_2$. Lower part: Histogram showing the distribution in the feature $x_1$.](image)
9.2.3 - 1 Studying features

It is important to study the realisations of selected features. Features can be correlated, and they can contain low explanatory power. Applying too many features might reduce, rather than improve a system’s ability to differentiate the classes. The distributions of the features are of great importance and control the selection of classification methods. Being able to assume normal distributions can simplify the classification and enables the application of parametric methods. Linear discriminant analysis assumes that the covariance matrixes are similar within the various classes. Studying plots of the individual features and estimating higher moments like the variance, skewness, and kurtosis can show the variability and reveal discrepancies from the normal distribution. Studying the correlation between the features is also important.

Situations with two classes and one or two features are easy to handle. It becomes difficult to plot and study the relations when the number of classes and features increases, however. Methods like principal component analysis and principal factor analysis have been developed to study the variance and covariance structures of the features. General objectives are feature reduction and interpretation.

The significance of the features’ ability to separate classes can be studied by multivariate F-tests or by measuring statistical distances between the objects in the different classes. Calculating the Jeffrey-Matusita distance is one way to do this (Equation (16)).

As already stated, it can be desirable to reduce the number of features in a classification system by selecting a smaller subset. This reduces computational effort and can increase the explanatory power of the remaining set. Stepwise discriminant analysis is one way to do this. With multivariate classification, however, there are no guarantees that the subset selected is the "best". Minimising the apparent error rate or maximising the explanatory power in a training set can perform poorly in future samples and the results should therefore always be evaluated with a validation sample (Richard and Dean, 1986 p 356). Stepwise selection is performed in similar ways as with model building in linear regression. First, all available features are tested and the one that separates best is chosen. Next, this feature together with one and one of the remaining features are tested to find the best set of two features. The process continues until the explanatory power of the set stops improving. Backward selection is another possibility. It is also possible to test all features
against all other features, but with many features this will result in an overwhelming amount of computation.

9.2.3 - 1.1 Class separation by Jefrie-Matusita distance

One way of calculating the statistical distances between classes is provided by the Jefrie-Matusita distance (JM distance) (Niblack, 1986). The JM distance between two classes \(i, j\) is defined as:

\[
JM_{i,j} = \left[ \int \left( \frac{q(x|i)}{q(x|j)} - \frac{1}{2} \right)^2 dv \right]^{1/2}, \quad i, j \in 1..K
\]

where \(i\) and \(j\) indicate two classes and \(q(x|i)\) and \(q(x|j)\) are the probability of observing a particular realisation of the multidimensional feature vector \(x\) if it is known that it belongs to the class \(i\) or \(j\). The square root terms within the integral of the JM distance formula can be interpreted as the non-overlapping areas seen in Figure 24. Increasing these areas increases the accuracy of the classification. If multivariate normal distribution is assumed, the JM distance formula can be rewritten

\[
JM_{i,j} = \sqrt{2(1 - e^{-a})}
\]

\[
a = \frac{1}{8} (m_i - m_j)^T \left( \frac{S_i + S_j}{2} \right)^{-1} (m_i - m_j) + \frac{1}{2} \ln \left( \frac{|S_i + S_j|/2}{\sqrt{S_i S_j}} \right)
\]

where \(i, j \in 1..K\) classes, \(S\) is the sample covariance matrix for the involved features and \(m\) represents the vector mean values. The parameter \(a\) is a scalar.

This gives the class separation between two and two classes. To find a single measure for the overall class separation, the average JM distance weighted by the a priori probabilities \(q\) for all classes can now be calculated:

\[
JM_{\text{average}} = \sum_{i=1}^{K} \sum_{j=1}^{K} q(i)q(j)JM_{i,j}
\]
9.2.3 - 1.2 Studying features with principal component analysis

Principal component analysis (PCA) also known as Kahrunen-Love/Hotelling transformation (Hotelling, 1933) can be used to study the variance and covariance structure of the features. Its general objectives are data reduction and interpretation. PCA is well described by Richard and Dean, (1986 p356).

PCA transforms the features into a new feature set so that the new features are organised with descending explanatory power. In PCA terminology, these transformed features are called components. Each component is a linear combination of the original features and the components will be ordered with descending explanatory power. There will be as many components as original features, but due to the ordering it can be found that only a few of the components are needed. The new components form an orthogonal set. This is advantageous, e.g., because it enables the usage of Euclidean metrics. The original space spanned by the features will most probably not be orthogonal due to correlation.

Solving the characteristic equation and the eigenvector equation performs the PCA. The total covariance matrix $C_v$ is first calculated from the original features extracted from the data in question. The eigenvalues are then found from the characteristic equation

$$AC_v = \Lambda A$$  \hspace{1cm} (19)

where $\Lambda$ is a diagonal matrix of the form

$$\Lambda = \begin{bmatrix}
\lambda_1 & & \\
& \ddots & \\
& & \lambda_p
\end{bmatrix}$$  \hspace{1cm} (20)

The eigenvector matrix $A$ is the solution of the equation

$$|C_v - \Lambda| = 0$$  \hspace{1cm} (21)

were the eigenvectors are found in the rows of the matrix $A$. PCA is a unitary transform (Pratt, 1991). With such transforms, we can write that $A^{-1} = A^T$. Having found the eigenvector matrix $A$, the transform to and from the original feature space $v$ and the new orthogonal component space $c$ can be expressed as:
Applying PCA to a training set of 115 tracked single echo detections in the River Numedalslågen (southern Norway) separated the classes into upstream migrating fish, debris and noise, and resulted in the eigenvalues and the eigenvectors shown in Figure 25 and in Table 2. Ten track features were applied in this test. These were the number of detected echoes in a track (NrE), the sum of missing detections between the detected echoes (NrM), coefficient of variability in the target strength cv(TS) and smoothness of the track defined as the distance between first and last echo divided by the sum of distances between all echoes. The six last features were defined as the three spatial components of the track velocity and their standard deviations.

\[
c = Av \quad \text{or} \quad v = A^T c \tag{22}\]

Figure 25. Sorted eigenvalues. The horizontal line marks the eigenvalue threshold applied to reduce the dimensionality of the new feature space.
Table 2. Eigenvector matrix $A^T$. Only the four eigenvectors corresponding to the four most significant eigenvalues are shown. The eigenvector matrix is used to transform to and from the new orthogonal feature space. The size of the elements in the eigenvectors can be interpreted as the importance of the respective features. In the column for eigenvector 1 it is seen that Smoothness and the standard deviation of the velocity in the x and y direction are the most important elements.

The transformation from the feature space to the new component space is demonstrated with parts of the two first component equations in the following expression:

\[ c_1 = 0.0728 \cdot NrE + 0.0006 \cdot NrM - 0.2423cvTS - 0.5049 \cdot sm + \ldots \]
\[ c_2 = 0.5218 \cdot NrE + 0.4837 \cdot NrM - 0.4384cvTS - 0.1094 \cdot sm + \ldots \]  

The size of the weights can be interpreted as the importance of the features. In the equation for the first component, $c_1$, it is seen that the feature Smoothness explains most of the variance.

9.2.3 - 2 Studying features with principal factor analysis

Principal factor analysis (PFA) was developed in the early twentieth century as a tool for studying intelligence. It can be considered as an extension of PCA. Both methods can be viewed as attempts to approximate the features covariance matrix. The primary question in PFA is whether the data are consistent with a prescribed structure.
Like PCA, PFA is based on eigenvalues. A different view on variance and a rotation process is involved, however. The result of a PFA is a set of linear equations based on the original features. In PFA terminology, these are called factors. Like components, factors are ordered and form an orthogonal basis. In most cases, the two methods usually yield very similar results, but PCA is often preferred as a method for data reduction while PFA is preferred when the goal of the analysis is to detect structures in the features. PCA assumes that all variability in the features should be used in the analysis. PFA applies only the variability that a feature has in common with the other features. With PFA terminology, this is called communality.

9.2.3 - 3 Classification methods

Classification methods can be selected when a set of features capable of separating the classes has been found and the feature distributions have been studied. Classification is here a question of how to apply the decision rules. Neural network, linear discriminant, and Bayes classification can be used.

9.2.3 - 3.1 Absolute classification

The simplest classification method is the absolute classification. Absolute requirements or demands are defined for each class. As an example, in a river sonar system, all tracks with velocity $> 0$ can be defined as fish up and otherwise as drifting debris or fish down. Velocity distribution overlap due to measurement error can be resolved by defining a third class as illustrated in Figure 26. Tracks ending up in this class can then be checked manually by an operator. The system will still be better than a non-classification system where all tracks must be checked manually.

![Figure 26. Absolute classification of tracks based on detected values of the variable x.](image-url)
9.2.3 - 3.2 Bayes maximum likelihood classification method

Bayes maximum likelihood method is a well-developed method from statistical decision theory. This description is basically taken from Niblack (1986). Maximum likelihood is calculated from the following probabilities:

- $q(i)$ The a priori probability that an object belongs to a class $i$.
- $q(x|i)$ The probability of observing a feature value $x$ under the condition that it belongs to class $i$.
- $q(x)$ The total probability distribution for all feature values $x$. $q(x)$ is a normalisation factor equal for all classes. It can therefore be ignored.
- $q(i|x)$ The probability that an object belongs to class $i$ under the condition that a feature value $x$ is observed.

Bayes formula:

$$q(i \mid x) = \frac{q(x \mid i)q(i)}{q(x)}$$ (24)

Bayes decision rule:

Given an object with feature values $x$ and, for each class $i$, the probability $q(i|x)$ that the object is from class $i$, then the best class to assign the object to is the class for which $q(i|x)$ is maximum.

An advantage with Bayes method is that it does not assume anything about the statistical distributions of the features. Calculating $q(x|i)$ can be cumbersome, however. If $x$ is an $F$-dimensional feature vector and each feature can take on $J$ different values, calculating each $q(x|i)$ with a computer will require a table size of $J^F$ elements. A $g$-class problem will then need a table size of $gJ^F$ elements. With $F=5$ features in each feature-vector containing features that can take on $J=500$ possible values, and having $g=3$ different classes, we get $gJ^F = 3 \cdot 500^5 = 9.3 \cdot 10^{13}$ table elements, which indeed can be problematic. We can reduce the number of table elements by reducing the resolution in
each feature or by reducing the number of features. If this is not sufficient, parametric solutions are an alternative. The feature distributions are then modelled with distributions like the normal distribution. This is demonstrated in the following equation.

\[
q(i \mid x) = q(i) \frac{1}{\sqrt{\frac{F}{(2\pi)^{\frac{d}{2}}}} e^{-\frac{1}{2}(x - m_i)^T S_i^{-1} (x - m_i)}}
\]

In this expression the term

\[
(x - m_i)^T S_i^{-1} (x - m_i)
\]

expresses a statistical weighted distance from the actual feature vector \( x \) to the mean feature value \( m_i \) of the \( i \)th class. This distance is called the Mahalanobis distance. The term

\[
\frac{1}{\sqrt{\frac{F}{(2\pi)^{\frac{d}{2}}}}}
\]

can be regarded as a normalisation factor. For computational efficiency, the constant term can be dropped and the exponential expression avoided by applying logarithms. By doing so and by skipping the normalisation factor, a likelihood estimator \( u(i \mid x) \) is found:

\[
u(i \mid x) = \ln(q(i)) - \frac{1}{2} \ln(|S_i|) - \frac{1}{2}(x - m_i)^T S_i^{-1} (x - m_i)
\]

This gives the likelihood that an object with a feature vector \( x \) belongs to class \( i \). As for \( q(i \mid x) \), \( u \) has to be computed for all classes. The classification rule will then be to assign the object in question to the class giving the highest \( u \)-value.

### 9.2.3 - 4 Neural network

The neural network technique was developed during the sixties. A neural net imitates the nerve cells and their connections in the brain. In the beginning, neural nets were believed to be "the way" to develop artificial intelligence. Today, the optimism is not that high. Neural nets have found applications in many professions like pattern recognition and classification, however. A neural net consists of a set of layers. Each layer is
constructed of a set of neurones or nodes. Nodes in neighbouring layers are connected through "synapses" represented by linking functions in a computer. Two node layers are said to be visible. These are the input and the output layers. Layers between these are invisible. When a set of input values are presented to the input nodes, these will propagate through the net depending on the linking functions, and result in signals on the output nodes. The net is trained by adjusting weights in the linking functions until the highest degree of correct classification is obtained in the training set. When applied to echo-signals, each of the extracted features from an echo object will be fed into separate input nodes and the output nodes will represent the classes. The node with the strongest signal gives the classification result. Figure 27 demonstrates the principle of applying a neural net for classification of echo objects tracked in a river. Haralabous and Georgakarakos (1996) have demonstrated the application of neural nets to identify Anchovy, Horse mackerel, and Saith in fish schools.

![Neural net diagram](image)

*Figure 27. Neural net for classification of echo-tracks recorded in a shallow river.*

### 9.2.3 - 4.1 Discriminant function analysis

The principles of linear discriminant analysis are illustrated in Figure 28. This is the same figure as Figure 24 except that the observations described by the feature $x_1$ and $x_2$ now have been linearly transformed into one single variable $y = w_1 \cdot x_1 + w_2 \cdot x_2$. This has been done in a way that maximises the distance between the classes and minimises the variance within the classes. Expressed with the new variable $y$, simple Euclidean geometry can be applied in order to derive a classification rule.
Moreover, it is important to note the reduction in the system’s dimensionality. The two features $x_1$ and $x_2$ have been combined into one single feature $y$. If multiple features $X_1..X_F$ had been applied, a single variable $y$ would still have been the result. This enables the plotting of complex systems in a simple way. The number of dimensions in the resulting system will increase with the number of classes, however. Fisher (1936) proposed the method.

\[
if \ y_0 < m = \frac{1}{2}(\bar{y}_1 + \bar{y}_2) \ then \ assign \ y_0 \ to \ R_1 \ else \ R_2 \quad (29)
\]

Fisher's idea was to maximise the class separation by maximising the ratio between the between-class and the total-class sums of squares.

\[
r = \frac{\text{Between class sum of square}}{\text{Total class sum of squares}} \quad (30)
\]

Where between class $B$ and within class $T$ are defined as:
\[
\mathbf{B} = \sum_{i=1}^{g=3} (\mathbf{x}_i - \mathbf{\bar{x}})(\mathbf{x}_i - \mathbf{\bar{x}})' \\
\mathbf{T} = \sum_{i=1}^{g} \sum_{j=1}^{n_i} (\mathbf{x}_{i,j} - \mathbf{\bar{x}}_i)(\mathbf{x}_{i,j} - \mathbf{\bar{x}}_i)' 
\]

With \( \mathbf{B} \) and \( \mathbf{T} \) being multidimensional matrixes, \( r \) has to be found by multiplication with the inverse of the matrix \( \mathbf{T} \). In a \( g=3 \) class system \( \mathbf{R}, \mathbf{B}, \mathbf{T} \) takes on the dimension 2x2.

\[
\mathbf{R} = \mathbf{T}^{-1}\mathbf{B} = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix} 
\]

The vector of coefficients \( w_1..w_F \) that maximise \( \mathbf{R} \) is the elements in \( \mathbf{R}' \)s eigenvectors, which can be found by solving the characteristic equation

\[
| \mathbf{R} - \lambda \mathbf{I} | = 0 
\]

and the eigenvector equation

\[
\mathbf{R} \mathbf{e} = \lambda \mathbf{I} \mathbf{e} \\
(\lambda \mathbf{I} - \mathbf{R}) \mathbf{e} = 0 
\]

Examples of calculations can be found in Richard and Dean (1986). Vray et al., (1990) uses the method to classify fish species in a lake based on features extracted from single echo-pulses.

In situations with more than two classes, linear discriminant analysis results in more than one variable. It is then difficult to apply the simple half point classification rule based on Euclidean geometry. A common solution is to calculate the distances between each new observation and the class centroids. The observation will then be assigned to the nearest class. By the nature of eigenvectors, the transformed features will span the vector space in an orthogonal way and Euclidean metrics is therefore appropriate in calculating the distances.

In commercially available software like Statgraphics PLUS, a sum score is calculated. A new observation will then be assigned to the class resulting in the highest score. The sum score functions are called classification functions.
9.2.3 - 5  Implementation of classification methods in Sonar5

When it comes to the question of implementing methods in software, the question is not only to select the best theoretical method. It must also be possible to perform the necessary calculations in practice and to find ways so this can be done efficiently.

Chen (1986) evaluated Fisher's method, Bayes method, and an unsupervised method based on the nearest neighbours on seismic data. He found that Bayes and Fisher's method worked about equally well. Non-parametric versions of Bayes method are difficult to implement due to the amount of memory needed, while parametric versions assume Gaussian distribution in the features. Features from sonar data are often not Gaussian, and Fisher's method was therefore selected for classification of fish-echo tracks from rivers. Another reason for selecting Fisher's method was that this method is implemented in commercial available statistical programs like Statgraphics PLUS. It could be tested on sonar tracks directly before writing any code. We found that the method worked well, and that the method was easy to use with the already existing Sonar5 software (paper VI).

Three classification methods have been implemented in Sonar5. This is the absolute classification method and two variations of linear discriminant function analysis. Absolute classification discriminates by setting absolute demands directly on one or a few features as described in 9.2.3 - 3.1 Linear discriminant analysis can be used either by setting demands on the transformed features or by calculating the highest sum score.

In the program, the classification system consists of a classification window, a feature library dialog, and a number of storage units named baskets. The library, which is accessed from the system menu, lets the operator select a number of track features like smoothness and velocity. 66 different track features are available for selection.

The classification window allows the operator to generate a desired number of baskets. Each basket can be given an individual name like large fish, small fish, stones, debris etc. Figure 29 shows the classification window with four classes defined on the upper listbox. Double clicking on one of the names with the left mouse button, opens that particular basket.

A basket is an object designed for storing and editing tracks and for generating statistics. The basket has three tabbed pages where one is named track-filters (Figure 30). This page is an important part of the classification system. Each line in the page grid displays one of the features selected in the library. The column labelled "Track" gives the
feature realisation of the last combined track, while the following three columns allow the operator to describe the decision rules or track demands.

9.2.3 - 5.1 Absolute classification

Whenever a module in the Sonar5 generates a new track, a fish track message is broadcast. The classification window responds to this message. If absolute classification has been selected, the feature realisation of the new track is compared to the demands in each of the defined baskets. One can say that the classification window asks each basket if it wants the track. Each basket answering "yes" will receive a copy of the track. If none of the user-defined baskets accepts it, the track will end up in the system's wastebasket, where it can be evaluated manually or deleted.

9.2.3 - 5.2 Discriminant function analysis

The discriminant function weights can be written in the basket’s right column marked "Factor" on the track-filter page seen in Figure 30. The factors are the results from the discriminant function analysis. Each of the values in the track column is multiplied by its respective factor in the factor column, summed into a single discriminant function value, and presented in the track column's discriminant function row as seen in Figure 30. Decision rules or demands can now simply be stated directly in the discriminant function row in the same way as with the absolute classification.

9.2.3 - 5.3 Discriminant function analysis by sum scores

Sum score classification is particularly useful in problems involving more than two classes. The factors in the factor column of Figure 30 now contain the classification function factors and not the discriminant function classification. A sum score is calculated for each track and for each basket. This sum score is displayed in the lower right cell in Figure 30 and the basket with the highest score, receives the track. A score threshold can be defined in the classification window. If no basket produces a score higher than this level, the track in question will be added to the wastebasket.

9.2.3 - 5.4 Training and verification

The discriminant function weights or the sum score weights have to be obtained from a set of manually tracked and classified echo objects. This forms the training set. When a representative number of tracks have been obtained for each class or basket, Sonar5 calculates the features listed in Table 2.
The manually classified observations have to be transferred to a statistical program where they are studied and the features with the most explanatory power are selected. The statistical program calculates the factors for the discriminant or sum score functions. The factors are written back to the basket’s factor column in Figure 30.

This solution was chosen because we did not want to complicate the Sonar5 code with a large statistical package. The shared solution might sound more complicated than if all operations had been performed in the same program, but this is not the case. Routines have been implemented in Sonar5 to simplify the process. First all track features in the obtained training set are calculated automatically. From the popup menu in the classification window, all these features are copied to the clipboard with a simple mouse or keyboard operation and then pasted into the statistical program with another click on the mouse. The resulting discriminant function or sum score factors are copied back to Sonar5 in the same simple way and Sonar5 sets up all necessary classification parameters automatically. This has been tested with Statgraphics PLUS 4.0.

![Sonar5's classification window.](image)

Figure 29. Sonar5's classification window.
Figure 30. The track filter in Sonar5’s fish basket.

<table>
<thead>
<tr>
<th>#</th>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>NrE</td>
<td>Number of detected echoes in a track</td>
</tr>
<tr>
<td>5</td>
<td>MPG</td>
<td>Max. Ping-Gap. Largest successive number of missing ping in the track.</td>
</tr>
<tr>
<td>6</td>
<td>suMP</td>
<td>Sum of missing ping within a track.</td>
</tr>
<tr>
<td>7</td>
<td>suP</td>
<td>Sum of ping. Total numbers of ping from the first to the last detection.</td>
</tr>
<tr>
<td>8</td>
<td>TTT</td>
<td>The tracks transit time through the beam. = TCP/Pingrate.</td>
</tr>
<tr>
<td>12</td>
<td>mTSc</td>
<td>Mean off-axis-compensated target strength.</td>
</tr>
<tr>
<td>14</td>
<td>mTSu</td>
<td>Mean TS before beam compensation.</td>
</tr>
<tr>
<td>18</td>
<td>VOL</td>
<td>Volume of the beam surrounding the track.</td>
</tr>
<tr>
<td>19</td>
<td>cvTSc</td>
<td>Coefficient of variability in mTSc.</td>
</tr>
<tr>
<td>20</td>
<td>cvTSu</td>
<td>Coefficient of variability in mTSu.</td>
</tr>
<tr>
<td>21</td>
<td>BC</td>
<td>Off-axis beam compensation factor.</td>
</tr>
<tr>
<td>22</td>
<td>mAth</td>
<td>Mean athwart-ship position.</td>
</tr>
<tr>
<td>23</td>
<td>mAlo</td>
<td>Mean along-ship position.</td>
</tr>
<tr>
<td>24</td>
<td>mR</td>
<td>Mean range of the track.</td>
</tr>
<tr>
<td>26</td>
<td>sAth</td>
<td>Sample deviation in the Ath estimates.</td>
</tr>
<tr>
<td>27</td>
<td>sAlo</td>
<td>Sample deviation in the Alo estimates.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>28</td>
<td>sR</td>
<td>Sample deviation in the range estimates.</td>
</tr>
<tr>
<td>29</td>
<td>aspect</td>
<td>Angle between track and the transducer centre axis.</td>
</tr>
<tr>
<td>30</td>
<td>tilt</td>
<td>Angle between track and the beam’s Ath-axis.</td>
</tr>
<tr>
<td>31</td>
<td>SM1</td>
<td>Smoothness 1. Distance ratio between the 3 dim. Euclidean first-last echo distance and the sum distance normalised by log10(NrE)</td>
</tr>
<tr>
<td>32</td>
<td>SM2</td>
<td>Smoothness 2. Mean angles between two and two echoes in the xy-domain.</td>
</tr>
<tr>
<td>33</td>
<td>SM3</td>
<td>Smoothness 3. Sample deviation ratio = sx/sy The track is first rotated so that the xy regression line through the track is parallel with the x-axis.</td>
</tr>
<tr>
<td>34</td>
<td>CDx</td>
<td>Number of times the track changes direction along the x-axis</td>
</tr>
<tr>
<td>35</td>
<td>Cdy</td>
<td>Number of times the track changes direction along the y-axis</td>
</tr>
<tr>
<td>36</td>
<td>CDz</td>
<td>Number of times the track changes direction along the z-axis</td>
</tr>
<tr>
<td>37</td>
<td>NrCx</td>
<td>Number of times the track crosses the x-axis (y=0)</td>
</tr>
<tr>
<td>38</td>
<td>NrCy</td>
<td>Number of time the track crosses the y-axis (x=0)</td>
</tr>
<tr>
<td>39</td>
<td>flDx</td>
<td>Distance between the first and the last echo along the x-axis</td>
</tr>
<tr>
<td>40</td>
<td>flDy</td>
<td>Distance between the first and the last echo along the y-axis</td>
</tr>
<tr>
<td>41</td>
<td>flDz</td>
<td>Distance between the first and the last echo along the z-axis</td>
</tr>
<tr>
<td>42</td>
<td>Dfl abr</td>
<td>Distance between the first and the last echo along in spherical domain.</td>
</tr>
<tr>
<td>43</td>
<td>suDxyz</td>
<td>Sum of Euclidean distances between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>44</td>
<td>mDxyz</td>
<td>Mean Euclidean distance between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>45</td>
<td>flSxyz</td>
<td>Speed between the first and the last echo in the xyz domain.</td>
</tr>
<tr>
<td>46</td>
<td>mSxyz</td>
<td>Mean speed between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>47</td>
<td>flVx</td>
<td>Velocity along the x-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>48</td>
<td>flVy</td>
<td>Velocity along the y-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>49</td>
<td>flVz</td>
<td>Velocity along the z-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>50</td>
<td>suAVx</td>
<td>Sum of all absolute velocities along x-axis</td>
</tr>
<tr>
<td>51</td>
<td>suAVy</td>
<td>Sum of all absolute velocities along y-axis</td>
</tr>
<tr>
<td>52</td>
<td>suAVz</td>
<td>Sum of all absolute velocities along z-axis</td>
</tr>
<tr>
<td>53</td>
<td>mVx</td>
<td>Mean of all the ”between echo x-components” of the velocity.</td>
</tr>
<tr>
<td>54</td>
<td>mVy</td>
<td>Mean of all the ”between echo y-components” of the velocity.</td>
</tr>
<tr>
<td>55</td>
<td>mVz</td>
<td>Mean of all the ”between echo z-components” of the velocity.</td>
</tr>
<tr>
<td>56</td>
<td>sVx</td>
<td>Sample deviation from all the x components of the velocity.</td>
</tr>
</tbody>
</table>
Table 3. Track variable definitions. D=Distance, V=Velocity, N=Number, S=Speed, A=Absolute, su=Sum, fl=first last, m=mean s=sample deviation. v=sample variance, x,y,z =Cartesian co-ordinates, abr=spherical co-ordinates.

9.2.4 The sample data analyser

EY500 is capable of storing not only the processed echo-signals, but also the digitised signals from the amplitude and phase detectors. (Sample power or W-telegram and sample angle or B-telegram in Simrad terminology). This has enabled us to experiment directly with the recorded echo intensities and angular measurements with a range resolution down to 3 cm. This has been essential in the investigation of problems related to single echo detection and in the development of alternative analysis methods. It has also been important for studies of sound behaviour in experiments.

A sample analyser was implemented in Sonar5 to analyse the samples. The analyser is operated in the following way. A region containing the echoes of interest is selected with the mouse in the Sonar5’s SED or Amp-echogram. This generates an analysis message broadcast by the system. The message contains a description of location and size of the selected region. The sample analyser receives this message and opens the original dg-file. If the W and B telegrams are stored here, the samples from the selected area is loaded into Sonar5’s memory and analysed.

A peak detector detects the peak amplitudes in each ping within the selected region. A threshold relative to the peak is set and all samples with intensities between the detected peak and the threshold are analysed and presented numerically and graphically. Figure 31 illustrates this, displaying the recorded Ath-angles with a 100 dB threshold. By applying 6, 12 or 18 dB thresholds; single echo features like pulse-length, shape, and phase deviation can be studied.

Messages are automatically sent back to the echogram to mark exactly what was detected and analysed. All angle and power samples from the selected region can be
presented in tables, plotted graphically in 2 and 3 dimensional charts, or pasted into programs like Excel. The magnitude and the differentiated angle signal can be plotted as well. Statistics and traditional SED-criteria are calculated from each echo and presented.

![Graphical chart showing data analysis](image)

**Figure 31.** Parts of the sample data analyser showing statistics from a selected region in the echogram. The bottom chart can display angle and power samples in two and three dimensions. In this example, Ath angle samples from a passing target are seen.

### 9.2.5 TS and fish size

Estimating fish size from target strength is a nontrivial task. The echo will depend on the acoustic size of the fish. However, other factors like the aspect toward the transducer and the actual fish specie also influence the returned echo. A fish retransmit sound with a beam pattern in a similar way as a transducer with main and side-lobes (FAO 1983). Different species have different types of swim bladder (none, open or closed) and bone structures giving different reflective features. The interference phenomena that can add echo intensity to the echoes from a fish, is another problem specially related to rivers.
In the River Tana, we saw that when we lowered a standard target into the beam at certain ranges, this target was estimated with increasing TS with increasing range (R). The increase was approximately 10log(R). The echo sounder had then already applied a TVG of 40log(R) (see Table 29 in paper VII).

In order to estimate the correct TS, and to convert TS to fish size, various tools have been implemented in Sonar5. When a target has been tracked, mean TS is calculated by averaging the individual echoes. An option controlled from the program's system parameter dialog lets the operator select if averaging should be applied in the logarithmic or in the linear domain. This results in the beam-pattern corrected mean value (mTSc). If beam mapping has shown that range-dependent variations exist at the site, adding correction parameters in the parameter dialog can compensate for this. The mTSc is then adjusted and presented as mTSadj.

The aspect angle is calculated from the individual echoes in the track by linear regression of the x, z co-ordinates. x and z are respectively the Cartesian versions of the spherical transducer co-ordinates, Ath and R.

The mTSadj is now combined with the xz-angle and species-dependent measurements from fish in carousel, to estimate the actual fish length or weight. This is done by the method developed by Kubecka and Duncan, (1998). The TS correction process is demonstrated in the following equation.

\[
TSc = TSu + BeamComp(Ath, Alo)
\]

\[
MeanTSc = \frac{1}{N} \sum_{i=1}^{N} \sigma c_i \quad \text{or} \quad \frac{1}{N} \sum_{i=1}^{N} TSc_i
\]

\[
MeanTSadj = MeanTSc + a \cdot \log(R) + b
\]

\[
FishSize = 10 \left( \frac{MeanTSadj - S + (S - Q) \cos^3(2\theta)}{R + (P - R) \cos^3(2\theta)} \right)
\]

where \( S, Q, R, \) and \( P \) are regression coefficients from carousel measurements, \( \theta \) the detected xz-angle from the passing fish, and \( a \) and \( b \) the range compensation factors.

In Sonar5, the operator can write the regression parameters in the program’s system parameter dialog seen in Figure 32, and select the set that apply to a particular survey. The regression parameters decide whether TS will be converted to weight or length. For vertical application, the operator can select the formula from Love, (1997).
The track feature, named fish size, is presented in the lower listbox in Sonar5's classification window, provided that this feature has been selected in the track feature library (Table 3). If tracks have been stored in a basket, opening this basket and clicking on the fish size column generates the fish size distribution.

![Figure 32. Sonar5's system dialog for entering regression parameters.](image)

9.2.6 The site descriptor program

In river surveys with fixed installations, it can be important to describe the positions of the equipment. It can also be of great help to be able to relate positions of targets observed in the sonar beam to more permanent river co-ordinates.

A natural, local river co-ordinate system is the one describing a position by the distance from the riverside and the up-stream down-stream positions along the river from a fixed landmark or an installation like a bridge. It can, however, be difficult to define the riverside and to find a suited landmark close enough to utilise measurements with common
tools. In the River Tana, we wanted to describe the positions of the transducers so that we could find the same positions next year. These locations could not be marked with poles or sticks in the river bottom due to the winter ice and spring flooding.

To describe the positions, two points A and B (Figure 33) were marked on the riverside and the distance between these points was measured with a tape measure. A line \( z \) normal to the river was defined, and the angle \( BAz \) was measured. So was the distance from A to the actual riverside. Another line \( x \) was defined through point A, normal to \( z \). The lines \( x \) and \( z \) with A as the centre will now span the new river co-ordinate system. With \( T \) as the transducer or any other installations in the river, measuring the angle BAT and ABT enabled conversion to the river co-ordinates.

If a target is observed at an off-axis position with \( T \) as the transducer and the transducer paned upstream and tilted downwards, converting this target’s position to river co-ordinates by hand becomes tedious.

A site descriptor program was therefore developed. Equation (34) and (35) gives the calculations and Figure 34 demonstrates the layout of the site descriptor program. The program is activated from Sonar5's tool menu.

\[
\begin{align*}
\text{ATB} &= 180 - \text{BAT} - \text{ABT} \\
\text{AT} &= \text{AB} \cdot \frac{\sin(\text{ABT})}{\sin(\text{ATB})} \\
\text{T.z} &= \text{AT} \cdot \sin(\text{TAB}) \\
\text{T.x} &= \text{AT} \cdot \cos(\text{TAB})
\end{align*}
\]

\( (36) \)

Figure 33. Definition of the landmark co-ordinate system and the river co-ordinate system.
Hor_angle = Transducer_Pan + Ath
Vert_Angle = Transducer_Tilt + Alo
TanAlo = tan (vert_angle)
TanAth = tan (hor_angle)
\[ z = \frac{R}{\sqrt{1 + \tan^2 \text{Alo} + \tan^2 \text{Ath}}} \]  
\[ x = z \cdot \tan \text{Ath} \]
\[ y = z \cdot \tan \text{Alo} \]
P(xyz) = (T.x + x, T.y + y, T.z + z)

Figure 34. Layout of the site descriptor program. A, B are marked points, x, z are coordinate axes parallell and normal to the river bank respectively, T the transducer position, P the position of a target in the beam and N is North.
9.3 Fieldwork

This chapter describes some of the fieldwork we have performed during the four years of study, how it has been carried out, and what we have learned. Fieldwork has played an important part in this study. Through fieldwork we have learned to use the equipment, recorded data for the presented articles, and experienced the difficulties involved in hydroacoustic fish stock assessments. We have also experienced how simple things might look from the office desk when one feels nice and warm in contrast to the disaster felt by losing a crucial nut through a hole in the ice. Sitting at remote places waiting for days for a new computer because the old one got a few drops of rain on the keyboard, or coming home after a long survey, finding that the data seen on the screen differs from the data stored on the disk. These things cannot be learned by reading books. An overview of fieldwork carried out during the study is given in Table 4.

Our first fieldwork was held in the River Tornionjoki in northern Finland July 1997. Here we participated in the work carried out by the Finnish Fish and Game Research Institute RKTL (Romakkianemi et al., 2000). The main purpose was to learn the hydroacoustic fish detection method and to test and compare our EY500 echo sounder with the HTI equipment deployed by RKTL. More experience was gained later the same year, when the EY500 was tested in the fjords around Hidra, an island in southern Norway. The fieldwork in the River Tana 1997, 1998 and 1999 has been our main fish-monitoring project. Data from this project has been essential in the development of new analysis methods. Sound experiments have been carried out in the River Lysaker, on the ice of Lake Semsvann and in the Rimov pond in the Czech Republic. The River Lysaker and Lake Semsvann are situated close to Oslo. Lake Semsvann and the River Tana fieldwork will be described further in this chapter.
Table 4. Overview of fieldwork and experiments carried out during the study.

<table>
<thead>
<tr>
<th>Time</th>
<th>Site</th>
<th>Last for</th>
<th>Type</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun. 1997</td>
<td>Tornio, Fi</td>
<td>2-weeks</td>
<td>River</td>
<td>Training with equipment</td>
</tr>
<tr>
<td>Aug. 1997</td>
<td>Hidra, No</td>
<td>2 weeks</td>
<td>Sea</td>
<td>Training with equipment</td>
</tr>
<tr>
<td>Sept. 1997</td>
<td>Tana, No</td>
<td>4-days</td>
<td>River</td>
<td>Preparing next summer’s fieldwork</td>
</tr>
<tr>
<td>Jun-Jul 1998</td>
<td>Tana, No</td>
<td>40 days</td>
<td>River</td>
<td>Fish monitoring</td>
</tr>
<tr>
<td>Jun-jul 1999</td>
<td>Tana, No</td>
<td>40-days</td>
<td>River</td>
<td>Fish monitoring</td>
</tr>
<tr>
<td>Apr. 1998</td>
<td>Semsvann, No</td>
<td>3-days</td>
<td>Lake</td>
<td>Near boundary experiments on ice</td>
</tr>
<tr>
<td>Apr. 1999</td>
<td>Semsvann, No</td>
<td>3-days</td>
<td>Lake</td>
<td>Near boundary experiments on ice</td>
</tr>
<tr>
<td>Feb. 1999</td>
<td>Semsvann, No</td>
<td>1-day</td>
<td>Lake</td>
<td>Near boundary experiments on ice</td>
</tr>
<tr>
<td>Nov-Apr.1998</td>
<td>Lysaker, No</td>
<td>-</td>
<td>River</td>
<td>Fish counting. Lost all data</td>
</tr>
<tr>
<td>Nov. 1999</td>
<td>Lysaker, No</td>
<td>1-day</td>
<td>River</td>
<td>Experiments. Testing the EY500</td>
</tr>
<tr>
<td>Jun. 2000</td>
<td>Rimov, Cz</td>
<td>5-days</td>
<td>Pond</td>
<td>Various experiments</td>
</tr>
</tbody>
</table>

9.3.1 Problems with the equipment

The EY500 echo sounder has proved to be robust, easy to handle and well suited for our purpose. The manufacturer, Simrad AS, has been most helpful and service minded and they have supported us with equipment, spare parts, advice and manpower. It is important for us to emphasise this before we describe the problems we have experienced with the sonar.

After four years with fieldwork, we have learned to live with equipment failure. A bug in the EY500's program tends to reset the calibration parameters. The sonar does not store the parameter setting automatically in the recorded sonar files, and it can be difficult to trace when an unmotivated change due to the bug actually took place. We suspect that the bug is related to the EY500's replay function and recommend that the calibration parameter are checked whenever the replay has been used. We soon learned to use the parameter enter function and to force the echo sounder to store the calibration parameter to disk every now and then. Later, tools for checking the parameters was implemented in
Sonar5. Another problem has been related to our ES120-4 transducer. It seems that the sensitivity in this transducer can drop with up to 20 dB under certain conditions. This might be related to very cold water situations. Other parts of the involved equipment have caused problems as well. All data from the first Lysaker trial were lost because of a hard disc crash. In the River Tana, the master card in the EY500, a JASS drive, a SCSI card in the main computer, and a laptop broke down. The rotors from the UiO were found not to be waterproof and the construction had to be changed.

### 9.3.2 Report from the fieldwork on the ice of Lake Semsvann

A total of three surveys have been carried out on the ice of Lake Semsvann. The ice provides an easy way to place targets at known positions that can be compared to the position estimates from the sonar. The transducer can be aligned both horizontally and vertically which enables us to compare open water and near boundary situations. Gaining experience with the sonar, studying boundary effects and the echo sounder’s ability to estimate target positions and size was the aim of these experiments.

The 1998 and 1999 fieldwork was a joint venture between the University of Oslo and Simrad. Frank R. Knudsen from Simrad took part in the actual work on the ice. In 1999, we also had help from Martin Cech from the Hydrobiological Institute, Academy of science of the Czech Republic. In 2000, the fieldwork was assisted by Jørgen Døvle from the University of Oslo. The nearby horse stable Tveiter run by Hans Christian Aaby has provided storage space for equipment, accommodations, power for charging batteries, etc. This has been of major help for which we are very grateful.

### 9.3.2 - 1 Material and methods

Lake Semsvann is located 20 km south of Oslo. It was found suited for the experiments because of its depth and easy accessibility by car.

The recordings were done with an EY500 echo-sounder equipped with an ES120-4 4x10 deg. split-beam transducer. The system operated at 120 kHz, transmitting 0.3 ms
pulses, and with a power of 63 W. A tent provided shelter from sun, wind, and snow. The system was powered with two 120 ampere, 12 v car batteries.

A stand made of waterproof plywood mounted the transducer under the ice. The stand consisted of a base platform with holes allowing targets to be positioned close to the transducer. The stand's base plate was nailed to the ice with ordinary nails. A profiled aluminium pole was mounted on hinges through a centre hole in the base plate. Vertical guiding plates provided stability and could lock the rafter in different angles. At the other end of the pole, under the ice, the transducer could be mounted either vertically or horizontally.

![Figure 35. Transducer stand with transducer mounted for vertical experiments.](image)

A site with a water-depth of 30 m was located. The ice was cleared of snow and holes for the transducer and targets were drilled. In the February 2000 fieldwork, preparing the site was simple. In the April 1998 and 1999 fieldwork, ice and snow condition made working difficult. The ice was divided into two layers, one thin 5 cm rotten layer above and a second 80 cm thick layer of hard ice. The layers were separated by 20 cm of water. With a total thickness of 1.05 m, it was difficult to make the holes for the transducer with the available tools. (Ice drill, wood saw and an axe).

For the vertical measurements, holes were drilled along the vertically aligned transducer's $A_{th}$ and $A_{lo}$ axis and along a line drawn at 45 deg. between these axes. For the measurements with horizontally aligned transducer, holes were drilled above the acoustic axis at 5, 10, 15, 20, 25 and 30 m ranges, and to the sides of the axis with 1 m separations as seen in Figure 37. Steel wires were shaped and forced down into the ice to give well-defined horizontal target positions in the too large drilled holes. A long wooden plank with an attached mm ruler enabled accurate depth measurements of the targets.
Standard Cu-spheres (23.0 mm, 120 kHz, -40.3 dB), Tu spheres (38.1 mm, 120 kHz 39.55 dB), wooden chips, and fishing sinkers of lead were used as targets. The targets were mounted with 0.20 mm monofilament fishing line. The targets were washed and placed in soapy water for a quarter of an hour before use.

The transducer was first mounted vertically. Calibration was performed with the program Lobe.exe from Simrad AS. This program reads the echo from a known standard target positioned at various off-axis positions and estimates the gain and the off-axis adjustments. We first tried to mount the target with three fishing lines from three holes through the ice. It proved to be difficult to align the target correctly in this way. Mounting the target in a line trough a hole close to the transducer and then tilting the transducer stand to fill all beam quadrants with detection was found to give better results.

The target was placed at different positions. At each position and for each target a new sonar file lasting two minutes was recorded and the target position measured with the ruler. The last 200 echoes were later selected and applied in the statistics. The procedure was repeated with the transducer mounted horizontally under the ice, tilted downwards by 3 deg.

The post processing program Sonar5, the statistical program Statgraphics PLUS 4.0, and the spreadsheet Excel were used in the analysis of the data.

![Diagram](image)

*Figure 36. Side view of the horizontal experiment. $\phi$ denotes the downward tilt of the acoustic axis, $R$ the range or the transducer/target distance, $B$ the transducer depth, and $\theta$ the angle between the transducer/target line and the ice. Alo is the angle between the transducer/target line and the acoustic axis.*
9.3.2 - 2  Testing the sonar's ability to position the target

In this experiment we wanted to test how well the sonar managed to estimate target positions and whether the ice would influence this estimate when the beam was aligned close to the ice. Kieser et al., (2000) have reported that targets were detected as being closer to the acoustic axis than they should and that a statistical model could explain this in situations with low signal to noise ratios.

The experiment showed that the sonar tended to estimate the target with higher off-axis position than measured with the ruler and that this discrepancy increased with increasing target off-axis position. This is readily seen in Figure 38 where the target has been lifted through a horizontally aligned beam at 20 m range and through a hole 2 m to the side of the acoustic axis. The track forms a clear outward arc. The observation was the same in both the horizontal and the vertical situations, and the phenomenon could therefore
not be caused by influence from the ice. A complete mapping of the beam is seen in Figure 39. Because the target is estimated with higher off-axis positions than the ruler measured positions, the experiment does not verify the observations reported by Kieser et al., (2000).

The explanation of the observation was given by Helge Bodholt at Simrad, finding that the angular sensitivity parameters AngleSensAlo and AngleSensAth in the echo sounder did not correspond to the actual stiffness in our transducer. This parameter is involved in converting the measured electrical to mechanical degrees. The parameter is set at the factory and it is not corrected by the calibration routine. Dropping the target through the horizontal beam and adjusting the sensitivity until the target falls in a straight line might do the calibration.

If the parameter does not match the transducer, calculations of the target’s passing velocities will not be correct. Overestimating the off-axis position will lead to overestimates in the beam compensation factor and thereby to overestimates in the target strength as well.

\[
TS_u = P_R + 40 \log(R) + 2R\alpha - 10 \log \left( \frac{G^2 \cdot \lambda^2}{16 \cdot \Pi^2} \right) - 10 \log(P_t)
\]

\[
TS_e = TS_u + BC(Alo, Ath)
\]

\[
BC = 2 \cdot 3 \left( Alo^2 + Ath^2 + 0.18 \cdot Alo^2 \cdot Ath^2 \right)
\]

\[
Alo = \frac{Alo_e - AloOffset}{\text{AngleSensAlo} / 2}, \quad Ath = \frac{Ath_e - AthOffset}{\text{AngleSensAth} / 2}
\]

Here, \(Pr\) is the received power, \(P_t\) the transmitted power, \(BC\) the beam compensation factor, \(TS_u\) the uncompensated target strength and \(TS_c\) the compensated target strength. Subscript \(e\) denotes electrical and not mechanical values.
9.3.2 - 3 Resonant target behavior

The Cu and Tu targets were positioned in the center of the horizontally aligned beam at 5, 10, 20, and 30 meters. It was seen that the Cu target gave the most well defined echoes at all ranges, and that the uncertainty in the position estimates was higher with the Tu target. At the 10 m range, a special phenomenon occurred. Here it seemed as if it was impossible for the sonar to position the targets and especially the Tu target. They were both detected, but never at the same position as the previous detection. Figure 40 demonstrates the target observations at 10 and 30 m. The phenomenon was only observed in 1998 and we have not been able to repeat it later.
9.3.2 - 4 Discrepancy between the measured and observed tilt

Discrepancy was observed between the transducer’s tilt and the beam in 1998 and 1999, but not in 2000. In 1998, the transducer was mounted under the ice with a 3 deg. downward tilt from the horizontal line. Targets were lowered from holes in the ice until they were observed in the centre of the sound beam by the echo sounder. From the measured depths at the different ranges, it was seen that the targets lay on a straight line, but that the tilt of this line was 6.2 deg. and not 3 deg. as expected. We explained this by inaccuracy in the transducer stand and mounting, but wanted to repeat the experiment. In 1999, a new and better stand with good tilt control was used, and the transducer was mounted with the same tilt ($\phi = 3\,\text{deg.}$) downward. Cu-spheres were placed in the centre of the side-looking beam at 5, 10, 20 and 30 m ranges. Again, a straight line could be drawn through the target depths measured with the ruler. The line indicated an even higher discrepancy between the mounted and measured transducer tilts than the year before. A total of 7.71 deg. or a discrepancy of 3.71 deg. was the result.
The experiment was redone with the same equipment in 2000, but no discrepancy was observed at that time.

Trying to explain the observations, the target was lifted up and down in the beam. The sonar estimated the direction of the movement correct, which indicated that the beam was not reflected from the surface. The straight line that could be drawn through the observations indicated that the beam had been refracted downwards at a point close to the transducer. Refraction can be calculated from the sound speed by applying Snell's law.

\[
\frac{\cos(\phi_1)}{c_1} = \frac{\cos(\phi_2)}{c_2} \Leftrightarrow r = \frac{c_1}{c_2} = \frac{\cos(\phi_1)}{\cos(\phi_2)}
\]

where \( c \) is the sound speed in \( \text{ms}^{-1} \) and \( \phi \) the angle between the beam and the a thermal layer as indicated in Figure 41. With a horizontal layer, the incident angle will be 3 deg. and the refracted angle 7.71 deg. This gives a sound speed ratio of \( c_1/c_2 = 1.00774 \). Close to the ice the temperature will be 0 deg. and increase to 4 deg. deeper down. In this temperature range, the water density and the sound speed increases. According to Snell's law, the sound speed \( c_2 \) would have to be less than in \( c_1 \) in order to refract the beam downwards. We measured the opposite. Hence we are not able to explain the observations neither as reflections from the ice, nor as refraction caused by changes in the sound profile.

In the year 2000 experiment, no refraction was observed. Accurate instruments for measuring the sound profile have not been available to us before this year (2001) and further experiments should be carried out on the ice to repeat and try to explain the observations.

![Figure 41. Refraction of the beam.](image-url)
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Sound speed</th>
<th>Temp. Celsius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1402.7</td>
<td>0.1</td>
</tr>
<tr>
<td>0.5</td>
<td>1406.7</td>
<td>0.9</td>
</tr>
<tr>
<td>1.0</td>
<td>1407.6</td>
<td>1.1</td>
</tr>
<tr>
<td>1.5</td>
<td>1407.2</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>1406.7</td>
<td>0.9</td>
</tr>
<tr>
<td>2.5</td>
<td>1406.7</td>
<td>0.9</td>
</tr>
<tr>
<td>3.0</td>
<td>1406.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Table 5. Sound and temperature profiles from Lake Semsvann 2000.*

### 9.3.2 - 5 Multiple detection of the target with downward-looking sonar

When the target was lowered through the downward-looking sonar beam, the target was detected at four positions as seen in Figure 42. The lowest echo represents the actual target while the other echoes are false ghost echoes. Because they follow the target's movement, they cannot be reflections from thermoclines. An explanation could be repeated sound reflections between the target and the ice surface. With an assumed sound speed of 1407.2 m s\(^{-1}\) and a target depth of 24.89 m, the echo would reach the transducer within 35 ms. With a ping rate of 8.22 pings per sec., the time between two transmissions is 122 ms. The echo could, therefore, bounce up and down 3 times between each transmission. However, the second and third reflection would be detected at positions below the target (49 m and 74 m) and not above. We recorded the echo-signal down to the bottom of the lake at a range of 30 m only, hence it is not possible to say whether these echoes existed or not. The fourth detection would be received after the next sound transmission (ping) and should thereby be observed at a depth of 14 m followed by the fifth reflection at 3 m. Echoes caused by higher number of reflections should be observed at 17, 6, 20 and 9 m ranges. The respective numbers of reflections necessary to produce these echoes, are 4, 7, 11, 14, 18, and 21. We observed ghost echoes at 9, 14 and 20 m ranges only. According to the number of reflections, the echo observed at the 9 m range
should be the weakest echo having bounced up and down 21 times. The echo at the 14 m range should be the strongest echo second to the primary echo. This actually agrees with the observations. The echo observed at the 9 m range has a TS of -75.1 dB, the echo observed at the 14 m range has a TS of -60.3 dB and the echo observed at the 20 m range has a TS of -57.3 dB.

However, with this explanation, the echo at the 9 m range has travelled more than 1 km. Even with the ice as a 100% reflector, the geometrical damping would be too high to allow any observations. With the target as a point source and the ice as a total reflector, the transmission loss (TL) can be modelled with $\text{TL} = 40\log(R/2) + 20\log(R/2)$. With the sound travelling a distance of 1 km, this will give a TL of 160 dB, thus it should not be possible to detect this the echo. We must also ask why we only detected the 1, 18 and 21 reflections and not the 7, 11 and 14th. Without the answers to this, we are not able to explain the observations. Other explanations like ice on the line might be searched.

Figure 42. Multiple observations of the target. (Vertical application).

9.3.2 - 6 Rotation of the beam in horizontal applications

In 1998 and 1999, we observed a significant rotation of the beam when the transducer was mounted horizontally under the ice. This was most dominant in the 1998 trial with a rotation of 14.3 deg. Minor rotation can be seen in Figure 39 from the 1999 trial. In 2000, rotation was not observed. We have no explanation for this.

9.3.2 - 7 Summary of observations from Lake Semsvann

The sonar estimated the target at too high off-axis positions and with increasing error with increasing off-axis position. This was explained by erroneous setting of the angle sensitivity parameters and could be corrected. Uncertainty was seen to increase in
position estimates with increasing off-axis position. This relates to the transducer detection technique and must be accepted. With downward-looking sonar, the target was observed at four ranges at the same time in 1999. We could not explain the phenomenon.

Downward refraction of the horizontally aligned beam was observed in 1998 and 1999, but not in 2000. According to the expected sound profile, the opposite should have been observed. Rotation of the beam was observed with side-looking sonar. This was observed in 1998 and 1999, but not in the 2000 experiment. We have no explanation. Significant ping to ping variations in the position estimates and TS variations observed at a certain ranges in 1998. The increase was more dominant with the Tu-sphere than with the Cu-sphere.

In order to verify the observations and to find explanations, the experiments will be repeated in the near future. With our increasing experience from fieldwork on ice and with new equipment, we might have a chance to improve the experiments and find some explanations.

9.3.3 Report from the fieldwork in the River Tana

The River Tana is a sub-arctic river situated in the north east part of Norway (70ºN, 28ºE.) The upper part of the river forms the border between Norway and Finland. It is the largest salmon river in Norway and Finland with a catchment area of 16.386 km² and annual catches between 100 and 200 tonnes of Atlantic salmon (Salmo Salar). About 1100 km of ascending stretches is accessible to salmon. No man made structures such as dams hinder the migration. The longest distance salmon may migrate is about 300 km, and the most important fishing methods are weirs, fixed gill nets, drift nets and rod and line.

On request from the County governor in Finnmark and the Directorate for Nature management (DN), the University of Oslo, Simrad AS and the Finnish Fisheries Research Institute (RKTL) were asked to test the hydroacoustic assessment method in the River Tana. A preliminary site study was carried out in September 1997, followed by a 6 weeks study summer 1998 and 1999. The RKTL
together with the County governor in Finnmark had already selected and mapped some possible sites.

In 1997, test recordings and site evaluation was performed and discussed. The site at Polmak 70 km from the river mouth was found to be the most promising. Here, the bottom profile fitted the sonar beam quite well with a smooth, sandy, declining bottom from the west riverbank. An island divides the river course in two. One course well suited for acoustics and the other wide and shallow. The shallow course would serve as an overflow system limiting changes in the water level in the main course. Due to the shallow sandy bottom, it was not believed that salmons would pass here. Experienced fishermen from the area confirmed this. The main course was 257 meter wide with a maximum depth of about 5 m. The current was fairly laminar and the site was far from any rapids that could introduce disturbing air bubbles into the water.

9.3.3 - 1 Material and methods

In 1998, one EY500 sonar was mounted on the west riverbank. A 120 kHz split-beam transducer with an opening angle of 4x10 degrees was mounted on a tripod in the river. The tripod had been developed at the University of Oslo for this purpose. Aiming was done by a remote controlled rotor system (Remote Ocean Systems, PT 10). A guiding net forced salmon to pass in front of the transducer at a shortest range of 8 m. Underwater cameras were applied to monitor fish behaviour and specie distribution. Lead accumulators powered the sonar. Petrol generators (Honda EX1000) provided charging and electric power to the camp that consisted of three caravans, one for equipment and two for accommodation. Trace telegrams containing the output from the echo sounder’s single echo detector were recorded on a Toshiba 460 CDT laptop computer and later stored on 100 MB zip drives. The data was later analysed by the Sonar 5 post-processing program.

A similar camp was set-up in 1999, but this time two synchronised sonar systems were applied in the assessment. One at the same position as the previous year and another placed at the riverbank of the Polmak Island aiming in the opposite direction towards the first one. A communication cable crossing the river on the bottom provided the
synchronising signal, ensuring that the two systems pinged at the same time. In this way, a high degree of river cross-section coverage could be combined with maximal ping-rate.

A new rotor system made at the University of Oslo was used to aim the west riverbank transducer while a PT 10 rotor from Simrad controlled the transducer at the east riverbank.

One of the results from the previous year was that the SED data did not provide sufficient information for fish counting. This year, both trace and echo telegrams (SED and Amp-echogram) were recorded. In order to take care of the increased amount of data, the recording laptops were "milked" once every 24 hours. Data was first transferred to 2GB JASS disks and later stored on a main computer equipped with a 20GB disk. Here, preliminary analysis was performed before the data was stored on tape and CDs for later analysis.

Accurate calibration in a river is difficult and the transducers were therefore calibrated at Simrad's test station before the equipment was shipped to Tana. A weather station of the type Hugher from Hugher Electronics was set-up to reveal correlation between the salmon run and different weather parameters like rain, temperature, pressure and light (lux). The weather station could originally not measure lux, but this was fixed by replacing the humidity sensor with a photo resistor. Humidity was not expected to be of any importance for the migration. Weather reports were written to a Toshiba T2150CDS laptop computer every 10 minutes.

Water level was measured with a water level ruler every evening. Water temperature was measured automatically by a Tiny Talk temperature logger and with a standard mercury thermometer as a backup.

9.3.3 - 2 Results

The main aim for the survey in the River Tana was to test the hydroacoustic fish detection method. The most important results are therefore not the actual fish counting results, but the experience, which provides a platform for further development of the method in the River Tana. We do not believe that accurate counts can be gained. However, it is possible to obtain a fairly accurate index for the run.
In the 1998 trial, recording went fairly well. One transducer was operated from 24 June to 20 July. The transducer was first mounted close to the west riverbank and then moved further out when the water level sank. An overall time coverage of 86% was achieved. The two first and the last days had only ~50% coverage due to testing and packing. Battery capacity was found to be too low, and periods without recording occurred the first days. Later, more batteries were added and it was possible to run the sonar with up to 99% time coverage.

With high water current, fish passed fairly normally to the transducer beam. With low water current later in the period, fish were not always passing straight through the beam, but could stay in the beam for a while or pass with increasing or decreasing range. This behaviour was also observed in 1999.

The size of the 1998 experiment, the amount of data to be handled, and the amount of work were practicable for two persons. However, the analysis of the sonar and video data was difficult and time consuming. Long periods with wind from the north, up the Tana valley, created waves on the river surface and increased the noise level in the recorded data. It was difficult to find good parameters for the single echo detector and manual interpretation of the recorded SED-echograms was time consuming and difficult. Automatic tracking methods did not work.

In the 1999 trial, it was decided to mount the west riverbank transducer at the same position as the outer position used in 1998 to avoid repositioning during the trial. Longer nets and iron poles were mounted in the river to guide the fish. We managed to position the equipment, but shortly after, a period with rain increased the water level. The transducer stand and the net disappeared under water. An error in the transducer, reducing its sensitivity, combined with an unsuitable position, resulted in no detection of fish in this period. It was, however, impossible to reposition the system until the water level had decreased sufficiently. It was possible to start working with the equipment in the river again from the first of July. The transducer was replaced and the stand was moved closer to the riverside and re-aimed (Position W2 in Figure 46). From now on, the system started to detect fish.

At the riverbank on the Polmak Island, it was difficult to find a good position for the sonar. Rocks and unsuitable bottom profile made it impossible to align the beam close to the bottom, and fish could easily pass under. It was also difficult to build the guiding nets because of the rocky bottom and the strong current. The first selected position at E1
(Figure 46) did not detect well. A new position closer to the shore was found by mapping the bottom profile. This position detected fish better, but the data series was already split and we decided to experiment with two other positions, E3 and E4, to learn more about the east side.

The 1999 trial was hard work. Three times more equipment and the huge amount of data involved in recording both the SED and Amp-echogram from both sides of the river was nearly not possible to overcome for two persons. Transferring data, charging batteries, running three fuel generators, cleaning guiding nets, testing transducer positions and performing beam mappings was hard work. Much equipment broke down and had to be replaced or repaired.

High ping to ping intensity variations in echoes from fish was observed. Echoes with target strength (TS) as high as +5 dB were detected. Interference, fish side aspect variations, avoidance of spherical spreading and the "Tana phenomenon" were recognised as reasons for this. From beam mapping with standard Cu-spheres, the 40log(R) compensated echo intensity increased with range. Applying a 30log(R) model gave better prediction of the target size than the expected 40log(R) model in ranges between 6 and 50 m. This might indicate that the sound propagated by a cylindrical spreading model in the shallow water.

The Tana phenomenon influences the transducer's beam pattern. Instead of the expected 4 deg. vertical opening-angle, the sound field is observed to fill the total water cross section from surface to bottom independent of range. At the same time, the vertical angular estimate becomes unreliable and not suited for beam pattern compensation of the TS estimates. The phenomenon seems to occur with low water level in combination with a smooth and hard bottom. It was only observed at the west riverside. Paper VII describes this.
9.3.3 - 2.1 Data analysis and fish monitoring results

In 1998, only the output from the single echo detector (SED) was recorded. This is the data commonly stored in monitoring projects, and we did not have storage capacity to record the larger Amp-echograms from the sonar's amplitude detector. However, we soon found that analysing split-beam data based on the single echo detections was difficult. Echoes from fish had often been rejected and noise made detection of fish difficult. Hence, automatic tracking did not work, and all files had to be analysed manually. This was extremely time-consuming and the results must be regarded with caution. The noise and the missing echoes from fish made it difficult to obtain tracks, and tracks may easily have been overlooked. Other tracks looking like fish could have originated from noise.

A total of 980 upstream migrating targets believed to originate from fish were detected in data from the period 24.06 to 20.07.1998. These are targets observed with target strength larger than -30 dB. Applying time expansion, this represents 1100 fish or a fish passage rate of 41 fish per day.

Based on the experience with the analysis from 1998, it was decided that both the SED and the Amp-echogram should be recorded in 1999. This made the analysis far more reliable. The data had again to be analysed manually, but it was much easier to detect and determine the origin of the echoes with both echograms available.

The most reliable data series this year was for the period from 01.07 to 18.07 with the transducer placed in the W2 position. Here, a total of 2906 fish were detected. Applying time expansion and dividing by number of days, a fish passage ratio of 2906*(100/87)/27=124 fish per day was obtained.

Figure 43. Count from position W2 in 1999. The data has been time expanded according to the daily percentages of coverage.
A common interpretation method is to apply area expansion. This is difficult with the observed Tana phenomenon. If we assume that the phenomenon existed all through the period, range expansion would be a better interpretation method. In 1999, the total free river path, not closed by nets, was 74 m, which results in a range expansion factor of 74/12.

Most of the targets where detected at a range between 18 and 30 m in the beam (Figure 44). We have reasons to believe that this reflects the system’s detection probability and not the migration pattern. At a range longer than 30 m, noise from the bottom and surface started to disturb the signals. At closer range, the beam is thin with low water cross-section coverage. If we limit the count to these 12 m and apply time and area expansion, we obtain an estimate for the total run.

![Building the camp 1998](image)

**Figure 44. Range distribution of passing fish obtained with the transducer in the W2 position in the period from 07.01 to 07.19.**

2032 fish were detected in the W2 data from the 12 m effective beam. Applying time and range expansion, results in a total fish count of 2032*(74/12)*(100/86.5)= 14486 fish or 805 fish per day passing the site. We have not had access to any catch data for this period and can therefore not evaluate whether this result is likely or not.

### 9.3.3 - 2.2 Influence of from fishing

One aim of the monitoring project was to check the effect of the gillnet fishing on the migration. The fishing might take out so many salmons that the run is reduced. It is also possible that the fishing activity might trigger the salmon to move or to stop and wait. Fixed gillnet fishing are allowed from Monday morning at 06:00 to Thursday evening at
18:00. Comparing the number of fish detected by the sonar in periods with and without fishing resulted in a significant reduction in 1998. In 1999 the opposite was observed. This year actually indicated an increase in the fish passage ratio of 1.7 relative to periods without fishing.

Due to the uncertainty in the data analysis from 1998 and to the relatively short monitoring period in 1999, we do not want to draw any conclusions from these observations. However, we believe conclusive results can be achieved in future assessments.

9.3.3 - 2.3 Underwater video results

Video was used to detect the species composition and to monitor the behaviour of fish when passing the guiding nets. Video was recorded with a time compression of 1:4. The camera was mounted on a small tripod and placed on the river bottom looking slightly upwards and upstream. Passing fish was seen partly from the side with parts of the bottom in the foreground and with the surface as background. The camera gave wide angled black and white pictures. Analysis was time consuming and it was difficult to determine fish size and to distinguish between salmon and trout. The results cannot be regarded as accurate.

The results showed that at least 95% of the fish passing in the area in front of the transducer were Atlantic salmon (*Salmo salar*). Other species observed were flounder (*Limanda limanda*), grayling (*Thymallus thymallus*), pike (*Esox lucius*) and trout (*Salmo trutta*). It was seen that the migrating fish were guided by the nets and that they did not turn into the river side and behind the transducers.

9.3.3 - 3 Suggestions for future assessment in the River Tana

The hydroacoustic fish detection method can be applied to future salmon assessment in the River Tana. In order to achieve good results, three main areas have to be improved. a) The method is too labour intensive and complicated. Simplification is necessary. Exact recording procedures must be described, and analysis software must be
simplified and further automated. b) Temporal and spatial changes in fish detection probability caused by changes in weather and water conditions were observed. It is important to test methods to reduce the variation in the detection probability function. c) Estimating a reliable size distribution was difficult and ways to improve the accuracy should be tested.

9.3.3 - 3.1 Simplifying the work

Recording and analysing data was complicated and labour intensive. Improvements are needed for future assessment. The most time consuming part was the data analysis. New automatic methods have been developed, but it remains to test these methods at a large scale on the data from the River Tana. Software for interpreting the analysis results can reduce the work and should be developed.

The daily work during the recording period can be reduced by improving the power situation and by applying larger sonar data storage devices. The fuel generators charging the sonar batteries should be replaced by power sources with less need for maintenance. Larger data storage devices would reduce the need for daily halt and transfer to other storage media. Improving the power situation and the data storage capacity will also improve the daily recording time coverage.

Applying remote controlled methods can make it possible for experts to check the recordings without having to stay on the site. It would then be possible to run the recording for a local person checking the site every now and then.

9.3.3 - 3.2 Reducing variations in the detection probability

Methods for reducing the variations in detection probability should be investigated further. Limiting the fish passage to the most effective part of the sonar beam can be one way to do this. The fish passage area can be restricted with guiding devices like ropes and nets. From an experiment with a rope on the river bottom, video recordings indicated that fish could be "lifted" from the bottom and into the beam.

Guiding nets mounted with iron bars normal to the water current proved to be difficult to set-up and to maintain. Jon Viktor Aslaksen from the River Tana Salmon Fishing Rights Owner Association suggested that two towers with nets hanging downstream and gradually taken into the shore could be more suitable. It might also be that ropes could replace the nets in order to reduce the drag from the water current.
The detection probability depends on the noise level observed in the recorded echogram. Software methods should be developed to detect these variations and to take them into account in the interpretation of the counting result as indicated in chapter 7.3.2.

9.3.3 - 3.3 Improving the detection of fish size distribution

The data obtained from the transducer in the W2 position could not be applied in estimates of the size distributions because of the described Tana phenomenon and probably other interference phenomena. Occurrence of "unbelievable" intense fish echoes indicated this. Data from the transducer mounted on the Polmak Island gave a size distribution that was more realistic.

Different methods can be applied to improve the accuracy of the size distribution. From experiments in the Rimov pond (Cz) summer 2000, the transducer's opening angle was seen to influence the observed Tana phenomenon. A transducer with a 2 deg. opening angle should be tested in the River Tana. Using a narrow beamed transducer and adjusting the tilt in steps each hour might avoid the Tana phenomenon, give good area coverage and reduce the noise level in the recorded material.

Applying a separate sonar optimised for detecting the size distribution, is another possibility. A wide angled transducer aimed vertically up from the river bottom, or a narrow angled transducer placed sideways at a site not influenced by bottom and surface reflections, could be a good solution.

Mounting reference targets in the river should be tested. These targets would indicate interference phenomena and avoidance of spherical spreading. Echoes from passing fish could be adjusted according the known targets.

It might prove possible to detect and reject fish-echoes influenced by interference. Studies of single echo features and echo selection algorithms are then needed.
Figure 45. TS distribution from the Polmak east position E1 to E4 in 1999.

Figure 46. Site map marking the installations in the River Tana at the Polmak island summer 1999. W=West E=East. Transducer positions marked with numbers. WL = position for water level ruler. N1 and N2 mark the outer poles for the guiding nets. A and B are landmarks. Distance AB=157 m. (See also Table 6)
<table>
<thead>
<tr>
<th>Position</th>
<th>Equipment</th>
<th>Angle rel. ref. line AC</th>
<th>Dist in m</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>River width</td>
<td>0</td>
<td>157.4</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>Reference line</td>
<td>0</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>W1</td>
<td>Transducer stand</td>
<td>13.26' 20&quot;</td>
<td>40.0</td>
<td>23.06 - 01.07</td>
</tr>
<tr>
<td>W2</td>
<td>Transducer stand</td>
<td>00. 35' 40&quot;</td>
<td>30.0</td>
<td>01.07 - 18.07</td>
</tr>
<tr>
<td>W3</td>
<td>Transducer test pos</td>
<td>---</td>
<td>---</td>
<td>--</td>
</tr>
<tr>
<td>E1</td>
<td>Transducer stand</td>
<td>02. 35' 40&quot;</td>
<td>134.5</td>
<td>22.06 - 03.07</td>
</tr>
<tr>
<td>E2</td>
<td>Transducer stand</td>
<td>00. 38' 30&quot;</td>
<td>139.5</td>
<td>03.07 - 0807</td>
</tr>
<tr>
<td>E3</td>
<td>Transducer stand</td>
<td>13. 22' 40&quot;</td>
<td>141.1</td>
<td>08.07 - 1307</td>
</tr>
<tr>
<td>E4</td>
<td>Transducer stand</td>
<td>14. 00' 00&quot;</td>
<td>133.0</td>
<td>13.07 - 19.07</td>
</tr>
<tr>
<td>N1</td>
<td>Outer net pole</td>
<td>12 25' 20&quot;</td>
<td>54.4</td>
<td>23.06-19.07</td>
</tr>
<tr>
<td>N2</td>
<td>Outer net pole</td>
<td>05. 20' 00&quot;</td>
<td>126.7</td>
<td>23.06-19.07</td>
</tr>
</tbody>
</table>

Table 6. Description of equipment placement in the river. Positions are measured relative to point A and the reference line. B = river side. C = cabin housing the east sonar.
10 References


11 Paper I

Implementing and testing multiple-target trackers on split-beam sonar data recorded in lakes

Abstract

Target tracking is an important feature in a hydroacoustic monitoring system. State of the art multiple-target trackers can consist of four elements: track support, prediction, gating, and association. Different multiple-target trackers based on variations in these elements have been implemented in software and tested with simulated data and with data from lakes. The tracker's impulse response has been measured and special effects related to features of the sonar beam have been investigated in order to develop optimal tracking parameters. Tuning the tracking parameters has been recognised as difficult and a self-adjusting method has been designed and tested.

Keywords

Hydroacoustic, multiple-target tracking, split-beam, sonar, prediction, fish counting, programming, tracking algorithm.
Implementing and testing multiple-target trackers on split-beam sonar data recorded in lakes.

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Introduction

Tracking is an essential part of any hydroacoustic fish counting system. Fish passing the echo sounder can produce a number of echoes. Counting is only possible if we are able to track the echoes from each fish. Tracking is also recognised as important in reducing the variance of the target strength estimates and it can provide information about target direction and speed (Ehrenberg and Torkelson, 1996).

Tracking multiple-targets is a well-known problem in many different professions. In nuclear physics, tracking elementary particles from particle collision is important. A simple detector for displaying elementary particle trajectories is the bubble chamber. Radar-based satellite surveillance systems and air traffic control systems are other examples where tracking is essential. Extensive literature exists in both areas (Blackman, 1986).

During World War II, manual tracking of targets detected by radar was common. Detected targets were displayed as "blips" on the plane position indicator screen. These were connected by operators to track the targets. Wax, (1955) saw similarities between bubble chamber and radar tracks. Both have birth, life and death or initial track formation, track maintenance, and track deletion in common. He presented mathematical models for these processes. Other major contributions to the multiple-target tracking (MTT) problem were made by Sittler, (1964), who addressed the data association problem, and Kalman, (1960) who addressed the filter and prediction problem. Further developments in MTT are seen in the papers by Jaffer and Bar-Shalom, (1972), Singer and Stein, (1971), Singer et
that combine correlation and Kalman filter theory. The book by Blackman (1986) summarises the MTT development.

**Multiple-target tracking theory**

In an environment characterised by low signal to noise ratio and high track density, tracking is not a trivial task. Echoes from a fish might be difficult to detect when unwanted non-fish-echoes surround it. Parts of a fish track might be indistinguishable from the background noise and echoes from a group of fish might look like one single track.

Tracking can be divided into four fundamental elements: track supporter, data association, prediction, and gating (Figure 47). These elements are well described by Blackman (1986) and our brief description focus on sonar data.

**Track support**

The task of the track supporter is to give birth to, maintain, and to evaluate and kill tracks. When a new echo is observed in the sonar beam, this echo might be the first observation of a target or it might simply be noise. The track supporter cannot know this and the echo gives birth to a new track. The track supporter might support many tracks at the same time. If no observation has been associated with a supported track for a period of time, the track is evaluated and removed from the supporting system. In a sonar system, the number of missing echoes known as the ping-gap (PG), is a convenient estimator for deciding when to remove a track.

It is common that the tracker evaluate the quality of the resulting tracks. This is frequenly done by testing the track-length (TL) measured as the number of detections in a track. Other parameters like track smoothness and velocity can also be defined and applied. Tracks with qualities below a certain level are regarded as noise while the remaining tracks are accepted.

Optimal estimation of the two track supporter parameters PG and TL is important. High values in the PG parameter will reduce the tracker's ability to differentiate between adjacent tracks in situations with high track density. Low values in the TL parameter may result in a high number of noise-based tracks or a tendency to split longer tracks.

Due to the geometry of the sonar beam and to the attenuation of the sound intensity with increasing range, range dependence might be assumed with the TL and PG. It is
therefore important to find range invariant estimators or alternatively to estimate the parameters as optimally fitted functions of range.

**Prediction**

The predictor estimates the next echo position for each track that is maintained by the track supporter. A target moving through the sonar-beam can be described by its cinematic description or by its state vector. The state vector describes the target's position, velocity and acceleration. In a deterministic system, the predicted state at time \( k+1 \) is easily found from the previous state by multiplying the state at time \( k \) by the state transition matrix. These is demonstrated in the following expression

\[
\begin{bmatrix}
x \\
v \\
a_{k+1}
\end{bmatrix} = \begin{bmatrix}
1 & t & 0.5t^2 \\
0 & 1 & t \\
0 & 0 & 1
\end{bmatrix} \cdot \begin{bmatrix}
x \\
v \\
a_k
\end{bmatrix}
\] (1)

where \( t \) is the system's sample time, \( k \) the time index, and \( x, v, a \) the position, velocity and acceleration respectively.

However, in a system with live fish and a significant noise contribution, statistical methods might be better suited. Linear regression, weighted mean and Alpha-Beta prediction are examples of statistical predictors. These methods estimate the next position by applying not only the information from the last observation, but also taking into account earlier observations. The more advanced Kalman filter does the same, but it also takes into account a noise model (Kalman, 1960).

**Prediction with Kalman filter**

The Kalman filter can be applied in order to predict the next position of a target. The filter takes into account the transition matrix and the noise model in estimating state \( k+1 \) from the states at time \( k \). Brown and Hwang, (1983) describe the theoretical background for this prediction method. Examples and formulas for discrete Kalman filters are given. The filter elements are seen in Figure 48. Here \( x \) is the state vector containing the position, velocity and acceleration of the targets. Due to the noise in the measuring system, it is not possible to detect the actual target position, but only the position plus the noise. However, the application of a noise model allows an optimal prediction of the next
position. From the observation $z(k)$ and the Kalman gain factor $K$, the Kalman filter estimates the target state $\hat{x}_k$.

$$\hat{x}_k = \hat{x}_{k-} + K_k (z_k - H_k \hat{x}_{k-})$$

$$P_k = (I - K_k H_k) P_{k-}$$ (2)

In the above equation, $k$ is the sample index and $H$ is the measuring matrix. The super minus notation denotes the best estimate prior to assimilating the measurement at time $k$. $P$ denotes the error covariance matrix. This estimate is applied in the prediction of the next state observation

$$\hat{x}_{k+1} = \Phi_k \hat{x}_k$$

$$P_{k+1} = \Phi_k P_{k-} \Phi_k^T + Q_k$$ (3)

where $\Phi$ denotes the state transition matrix and $Q$ a white noise covariance matrix. From these estimates the Kalman filter gain is calculated

$$K_k = P_{k-} H_k^T (H_k P_{k-} H_k^T + R_k)^{-1}$$ (4)

where $R$ is the covariance matrix of the measuring noise.

**Alpha-Beta predictor**

The Alpha-Beta predictor is commonly applied in situations where only position estimates are available (Blackman, 1986). The predictor estimates the smoothed position $x_s$ from the measured observation $z(k)$ and the predicted position $x_p$ by the application of a constant Alpha and Beta filter gain. Smoothed velocity estimates are calculated from the position measurements and the predicted position. The elements of the Alpha-Beta predictor are seen in Figure 49. The following equation demonstrates the predictor's estimate and prediction functions.

$$x_s(k) = x_p(k) + \alpha [z(k) - x_p(k)]$$

$$v_s(k) = v_s(k - 1) + \frac{B}{qT} [z(k) - x_p(k)]$$

$$x_p(k + 1) = x_s(k) + T v_s(k)$$ (5)
Here, $x_S$ and $v_S$ are the smoothed estimates of the observed target cinematic and $x_P$ the predicted position.

**Linear regression and weighted mean**

Different approaches in predicting the target's next position are the linear regression and weighted-mean methods. The linear regression method estimates the next position by finding the parameters $v$ and $x_0$ of the line $\hat{x}_{k+1} = v \cdot \Delta t_k + x_0$ that best describes the positions of the known observations. Minimising the squared errors between the line and the observations yields the parameters $v$ and $x_0$. $\Delta t_k$ is the time between adjacent samples. The slope of the line $v$ can be regarded as the mean velocity of the applied observations while $x_0$ can be interpreted as the position of the observation at time $t_k=0$.

Prediction based on weighted-mean is a similar approach. Here the velocity $v$ is estimated from the known observations by applying increasing weight to the later observed velocities as seen in the equation below.

$$v = \frac{\sum_{k=0}^{M-2} k(x_{k+1} - x_k)}{(M-1) \sum_{k=0}^{M-2} k}$$

(6)

In this equation, $M$ is the latest observations in a track under formation and $x$ is the echo position at time $k$. Next position is then estimated from the last known echo position by the following equation.

$$\hat{x}_{k+1} = v \cdot \Delta t_k + x_k$$

(7)

**Gating**

The third block in the tracking system is the gating. Due to the uncertainty in the prediction, it is not guaranteed that the next observation will be found exactly at the predicted position. Defining a searching area around the predicted position is therefore important. In a multi-dimensional environment, the gate takes on multiple dimensions. With split-beam sonar data, 1 to 5 dimensions can be applied. These are the spatial
dimensions, range, along-ship\(^2\) (Alo) and athwart-ship (Ath), but also the echo intensity and the time can serve as gating axis. In a post-processing system or in a semi-real time system, time represented as a number of pings can be applied in the gating and treated as a dimension. Figure 51 demonstrates gating in the time/range domain.

The size of the gate is important. If the size becomes too small, observations belonging to a track might fall outside the gate and be lost. If the gate is too wide, the probability of mixing observations from different tracks increases. The size of the gate is determined by the uncertainty in the observations. With sonar data, different uncertainties are seen in the different dimensions. Range is the most accurate estimator while the angular estimates tend to take on higher variations due to the split-beam technique. If one or more observations are missing, the uncertainty in the predicted next positions increases.

**Data association**

The task of the fourth element in the multiple-target tracker (MTT) system is to solve the data association problem. In situations where only one single echo is seen within a defined gate, association is simple.

When two or more echoes are found within the gate (Figure 50), the tracker has to decide which echo has the highest probability of originating from the object being tracked. The other echoes might be from noise or from other targets. A frequently applied selection criteria is the nearest neighbour method (Blackman, 1986). The spatial distances between the predicted position and all observations that have been accepted by the gate are calculated, and the closest observation is selected.

However, the closest neighbour in space might not always be the best choice. If a track from a large fish is surrounded by low intensity noise, selecting the echo with intensity closest to the track's intensity might be a better procedure. This even if it is found that one of the low intensity echoes is positioned closer in space. Applying the target strength as a parameter in the distance estimate can be done. Equation (8) demonstrates weighted Euclidean distance taking into account the spatial dimensions as well as the target strength and the time between the observations.

\[^2\] Along-ship and athwart-ship are the names on the angular axes applied by Simrad AS.
In equation (8), \( w \) is a weighting factor, \( r \) is the range, \( \text{Alo} \) and \( \text{Ath} \) the angular positions, \( t \) the time and \( \text{TS} \) the target strength. Subscript \( p \), \( o \) indicates respectively predicted and observed values.

Applying track duration as part of the distance measure enables the tracker to skip all observations in the first predicted gate if the next gate contains a better-fitted observation (Figure 51). The track duration gate only applies to post-processing or to system where processing is delayed at least as many pings as used by the time gate.

The weights are needed for two reasons. (a) The axes have different units, and (b) the uncertainty varies between the different axes. It is not reasonable to put the same weight on an estimator with high uncertainty as on one with high accuracy. With different axis unit’s, normalisation is needed. Calculating the weights under these circumstances is not a trivial task.

It is also important to note that the uncertainty in this situation is not simply the standard deviation that can be calculated from the position estimates. This is because a target’s cinematic movement is described by velocity and acceleration as well as by its position. Position, velocity and acceleration can all take on stochastic variations.

One way to obtain a normalised estimate for the uncertainty in the cinematic movement along each of the axes, is by looking at the errors between the smoothed predicted tracks and the observed tracks. The smoothed trajectories provide the best available estimate of the trajectories without noise, while the actual observed trajectories can be regarded as the sum of the measuring noise and the actual trajectories of the targets. The difference will be the noise. The weights can then be calculated from the standard deviation of the prediction errors. This standard deviation will also serve as a normalised axis measurement. Equation (9) demonstrates this calculation.
\[
\overline{err} = \frac{1}{N} \sum_{i=0}^{N-1} (o_i - p_i)
\]

\[w = \frac{1}{\sqrt{\frac{N-1}{N-1} \sum_{i=0}^{N-1} [(o_i - p_i) - \overline{err}]^2}}\]  

(9)

Here, one weight \( w \) will be calculated for each available dimension. \( N \) is the total number of predictable observation, \( o_i \) and \( p_i \) are the \( i^{th} \) observation and prediction respectively.

Overlapping gates are another difficulty that the associating system should be able to solve. This situation can occur when trajectories from tracks are crossing or when multiple tracks follow each other closely. Figure 52 demonstrates four different outcomes with crossing tracks. If only one echo is available at the point of crossing, the tracker can assign the echo to the closest track or it can copy the echo and assign it to both tracks. This decision can lead to different tracking results.

**Material and methods**

Sonar data from lakes was studied by the application of the *Sonar5* post-processing program, Microsoft's Excel, and the statistical analysis program Statgraphics PLUS 4.0 from Statistical Graphics Corp. Based on the results from this study, a tracker was implemented in *Sonar5* and tested. *Sonar5* has been developed at the University of Oslo in order to study sonar data. It has been written with Borland's Delphi ([Miller et al., 1997](#)). Delphi is a graphical programming concept based on the computer language Pascal. It runs under Window 95 and 98. The program has tools for visualising sonar data, manually tracking, track storing, track editing and classification.

*In situ* and simulated sonar data were used for testing the tracker. Vertically recorded split-beam sonar data from three different lakes were studied. Data from Lake d’Annecy (France) recorded by Nathalie Gaudreau, Lake Stechlin (Czech Republic) recorded by Jan Kubecka, and from Lake Mjø sa (Norway) recorded by Simrad AS. All data sets were recorded with a Simrad EY500 split-beam echo sounder ([Anon., 1996](#)) equipped with a 120 kHz split-beam transducer. Transmit power was 63 W.

---

3 *Sonar5* can be downloaded from the author's internet homepage.
Sonar data from lakes

Sonar data from Lake d’Annecy (France) was recorded with a 15x15 deg. transducer pinging with a ping interval of 0.2 s and a transmitted pulse-length of 0.3 ms. The data was detected with EY500's internal single echo detector with Min. Value = −60 dB, Min. Echo Length = 0.8, Max. Echo Length = 1.2 and Max. Beam Comp. = 3 dB. The parameters are described in Anon, (1996). The files show three layers of fish. From 0 to 15 meters, the fish were almost only perch (*Perca fluviatilis*). Deeper, some Whitefish (*Coregonus sp.*) and near the bottom, Arctic charr (*Salvelinus alpinus*). Bottom is seen between 30 and 45 m. These files were recorded with the transducer mounted at the side of a boat moving with a speed of about 10 km/h.

The Lake Stechlin file was recorded with a 6x13 deg. transducer transmitting with a 0.1 ms pulse-length. The single echo detector was adjusted as above except for the Max. Beam Comp. which was 6 dB.

The Lake Mjøsa file was recorded with a 4x10 deg. transducer transmitting a 0.3 ms pulse. The Single echo detector was adjusted as in the first file except with Min. Value = −55 dB. Part of the echograms from the three lakes can be seen in Figure 53.

Simulated data

Various types of tracks were simulated and used for testing. Static tracks with one misplaced echo were generated in order to measure the tracker's impulse response. Staircase shaped and single sawtooth shaped tracks were generated in order to test the tracker's ability to track fish in high track density environments, while crossing tracks were generated in order to test the tracker's association ability. Normally distributed position noise was added to the individual echo positions. The noise was generated from Gaussian normal function and the Borland Delphi compiler's built-in random number generator. A random number generator was used to introduce ping-gaps (PG) into the echo traces. The random numbers were used to define a detection probability that then was thresholded. Each track contained 50 echoes. In order to simplify the testing and the evaluation of the results, the intensity was kept constant and the angular estimates (Alo and Ath) were set to zero. This gives a simulation in two dimension, time/range.

The staircase-shaped tracks were generated by adding a constant, \( b = 30 \text{ cm} \), to the range for all echoes in the last half of each track. The sawtooth tracks were generated with velocities in the range domain equal to \(-0.04 \text{ ms}^{-1}\) in the first part of the track and with
+0.04 ms\(^{-1}\) for the last part of the track. The single momentary acceleration was introduced between echoes number 30 and 31.

Examples of crossing tracks are seen in Figure 54. Pairs of tracks with velocity = 0.13 ms\(^{-1}\) and -0.13 ms\(^{-1}\) were generated so that the tracks crossed at echo number 16. Between echo number 30 and 31, acceleration was introduced so that both tracks came out with zero velocity for the last 10 echoes. This was done in order to avoid that the most rigid predictor system would give the best performance. E.g., linear regression based on long series of echoes would favour tracks forming straight lines. The crossing tracks were generated with one echo intensity in the up-going track and another intensity in the down moving track. This enabled Sonar5 to study each set of tracks separately by the application of thresholds.

**Implementing the tracker in software**

Data from the lakes was studied and a total of 575 passing objects were tracked manually. The range distribution of the track-length (TL) and ping-gaps (PG) from these tracks were studied (Figure 55). TL was measured in three different ways: i) In number of echoes (TLE), ii) by total elapsed time within the beam, measured as the total number of pings between the first and the last detected echo (TL\(_P\)) and iii) in total travelled angular distance (TL\(_A\)). PG was measured as number of missing observations. By the application of linear regression, a weak, but significant relationship between range and TLE, TL\(_P\) and PG was found on a 95% confidence interval. However, from Figure 55 it can be seen that any linear function between TL and range will result in large errors. The same was observed for the PG distribution. As expected, no significant relationship between the TL\(_A\) and range was found on a 60% confidence level. Applying a constant TL\(_A\) value for all ranges gave relatively low estimation errors.

In order to obtain optimal parameter values for TL and PG, stepwise constant functions were seen as the best solution. This function divides the sonar's range into a number of layers and applies individual levels for each layer. In this way any function can be approximated.

The MTT's track supporter was implemented based on this stepwise TL and PG function. Runtime dynamically allocated lists were used to store, maintain, and test multiple tracks. The application of dynamic lists ensured "no limitation" in the number of
tracks that can be maintained at any time. (Due to Window's memory swapping, the free hard disc space will be an upper limitation).

Four predictor algorithms were implemented. These were linear regression, weighted mean, Alpha-Beta, and the zero velocity. Kalman filter prediction was not implemented due to its complexity and computation demands.

Gating was implemented as a four-dimensional window based on the dimensions time, range, Alo and Ath. The window was made to expand in the spatial domain in situations with missing echoes. A set of expanding factors multiplied by the number of missing echoes did this.

Association was implemented as a recursive algorithm testing all maintained tracks against all candidates found within the gates of each track. The weighted nearest neighbour method was implemented as association criteria. Weights were calculated from the five available dimensions as demonstrated in equations (8) and (9). A dialog for entering tracking parameters was implemented. Elements from this dialog are seen in Figure 56.

**Automatic parameter detector**

The tracker was tested on the collected sonar data. It was found that it was difficult to set the tracking parameters correctly. Tracking parameters that worked well in one region of the echogram did not work in other regions. Another challenge was to determine which of the implemented predictor methods and track-length estimators would give the best performance.

A graphic performance window was implemented. It displays the observed and estimated echo positions and the associated gate (Figure 57). Methods for providing information on unacceptable tracks and for warning the operator were also implemented.

This window is helpful in visualising the tracking performance and in setting the tracking parameters. However, it did not give any indications whether one method was better than the another. It was also found time consuming to adjust the parameters in this way.

An automatic parameter selection method was therefore designed. It works by analysing a set of manually detected fish tracks (training set). The optimal predictor method is assumed to be the one that results in the lowest maximum error between the predicted and the observed positions. Maximum error is regarded as a more appropriate measure than the sum or mean error, as it is the maximum error that causes a track to break
out of the gating bounds. Breaking the gating results in split tracks. A procedure for calculating prediction errors for all possible parameter settings for each of the four methods was implemented. Prediction error in the range domain was given the highest priority due to higher accuracy than in the angular domain. Only when two methods result in the same error, are prediction errors in the angular domain considered. (error.Alo^2 + error.Ath^2).

The values for the stepwise constant max. PG function and the three min. TL functions are determined by testing PG and TL in the training set. This is done for each of the user-defined range layers. The optimal min. TL function is selected by calculating the sum of squared errors between each function and the observations in the training set. Lowest sum indicates the best TL function. With the optimal parameter setting for each predictor method, the errors are recalculated in order to determine the minimum gate size and the increasing gate function for each predictor method. The gate size is determined from the maximum prediction error found in situations with no missing pings. The increase gate function parameters are determined by the difference between the total error and the error determined from no missing ping situations. The association parameters were calculated following equations (8) and (9).

Results

In a hydroacoustic environment characterised by high signal to noise ratio, few echoes other than fish-echoes are observed. The tracker's ability to correctly connect echoes from each fish will depend on the fish density, the tracker's gate size, the min. track-length (TL) and the max. ping-gap (PG) functions. There will always be a fish density limit when the system will start combining echoes from different fish.

Testing the three track-length estimators.

The sample range was divided into layers of 10 m and alternatively into one layer of 100 m. Fish from the three lakes were tracked manually and the tracks were analysed by the automatic tracking parameter estimation function. In the Lake d'Annecy file, TLA gave the best performance both with a single 100 m layer and with the sample range divided into 10 m layers. With the Lake Stechlin and Lake Mjøsa files, TL_E was seen to give the best results for all layers. The tracks from these lakes are shorter with higher variability in the
angular estimates than the Lake d’Annecy tracks. Higher boat rolling and speed probably caused this. Table 7 presents the test results.

**Testing prediction and association**

Prediction and association are closely related elements and cannot be tested separately. The tracker should be able to separate tracks in high track density environments, to separate crossing tracks and to correctly combine echoes in situations with missing observations.

**Predictor impulse response**

Simulated tracks with all except one echo at the same range were used to test the predictor's impulse response. The response from the tracker with the weighted mean (WM), Linear regression (LR), and the Alpha-Beta (AB) predictor is showed in Figure 58. Optimal prediction of impulse (and staircase) tracks was found with the zero velocity (ZV) predictor.

The alpha factor in the AB predictor was seen to behave as a filter attenuation parameter while the beta parameter was seen to control the predictor's resonance frequency (Figure 58). With alpha = 0, the predicted positions started to oscillate with a constant amplitude and a frequency depending on the beta parameter. A higher beta value resulted in higher resonance frequency. Increasing the alpha lead to attenuation, but also to an increase in the amplitude of the first oscillation period. The smallest prediction error with the AB tracker was found with alpha = beta = 0. However, this setting just remembers the first echo position in the track and cannot be applied in prediction. The situation with alpha=1 and beta=0 turns the AB predictor into a zero velocity predictor applying the previous echo position as the next prediction.

With the LR predictor, the impulse response takes on a sawtooth shape. The maximum error reduces as an increasing number of echoes is available for in the prediction. However, increased parameter value resulted in increased relaxation time. Parameter = 4 resulted in minimum prediction error. Figure 58 demonstrates the LR predictor with parameter = 10. It is seen that the prediction error is lowest when the impulse is in the middle of the echoes applied in the regression and then increases towards the end.
With WM prediction, the error was reduced with increasing parameter value. Due to the weighting, the error never became smaller than the distance between the displaced echo and the rest of the track. Another characteristic of this method was short relaxation time.

**Optimal predictor for vertically recorded and simulated non-interfering tracks**

The four predictors were tested on the vertically recorded data from the three lakes and on the simulated sawtooth and staircase tracks. None of these tracks were seen to interfere with each other. Interfere in this context means coming so close in time and range that echoes from one track could be located within the gates surrounding echoes from another track.

Manually tracked fish and simulated tracks were analysed by the application of the automatic parameter detection function. Predictor errors for each file and for each of the fish tracks were noted. Table 7 gives an overview of the applied fish tracks and the optimal predictor with parameter setting. Table 8 presents the corresponding predictor errors. Table 9 presents the relative frequency of the optimal predictor for each track while Table 10 gives the results from the simulated tracks organised by increasing noise level.

For the individual tracks from the Lake d’Annecy files, ZV was the most frequently selected predictor while the AB tracker was the most frequently selected tracker in the Lake Stechlin and Lake Mjøsa files (Table 9). However, looking at the errors in Table 8 it is seen that the errors for the AB and the ZV methods are equal for the files where ZV has been selected as the optimal method. The reason for this is that the AB tracker in these situations takes on parameter settings that turn it into a ZV tracker. When examining the results from the simulated tracks, the AB tracker is found to be the optimal tracker when the noise increases.

The fact that all methods are selected with similar frequency, that impulse and staircase tracks without noise are best predicted with the ZV method, and that the AB tracker provides the optimal solution with normal distributed noise, indicates that it is merely a question of chance what method turns out to be the best choice for a particular sonar file.

However, because the AB predictor can be turned into a ZV predictor and because the overall error resulting from the AB predictor is low, this method might be seen as the best suited method in a sonar tracking system.
Testing for optimal prediction with simulated interfering tracks

The tracker's ability to correctly detect interfering tracks was tested with simulated crossing tracks. Various noise levels and situations with missing echoes were tested. For each noise level, 63 tracks were detected manually. From these tracks the optimal predictor and gating parameters were determined for each of the four predictors. With this optimal setting, automatic tracking of the crossing tracks was performed for each predictor with each noise level.

Sonar5's classification unit tested the tracking results by sorting tracks according to their mean velocity in the range domain. Tracks with absolute velocity higher than 0.03 ms\(^{-1}\) were registered as correctly combined tracks. Tracks with lower absolute velocity were registered as mixtures of up-moving and down-moving tracks, such as being combinations of the two lower parts or the two upper parts of the x-legs. Results from tracks with six different noise levels are presented in Table 11 while Table 12 presents tracking results in situations with various levels of missing echoes. All results clearly indicate that the AB predictor is the predictor that best manages to detect the tested interfering tracks.

Echo-association on weights calculated from the intensity and not only on the spatial domain was tested. Crossing tracks with noise N(0, 0.1) and missing echo probability = 0.17 were tested with equal association weights on TS and range. The intensity in the up-going tracks were set to \(-10\) dB while down-going tracks were set to \(-20\) dB. For all predictor methods the tracking accuracy increased dramatically. The AB predictor came out with 99\%, the LR and ZV with 98\% and the WM with 97\% accuracy. This represents an increase of 48\% for the ZM method.

Testing the time dimension in the gating

Gating with time being a fourth dimension was seen as a possible way of improving the tracking. Zero velocity tracks with one echo randomly misplaced in range were tested. When the time gate was set to accept one missing echo and the time weight in the association was set lower than the range weight, the tracker produced smooth tracks overlooking the misplaced echo when the misplacing exceeded a certain distance.

Sawtooth shaped tracks with normally distributed range noise N(0, 0.05) and PG introduced as a 5\% probability for missing echoes were generated. 20 randomly range distributed noise echoes were added to each ping. Various parameter settings were tested,
but it could not be proven that applying time in the tracking made any improvements with this type of data. Increasing the time gate frequently led to an increase in the number of generated noise-based tracks. An increase in splitting of wanted tracks was also observed.

**Discussion**

Testing a MTT tracking system is not a trivial matter due to the variations that can be found in the sonar data and to the number of possible permutations of the tracking parameter setting. With the sonar data, we want to follow tracks in situations with high track density, in situations with crossing tracks, and tracks with various kinds of noise. Testing all these situations is not possible and any absolute conclusions about the best tracking procedure can therefore not be found. The test results will only be valid for the applied data and test methods. Other data and methods might give different results.

**Summary**

An MTT tracker has been implemented in software. Four predictors, three minimum track-length estimators, a four dimensional gating with time being the fourth dimension and association based on 5 dimensions was tested qualitatively and quantitatively with vertically recorded and simulated sonar data.

The general impression was that the tracker managed to follow multiple-targets well. With the automatic parameter detection function, it was easy to obtain optimal tracking parameter setting.

The stepwise constant range dependent min. track-length (TL) and max. ping-gap (PG) function were found to be the best estimators for the TL and PG parameters. In situations with relatively stable angular estimates, as seen with the Lake d’Annecy files, angular distance gave the optimal unit for the TL parameter. In Lake Mjøsa and Lake Stechlin the number of echoes were found to be a more appropriate unit.

From testing prediction errors in non interfering vertically recorded tracks from lakes, simulated tracks with normal distributed noise and simulated interfering crossing tracks, the AB predictor was found to be the best suited for a sonar tracking system.

Applying intensity in the association weighting function was found to improve tracking of simulated crossing tracks.
Applying time as a fourth dimension in the tracker's gating function was not found to improve the tracking performance.

The tracker has only been tested on data from vertically aligned sonar in open lakes and on simulated tracks. Shallow rivers are relatively new environments for hydroacoustic fish monitoring methods and it remains to test the tracker in such environments.

Acknowledgements

We thank Nathalie Gaudreau, Jan Kubecka and Simrad AS for providing the sonar data applied in this article.

References


Tables

<table>
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<tr>
<th>Lake</th>
<th>File name</th>
<th># Track and echoes/track</th>
<th>Optimal Predictor</th>
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<th>TL multiple layers of 10m</th>
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<td>51/17</td>
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Table 7. Predictors and track-length estimators tested with data from three lakes. 
AB=Alpha-Beta, ZV=Zero Velocity predictor and WM=Weighted Mean predictor. AD and E measures track-length in angular distance and in number of echoes respectively.
Table 8. Measured maximum predictor errors in the range domain. Errors are measured in meters. In cases where ZV and AB resulted in equal errors, AB predictor parameter settings were found to be (1, 0). This turns the AB predictor into a ZV predictor.

\[ \text{AB=Alpha-Beta, WM = weighted mean and ZV=Zero velocity predictor.} \]

<table>
<thead>
<tr>
<th>Method</th>
<th>Annecy 1</th>
<th>Annecy 2</th>
<th>Annecy 3</th>
<th>Annecy 4</th>
<th>Mjøsa</th>
<th>Stechlin</th>
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Table 9. Relative frequency of best predictor method measured for individual tracks. The score for each method has been divided by number of tracks in each file. Highest total frequency is seen for the zero velocity method with a total sum score of 1.94.

<table>
<thead>
<tr>
<th>Method</th>
<th>Annecy 1</th>
<th>Annecy 2</th>
<th>Annecy 3</th>
<th>Annecy 4</th>
<th>Mjøsa</th>
<th>Stechlin</th>
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count
Table 10. Testing the influence from position noise on tracking of simulated tracks. 60 tracks have been tested in each case. Predictor parameters are given in parentheses.  
\(AB=\text{Alpha-Beta predictor and } ZV=\text{zero velocity predictor.}\)

<table>
<thead>
<tr>
<th>Track type</th>
<th>Noise level (\sigma)</th>
<th>Optimal predictor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staircase</td>
<td>no noise</td>
<td>ZV</td>
</tr>
<tr>
<td>Staircase</td>
<td>0.01</td>
<td>AB(.6, .0)</td>
</tr>
<tr>
<td>Staircase</td>
<td>0.05</td>
<td>AB(.6, .0)</td>
</tr>
<tr>
<td>Staircase</td>
<td>0.10</td>
<td>AB(.6, .0)</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>no noise</td>
<td>ZV</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>0.01</td>
<td>AB(.9, .1)</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>0.05</td>
<td>AB(.5, .0)</td>
</tr>
<tr>
<td>Sawtooth</td>
<td>0.10</td>
<td>AB(.3, .0)</td>
</tr>
</tbody>
</table>

Table 11. Influence of noise on the tracker's association function measured as percent correct association for the four predictors. The results are based on 252 simulated crossing tracks with acceleration and normal distributed noise. Mixture of echoes from the two tracks in the crossing zone was allowed. WM = weighted mean, LR = linear regression, AB=Alpha-Beta, and ZV=zero velocity. The parameter for each predictor is given in parentheses. Figure 59 plots the data in this table.

<table>
<thead>
<tr>
<th>Noise (N(0, \sigma))</th>
<th>WM</th>
<th>LR</th>
<th>AB</th>
<th>ZV</th>
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<tr>
<td>0.01</td>
<td>98(2)</td>
<td>100(3)</td>
<td>98 (2, 9)</td>
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<tr>
<td>0.03</td>
<td>57(4)</td>
<td>57(5)</td>
<td>95 (6, 2)</td>
<td>25</td>
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<tr>
<td>0.05</td>
<td>50(5)</td>
<td>50(6)</td>
<td>94 (3, 1)</td>
<td>41</td>
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<tr>
<td>0.10</td>
<td>50(12)</td>
<td>50(6)</td>
<td>89 (4, 1)</td>
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<tr>
<td>0.13</td>
<td>45(12)</td>
<td>45(7)</td>
<td>87 (4, 1)</td>
<td>44</td>
</tr>
<tr>
<td>0.15</td>
<td>55(3)</td>
<td>55(3)</td>
<td>88 (2, 1)</td>
<td>55</td>
</tr>
</tbody>
</table>
Table 12. Influence of missing echoes measured as percent correct association for the four tracker predictors. The results are based on 252 simulated crossing tracks with increasing probability of missing echoes. Each echo was removed with the probability given in the left column. Normal distributed noise with standard deviation= 0.1 was added to the remaining echoes range position. Acceleration was added between ping 30 and 31 in each track. Mixture of echoes in the crossing zone were allowed. AB=Alpha-Beta, LR = linear regression, WM = weighted mean, and ZV=zero velocity predictor. Parameters for each predictor are given in parenthesis. Figure 60 plots the data in this table.

Figures

Figure 47. The four basic elements of a multiple-target tracker.
Figure 48. Elements in the Kalman filter. Observation $z$ is a sum of the state vector $x$ and the measurement noise $V$. Based on the Kalman gain and the observation, an estimated state vector is produced.

Figure 49. Elements of the Alpha-Beta predictor.

Figure 50. A situation with three echoes in the neighbourhood of a track. The tracking algorithm has to select one of the three, but what echo should be selected?
Figure 51. Echo-association with time as a factor might result in rejection of the echo (marked e) when a better suited echo is located at a later time, even if the echo (e) is found within the predictor gate. This can result in a smoother track, but at the cost of an increased number of missing observations.

Figure 52. Two tracks under formation competing for one and the same echo. Four out of many possible association results.

Figure 53. Echogram of single echoes from Lake d’Annecy (Left), Lake Mjøsa (centre) and Lake Stechlin (right).
Figure 54. Echogram with two simulated crossing tracks. The noise standard deviation $\sigma=0.15$. Probability of missing echo is 0.17.

Figure 55. Upper chart: Track-length (TL) distribution measured from tracks detected in Lake d'Annecy. TL is measured in number of echoes. Lower chart: Ping-gap (PG) distribution measured as maximum number of missing echoes in each track.
Figure 56. Elements from the tracking parameter enter dialog implemented in Sonar5.

Figure 57. The tracker’s performance window. Results from tracking a fish in Lake d’Annecy (France). Upper and lower lines indicate the gating.
Figure 58. Testing the impulse response. Left: weighted mean WM (2). Centre: Linear regression predictor LR (10). Right: Alpha-Beta predictor AB (0.1, 0.5). The values in the parentheses are the applied predictor parameters.

Figure 59. Plot of data from Table 11. Influence of noise on the tracker's association function measured as percent correct association for the four predictors. The results are based on 252 simulated crossing tracks with acceleration and normal distributed noise. Mixture of echoes from the two tracks in the crossing zone was allowed. WM = weighted mean, LR = linear regression, AB=Alpha-Beta, and ZV=zero velocity.
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Evaluation of the hydroacoustic fish counting method based on single echo detection and tracking in shallow rivers

Abstract

In marine fisheries and science, split-beam echo sounders are frequently applied to monitor fish. A common data analysis method is the single echo detection and tracking method (STM). This hydroacoustic fish detection method has also been applied in many rivers around the world in recent years. Aligning one or a few transducers horizontally in a river provides a simple way of monitoring major parts of the rivers cross-section area. However, the horizontal shallow water application introduces fundamental changes to the method compared with its original usage. It has therefore been important to test the performance of the STM before accepting this application. Sonar data from seven different rivers and lakes have been recorded and analysed. Differences are measured and discussed numerically and quantitatively. The influence of water current, surface waves and rain is tested. The main conclusion is that the analysis method is not well suited for split-beam data recorded in shallow rivers.

Keywords

Hydroacoustic, multiple-target tracking, split-beam, sonar, prediction, fish counting, programming, tracking algorithm.
Evaluation of the hydroacoustic fish counting method based on single echo detection and tracking in shallow rivers.

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Introduction

The decline in salmon stocks and a growing environmental concern has resulted in an increased interest in monitoring systems (Jacobsen, 2000). Hydroacoustic fish stock estimation methods are common in ocean fisheries. This method is still on the experimental stage in rivers, however. Examples of rivers where the method has been or is being tested are the River Wye (Wales), the River Fraser in Canada, the River Tornionjoki and the River Simojoki in Finland, the River Tana and the River Numedalslågen in Norway and the River Kenai and the River Wood in Alaska. (Ransom and Johnston, 1998) reports about tests in more than 14 rivers. A description of a specific shallow river counting project can be found in Romakkianemi et al., (2000).

A commonly applied hydroacoustic fish-stock estimation method in shallow rivers is the method based on one or a few fixed side-looking transducers. Split-beam transducers providing information about the targets echo intensity, range and angular position are common. The recorded data are analysed by the application of a single echo detector (SED) and a tracking procedure (Enzenhofer et al., 1998).

The SED suppresses noise from the bottom and echoes from multiple-targets. Multiple-targets occur when two or more targets are found at the same range in the sound beam. These targets cannot be positioned correctly by the split-beam technique and they are therefore removed. SED is well described in a series of articles by Soule et al. (1995, 1996 and 1997).
A target passing the beam can result in more than a single echo. The task for the tracker is to combine these echoes so that the target can be counted correctly. Tracking is a well-described topic in radar applications (Blackman, 1986), but little has been published about fish tracking. (Xie, 2000) describes a fish tracking system tested in the River Fraser and addresses problems related to the range dependent echo detection probability. In (Balk and Lindem, 2001a) a multiple-target tracker is developed and tested on sonar data from lakes.

In 1997, the University of Oslo was asked to test hydroacoustic fish detection methods in the River Tana (northern Norway). This was done during the summers of 1998 and 1999. The first year, one sonar system was tested at the Polmak site 50 km from the river mouth. Next year two synchronised systems were tested, one at each riverbank. Analysing the data was found difficult and time consuming compared with analysis of data recorded with downward-looking sonar in lakes. Problems with analysing shallow river data have been reported from scientists working with hydroacoustics in other rivers as well. From the River Wye (Wales), difficulties of separating echoes from adult salmon and aquatic weed has been reported by Nealson and Gregory (2000). From the River Fraser in Canada, unwanted echo targets like debris and boat wakes have been reported to be a problem (Xie et al., 1997).

In order to adapt the hydroacoustic fish detection method to river usage, evaluating the method in this environment, and studying the reported and observed difficulties are important.

Material and method

Sonar recordings from rivers and lakes were compared in order to find differences and to pinpoint the reasons to why analysing river data seemed more difficult than analysing data from lakes. Sonar recordings from three lakes and four rivers were collected. The scientific echo sounder EY500 (Anon 1996) from Simrad AS and the HTI Model 243 Split-Beam Hydroacoustic System (Anon, 1999) from Hydroacoustic Technology Inc. (HTI) recorded the data. The echo sounders were equipped with split-beam transducers ranging from 70 kHz to 200 kHz. The specific recordings are described later.

The sonar's built-in detector performed the SED. The detector tests echo criteria such as echo intensity, length, shape, and off-axis position. There are some differences
between the two echo sounders’ detectors. Mod. 243 tests the echo shape by applying three individual echo length criteria at –6 dB, –12 dB, and –18 dB. EY500 tests the shape by slicing the –6 dB echo-pulse in 1.5 dB levels locking for double peaks. With EY500, an additional SED-criterion tests the standard deviation (Max. Phase Dev.) within the received echoes angular samples.

The responsible scientists selected the SED parameters for each of the applied data files. In the River Tana the following parameter were applied: received echo threshold (Min. Value) = –40 dB, Min. Echo Length = 0.5, Max. Echo Length = 2.4, Max. Beam Comp. = 6 dB and Max. Phase Dev. = 10. Echo length is measured relative to the transmitted pulse-length, Max. Beam Comp. restricts the maximum acceptance of an echo's off-axis position. The phase deviation is measured from the echo sounders internal phase step algorithm. 120 kHz sound-pulses were emitted with a power of 63 W, a pulse-length of 0.3 ms and a repetition rate of 5 ping per sec.

Echo information from the SED presented in a time range diagram will referred to as SED-echograms. Echograms presenting the information form from the sonar’s amplitude detector will be referred as Amp-echograms. With most of the sonar files applied in this article, both echograms have been stored during the recording process. The prefix will be applied when it is necessary to distinguish between them.

The sonar post-processing program Sonar5 was applied in the data analysis. Sonar5 has been developed at the University of Oslo in order to study data from commercially available echo sounders. Sonar5 has tools for visualising sonar data, routines for manual and automatic tracking, track storing, track editing and track analysis. The automatic tracker is a multiple-target tracker (MTT), which has been equipped with an automatic tracking parameter detection algorithm.

The tracker is based on four main elements: track support, prediction, gating and association. The track supporter maintains existing tracks, decides when a track has passed the beam or whether a track should be deleted as noise. Two range dependent parameters are applied in this testing. They are the max. ping-gap (PG) and the min. track-length (TL). Sonar5 can measure TL as angular distance (AD) as number of echoes (NrE) or as number of ping between first and last echo in a track (NrP).

Four prediction algorithms are implemented. These are the zero velocity (ZV), weighted mean velocity (WM), linear regression (LR) and the Alpha-Beta (AB) predictor. The predictors estimate the next position for an echo in a track under formation. The
tracking parameter detection algorithm test a set of verified tracks (training set) to find which of the four predictors that produces the lowest prediction error.

Gating or windowing defines a four dimensional frame placed around the predicted echo-positions. Next echo is searched within this gate. The four dimensions are the time, range, and the angular dimensions athwart-ship (Ath) and along-ship (Alo). With elliptical transducers, Ath refers to the main-axis, while Alo refers to the semi-axis. Time gating has not been tested in this article. Range is measured in meters while Alo and Ath are measured in degrees. In cases of missing echoes, Sonar5 can expand the gate linearly in the spatial domain by the factors given by the expand-gate parameters.

The last function in the tracking algorithm is the association. This element decides how new observations should be connected with the existing tracks in the track supporter. A weighted five dimensional distance measure evaluates new echoes and how they should be associated. Tracking conflicts, such as when two or more echoes are found within one gate, or when two or more tracks compete for the same echo, are solved by this function. The five dimensions are the time, range, Ath, Alo, and the intensity. The weights are detected from the uncertainty in the five domains by the tracking parameter detection algorithm. Spatial association is tested in this article. The tracker is described in (Balk and Lindem, 2001a).

In order to compare the echograms numerically, two quantitative definitions were found appropriate. These were the track quality (TQ) defined in equation (1) and the track signal to noise ratio (TSNR) defined in equation (2). In both cases only tracks believed to originate from solid moving objects were applied. TQ is defined as the ratio between the sum of echoes to the sum of missing echoes within these tracks. With increasing number of missing echoes, TQ approaches zero. With decreasing number of missing echoes, TQ increases and it will approach infinity when the number of missing ping approaches zero. The TQ ratio is invariant to the geometry of the beam, but it is influenced by the decreasing detection probability with increasing range. We have defined TQ in the following way:

$$TQ = \frac{\sum_{i=1}^{N} (\text{echoes in track}_i)}{\sum_{i=1}^{N} (\text{missing echoes in track}_i)} \quad (1)$$
Here, $N$ is the total number of tracks.

A related definition is the SED-detection probability (DP) discussed by (Xie, 2000). DP is defined by exchanging missing echoes in equation (1) by the total number of pings emitted between the first and last echo in each track. Xie demonstrates how DP increases with range and discusses what this means to target tracking in rivers.

TSNR was defined to be the ratio between the number of echoes in tracks, and the total number of echoes. Tracks in this context comprise tracks believed to originate from passing objects such as fish and debris. TSNR provides a way of measuring the noise level in the output from the SED. The definition should not be confused with the traditional signal to noise ratio (SNR) definition normally applied in signal analysis. In order to gain a file invariant measure, TSNR is normalised by division with the total number of ping and with the total number of fish tracks found within each file. The constant number in the numerator is arbitrarily selected and applied as a scaling factor. TSNR is defined as:

$$TSNR = \frac{10000 \cdot \sum_{i=1}^{N} (\text{echoes in track}_i)}{M \cdot N \cdot \sum_{j=1}^{M} (\text{echoes in ping}_j)}$$  \hspace{1cm} (2)

Here, $N$ is the total number of tracks, and $M$ the number of recorded ping.

Echoes from passing objects were tracked manually in each of the sonar files and the TSNR and the TQ were calculated. Manual and automatic tracking were applied and the results compared.

One major difference between rivers and lakes is the water current. The influence of water current on the sonar recording was tested in a pond by the application of an electric outboard engine of the type WonderTroll 909. An EY500 equipped with a 120 kHz, 4x10 deg. split-beam transducer was mounted horizontally at a depth of 80 cm in a 150 cm deep, 13 m long, and 6 m wide pond. The engine was mounted 6.4 m from the
transducer and 2.65 m to the side of the acoustic axis so that it produced a water current normal to the sound-beam.

In a river, the water current might cause stones and other objects to rattle. Knocking various sized stones together under water tested the generation of noise from rattling stones. For these tests the EY500 was turned into passive mode. The knocking was performed outside the sound-beam at the position R=3 m, Alo=0 deg. and Ath=90 deg.

Pressing a floater up and down in the pond tested the influence from waves. An ordinary fish basket was used as floater.

Rain was produced artificially from a water hose. Recordings were also made during periods of natural rain to determine any effects.

**Results**

Comparing echograms from lakes and rivers revealed many differences between these two applications. The most striking differences were the number of scattered echoes seen to originate from non-solid or non-existing targets, the long thin lines of echoes from stationary targets (Figure 61), and the many missing echoes in tracks from fish found in the river data. Figure 62 demonstrates the differences between a vertically and a horizontally recorded SED-echogram. Scattered noise echoes and lines with echoes from the bottom are seen on the echogram from the river. Table 13 and Table 14 present numerical results while Table 15 and Table 16 present the applied automatic tracking parameters. Clear differences are seen when comparing data from rivers and lakes. In the lake data, the mean probability of detecting an echo from a passing target is found to be 0.92 while it is only 0.39 in the river data. The mean TQ is found to be 58 times higher in the lakes, and the signal to noise ratio TSNR describing the relationship between echoes in tracks from solid passing objects and unwanted echoes are 12 times higher in the lake data than in the river data.
Describing track types found with the sonar recordings

With the sonar data from the lakes, echoes from fish and echoes from bottom can be seen on the Amp-echograms. Bottom echoes are generally consistently removed by the sonar's bottom detection algorithm. Only echoes from passing fish are observed on the SED-echograms.

Three different kinds of echo patterns were found in the river echograms. These patterns were: a) clusters of echoes seen as short curved lines, b) clusters of echoes seen as long straight lines and c) clouds of scattered echoes.

Echoes in the first group frequently formed tracks with a more or less determined horizontal angular movement. Tracks in this group seen with movement against the water current were interpreted as fish, while track seen to follow the current were interpreted as drifting objects. Tracks from fish were observed at most ranges, while the frequency of drifting objects was seen to increase with increasing range. Downstream targets were also often observed with smoother tracks and higher TQ values than the upstream moving fish tracks. This was especially significant with the tracks recorded in the River Numedalslågen. Mean vertical off-axis angles indicated that downstream tracks tended to move close to the surface. This tendency was not seen with tracks from upstream migrating fish. The observations seem reasonable when the tracks are interpreted as fish and debris. Debris are likely to drift close to the surface and should be more frequently observed further out in the beam where the beam approaches the surface. A drifting target following the current can also be expected to follow a smoother path than a fish swimming towards the current. Comparing fish tracks from the rivers with the tracks from the lakes, the number of missing echoes was found to be higher in the river tracks. Figure 63 demonstrates the differences between vertically and horizontally recorded tracks.

Tilting the transducer some degrees upwards or downwards highly influenced the occurrences of long, thin lines of echoes. It was therefore assumed that these echoes originated from stones or from bottom structures. The density and the echo intensity from the lines were seen to vary with range and time.

The third echo group, the scattered echoes, was also observed with increasing density with increasing range. The number of scattered echoes varied with transducer tilting, with rain, wind and passing boats. These echoes might originate from fluctuations
in the noise level, from air bubbles, from inhomogeneities in the turbulent water or from other unknown active or passive sources. From the fieldwork in the River Tana, it was seen that the amount of scattered echoes increased in periods with rain, flooding or when waves were generated by the wind.

**Testing sources of noise**

The water current experiment in the pond revealed that scattered noise echoes could be generated directly from turbulent streaming water. From Figure 64 it is seen how the echo intensity increases when the current reaches the sound beam. Counting echoes on the SED-echogram from this range layer shows that the number of detections per 400 ping increases from 4 to 300 when the current enters the beam. The mean target strength of the echoes from the current was measured to -42.7 dB with the application of the single target sonar equation. The reason for the increased echo level could be dispersion from thermal inhomogeneities, release of dissolved air by the suddenly change in pressure caused by the introduced turbulence or echoes from dust particles. Further experiments are needed to find the actual cause of the increased noise.

Turning the sonar into passive mode and knocking stones together under water demonstrated that active noise from rocks could be a source of noise. The EY500's SED produced echoes with TS values up to \(-41.1\) dB. The sound intensity produced by two small quartz stones is seen in Figure 65. The stones producing the sound in this figure had a diameter of about 2 cm.

Introducing surface waves in the pond resulted in a strong increase of single echo detections. In a layer from 2 to 5 m from the transducer, 638 detections with an average TS of \(-44.5\) dB were counted within 300 successive pings. No detections were observed in this layer before the waves were introduced.

The pond experiment applying artificial and natural rain did not reveal any influence on the sonar. Both passive and active sonar was tested but no sound or echoes were observed. From the literature it is known that rain can disturb the surface scatter from a sonar (Foerster, 1994). Large raindrops (> 2 mm diameter) can generate underwater sound with frequencies from 1 Hz to 50 kHz (Nystuen 1997). With a 120 kHz transducer, this should not be a source of disturbance.
Tracking results

With the recordings from the lakes, both manual and automatic tracking of fish worked well. Tracking parameters detected by the automatic parameter detector could be applied without any further trimming. Except for some cases of erroneous echo combination in high track density regions, automatic and manual methods resulted in the similar echo combinations. Reduced boat speed and pulse width, or increased ping rate would probably improve the tracking performance in the high track density regions.

With the data from the rivers, manual tracking was possible. However, with high number of missing echoes in tracks combined with numerous scattered noise echoes and echoes from bottom, tracking was found difficult and time consuming. In many cases it was not possible to determine the origin of a cluster of echoes by studying the SED-echogram and the position diagram. In these cases the Amp-echogram was found to be of great help. Missing echoes on the SED-echogram were often clearly visible on the Amp-echogram showing where the target had moved and which SED-echo that belonged to what track. Noise-based echoes from non-existing targets was less disturbing. Being able to see the background intensity level easily revealed if echoes originated from phenomena such as boat wakes. Figure 66 demonstrates the advantage of applying the Amp-echogram in a situation with low track quality.

Feeding manually detected tracks from river data to the automatic tracking parameter detector resulted in too high gating and ping-gap values. The detected parameters had to be reduced in order to work. No tracking parameters could be found that detected the tracks from moving objects correctly. The automatic tracker frequently split tracks from passing targets into smaller tracks, overlooked fish tracks or combined noise-based echoes into fish-like tracks. Splitting of passing tracks and tracks generated purely from unwanted echoes resulted in high overestimates in the automatic counting. By trimming the tracking parameters, removing noise-based tracks and combining split tracks from the output of the automatic tracker, fairly reasonable tracking results could be achieved. This was nearly as time consuming as the manual tracking, however.
Tracking targets in lakes

Lake Mjøsa southern Norway

Simrad AS recorded the file 06162341.dg3, Tuesday 16 June 1993 at night from 23:41 to 23:56. The 70 kHz, 4x10 deg. split-beam transducer was mounted vertically on a moving boat. High track density\(^4\) and short tracks (few echoes in each track) characterise this file. The depth along the transect increased from 30 meter to 110 m. Bottom echoes were well removed by EY500's bottom detection algorithm and therefore not visible on the SED-echogram. The short tracks are caused by low ping rate relative to the speed of the boat. (1.89 ping per sec.) Tracking with manual methods was possible, but the large number of fish, the high track density and the short tracks caused some difficulties. Automatic tracking worked fine and a total of 2073 fish tracks were detected.

Lake d’Annecy northern France

Nathalie Gaudreau recorded the file 09292220.dg7, Sunday the 29\(^{th}\) September 1997 at dusk from 22:20 to 22:22. An EY500 equipped with a 70 kHz, 11x11 deg. transducer mounted vertically on a boat was used for the recording. The depth at the site was about 42 m. Bottom echoes were well removed by the bottom detection algorithm. Medium fish density, long tracks, high track quality, and low signal to noise ratio characterise the data. Manual tracking was simple and automatic tracking gave the same count as the manual counting. Catch data show that fish tracks originated from perch (\textit{Perca fluviatilis}), whitefish (\textit{Coregonus sp.}) and arctic charr (\textit{Salvelinus alpinus}). A total of 51 tracks were detected in the file.

Lake Stechlin (Czech Republic)

Jan Kubecka (Cz) recorded this file from a boat Saturday 30 December 1997 at night (from 23:48 to 23:51). An EY500 equipped with a vertically aligned 70 kHz, 11x11 deg. transducer recorded the file. High densities of short tracks are seen on the echogram. The depth varied from 15 to 37 m. The bottom is well removed by the bottom detection algorithm and only echoes believed to originate from fish are seen on the SED-echogram.

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\(^4\) High fish density means that the target density is approaching the sonar's single-track resolution. The resolution is determined by the transmitted pulse length, the sample frequency, and the by the trackers ping-gap parameter.
At a layer from 4 to 6 m, the fish density is periodically "on the edge" of the sonar's resolution. 109 fish tracks were manually tracked and applied to the tracker's automatic parameter-detection algorithm. Automatic tracking with this parameter setting resulted in 843 tracks.

Tracking targets in rivers

The River Tana (northern Norway)

The file 07191939.dg9, was recorded by the authors Sunday 19th July 1999 in the evening from 19:39 to 20:05. An EY500 equipped with a fixed position horizontally aligned ES120-4x10 deg. transducer was applied in the recording. At the site the River Tana is 257 m wide. The river depth was 2.5 m at the transducer stand, increasing smoothly down to 4.2 m at a range of 50 m. The sonar file is characterised by medium track quality and numerous unwanted echoes. Distinct lines of bottom echoes are seen at four ranges. A large number of scattered echoes are seen at ranges greater than 35 meters. Manual counting resulted in 30 tracks from targets passing the sonar. Applying these tracks to the Sonar5's automatic tracking parameter detector resulted in high gate values (61 cm. in the range domain) and a ping-gap function accepting ping-gaps of up to 21 ping. With this parameter setting, automatic tracking resulted in a total of 520 tracks. Most of these tracks consisted of scattered noise echoes and echoes from the bottom. High echo to echo variation in range made these tracks look very different from manually detected tracks.

In order to gain a better tracking result, 10 tracks seen with high track quality were applied to the automatic tracking parameter detector. This resulted in lower gating and ping-gap. Automatic tracking with this parameter setting resulted in 208 tracks. These tracks had similarity with the manually combined tracks. Sorting out the tracks believed to originate from stones and scattered noise gave a fairly accurate result relative to the manual counts.
The River Tornionjoki (northern Finland)

Atso Romakkianemi and his team from the Finnish Game and Fisheries Research Institute (RKTL) recorded the file w1751100.raw, during a major hydroacoustic survey lasting from 1995 to 1999. At the site, the river was 275 m wide with a maximum depth of about 8.7 m. The river profile was V shaped with less steep wings. A total of four transducers were applied in the study in order to cover as much of the water cross-section as possible. Two HTI model 243 sonar's equipped with 200 kHz, 4x10 and 2x10 deg. transducers recorded the data. The file applied in this test was recorded with the 4x10 deg. transducer aiming from the west river bank and down into the central part of the river. The file was recorded Monday 24th June 1997 at 11:15 to 11:30.

A line with some echoes from the bottom is seen in parts of the file at a range of 10 m. Not many scattered noise echoes are seen in the file. However, manual counting was difficult due to the high number of missing echoes seen in tracks from solid targets. In three cases, targets were seen to pass the transducer in dense groups. Separating these was difficult. A total of 19 targets were detected manually. Automatic detection of tracking parameters resulted in too high gating and ping-gap values. With the parameters referred to in Table 15 and Table 16, the auto-tracker detected 40 tracks. Some of these targets originated from bottom echoes. Tracks from passing objects were frequently split into minor tracks and in a few cases not detected at all.

The River Simojoki (northern Finland)

Juha Jurvelius from RKTL recorded this file in the evening from 18:56 to 00:43 Tuesday 30th June 1999. An EY500 equipped with a side-looking 120 kHz 4x10 deg. transducer was applied. A split line of echoes from bottom is seen at a range of 43.7 m. on the SED-echogram. 134 tracks from passing objects were detected manually. The tracks are seen with high numbers of missing echoes. Manual tracking on the SED-echogram was difficult, but with the assistance of the Amp-echogram it was possible to "gain a feeling" of accuracy. Detecting tracking parameters from the manually detected tracks did not work well. A gate size of 300 cm. in the range domain and a maximum ping-gap of 91 missing echoes were obtained. Experimenting with the parameters resulted in the setting seen in Table 15 and Table 16. With this setting, a total of 741 tracks were detected. Scattered noise and tracked bottom echoes constituted many of the tracks. The echoes from the
moving targets were also detected, but they were frequently split into shorter tracks due to missing detection.

**The River Numedalslågen (southern Norway)**

A team from Simrad AS recorded this file in 1996. An EY500 equipped with an ES120-4x10 was applied in the recording. The file contained a large number of echoes from bottom and from scattered noise. 111 tracks from moving objects were detected manually. From these, 13 tracks were seen with distinct movement against the water current. Applying the 13 upstream migrating tracks to the automatic tracking parameter detector resulted in relatively high values of ping-gap (14) and gating (45 cm in the range domain). Tracking targets with this setting resulted in 1049 tracks. The tracks showed little similarity with the manually detected tracks. Reducing the gate size in the range domain, increasing the gate size in the angular domain and reducing the ping-gap parameter improved this. The tracking parameters referred in Table 15 and Table 16 resulted in 660 tracks. Most of the manually detected tracks were found among these.

**Discussion**

Sonar recordings from different sites, transducers, frequencies, SED-parameter settings and ping rates have been compared. It is appropriate to ask whether any significant conclusions can be drawn from such an inhomogeneous data set. It is obvious that the change of one or more of the involved parameters would influence on the result. A slight change in the transducer tilting or in the SED-parameter settings could have changed both the noise level and the track quality. Using a different automatic tracking algorithm could have resulted in different counting results. All this introduces uncertainties in the results and absolute conclusions cannot be drawn. However, the results clearly indicate that shallow river applications involve difficulties not found in lakes.

A problem not considered in this article is the effect of time dependent variations in the noise level observed in the river data. As indicated by the experiments in the pond, TSNR can be influenced by waves and by the water current. During the fieldwork in the River Tana it was found that the noise level and thus the ability to detect fish depended on both the weather and the water conditions and on the position and tilting of the transducer. This makes it difficult to interpret the counting results and to compare results from different periods from one year to another. Investigating these problems seems important.
Conclusion

Major differences were found between sonar data recorded in vertical and horizontal applications. In the vertical cases there were few problems with unwanted echoes and with missing echoes in tracks from fish. Short tracks with few echoes increased the counting uncertainty in the file from the Lake Mjøsa and Lake Stechlin, but this could have been avoided by increasing the ping rate relative to the speed of the boat. High track density also resulted in some problems, but the overall conclusion was that it was possible to gain good counting results with manual and automatic methods in the data from the lakes.

This was not the case with the river recordings. High numbers of missing echoes in tracks from passing targets combined with high numbers of unwanted echoes from various sources made tracking difficult. It was difficult to see the tracks from moving targets when the tracks were surrounded by noise with manual tracking. It was also difficult to determine how the echoes should be combined in situation with many missing echoes.

Applying the Amp-echogram was found to be of great help with manual tracking. On the Amp-echogram, scattered noise echoes were less disturbing, it was easier to follow tracks from targets and to determine the phenomena that caused the SED-detection. Clearly the SED-detector removes information important to the tracking.

Applying automatic tracking to the river data was generally found to be difficult. The low TQ and the TSNR resulted in high overestimates due to generation of tracks from noise-based echoes and to splitting of tracks from passing targets. However, counting fish by applying the automatic tracker and then removing unwanted tracks and combining fractionated tracks in the tracker’s output could be done in most of the tested river files. This was slightly less time consuming than manual counting.

Methods for reducing the overestimates from the automatic tracker should be studied. Solutions based on filtering and automatic track classification could be solutions to this problem.

The automatic tracking parameter detector worked well with the lake data, but tended to detect too high gating and ping-gap values in the river data. Here the obtained parameters had to be trimmed manually. Automatic parameter detection was found convenient and a method better suited for river data should be developed.
The SED seems to be a major cause of the analysis difficulties in the rivers. Frequent rejection of echoes from fish and acceptance of echoes from other sources and from noise was reasons to this. From the tests in the pond it was seen that the SED easily detected noise echoes from the water current and from the surface waves.

By comparing the Amp and the SED-echograms, it was seen that the SED removed important information from the echo-signal. Improving the SED or finding other analysis methods better suited for rivers is necessary in order to adapt the hydroacoustic fish counting method to rivers.

Indications of diurnal and seasonal changes in the sonar's counting efficiency were observed during the fieldwork in the River Tana. This can make the interpretation of the counting results difficult and further research is necessary.

**Acknowledgements**

The scientists, departments and companies who provided us with sonar data supported this work. We want to thank Jan Kubecka (Cz), Nathalie Gaudreau (Ca), Juha Jurvelius (Fi), Atso Romakkaniemi (Fi) and Simrad AS (No), for providing sonar data. We also want to thank Simrad AS, the County governor in Finnmark represented by Kjell Moen and the Finnish Game and Fisheries Research Institute (RKTL) for supporting the fieldwork in the River Tana. Support was given by means of funds, equipment and labour. Jan Kubecka and Jarka Froutzova (Cz) provided the equipment and assisted with the noise experiments in the pond.

**References**


Tables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lake d’Annecy</th>
<th>Lake Mjø sa</th>
<th>Lake Stechlin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ping in file</td>
<td>863</td>
<td>1666</td>
<td>1016</td>
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<td>Ping per sec.</td>
<td>10.76</td>
<td>1.89</td>
<td>6.23</td>
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<td>SED-detections</td>
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<td>5316</td>
<td>2000</td>
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<td>SED-detections per ping</td>
<td>1.02</td>
<td>3.19</td>
<td>1.97</td>
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<td>Echoes in track</td>
<td>865</td>
<td>5312</td>
<td>1901</td>
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<tr>
<td>Manually detected tracks</td>
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<td>1987</td>
<td>843</td>
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<tr>
<td>Mean no. of echoes in track</td>
<td>16.96</td>
<td>2.67</td>
<td>2.26</td>
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<td>Mean no. of tracks per ping</td>
<td>0.059</td>
<td>1.190</td>
<td>0.830</td>
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<td>700</td>
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<td>Mean missing echoes in tracks</td>
<td>2.04</td>
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<td>TSNR</td>
<td>0.2231</td>
<td>0.003</td>
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<td>TQ</td>
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<td>7.58</td>
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<td>0.88</td>
<td>0.99</td>
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<td>Automatic detection</td>
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<td>2073</td>
<td>843</td>
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<tr>
<td>Auto tracker overestimate %</td>
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<td>100</td>
<td>100</td>
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*Table 13. Numerical file and track descriptions for rivers.*
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<th>River</th>
<th>River</th>
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<td></td>
<td>Numedal</td>
<td>Simojoki</td>
<td>Tornio</td>
<td>Tana</td>
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<td>Ping in file</td>
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<td>69300</td>
<td>7145</td>
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<td>SED-detections per ping</td>
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<td>Manually detected tracks</td>
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<td>Mean no. of echoes in track</td>
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<td>12.13</td>
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<td>Missing echoes in tracks</td>
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<td>773</td>
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<td>Mean missing echoes in tracks</td>
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<td>41.13</td>
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<td>TQ</td>
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<td>Automatic detection</td>
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<td>Auto tracker overestimate %</td>
<td>595</td>
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<td>693</td>
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*Table 14. Numerical file and track descriptions for rivers.*

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Lake d’Annecy</th>
<th>Lake Mjøsa</th>
<th>Lake Stechlin</th>
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</thead>
<tbody>
<tr>
<td>PG</td>
<td>AB(8,6)</td>
<td>AB(1.2,2)</td>
<td></td>
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<tr>
<td>TL</td>
<td>AD(2.04)</td>
<td>NrE(1)</td>
<td>NrE(1)</td>
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<td>Gate</td>
<td>0.1, 5.2, 3.5</td>
<td>0.15, 9.6, 9.6</td>
<td>0.05, 7.0, 4.1</td>
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<td>Expand gate</td>
<td>0.04, 2.1, 1</td>
<td>0.05, 3.6, 2.6</td>
<td>0.01, 0.1, 0.3</td>
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<tr>
<td>Association</td>
<td>49, 2, 2</td>
<td>30, 1, 1</td>
<td>76, 1.3, 1.6</td>
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</table>

*Table 15. Tracking parameters for lakes.*
<table>
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<th>River</th>
<th>Prediction</th>
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<th>TL</th>
<th>Gate</th>
<th>Expand gate</th>
<th>Association</th>
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<td>Numedal</td>
<td>LR(3)</td>
<td>7</td>
<td>10</td>
<td>0.3, 10, 10</td>
<td>0.1, 0, 0</td>
<td>14, 4, 2</td>
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<td>Simojoki</td>
<td>ZV</td>
<td>10</td>
<td>5</td>
<td>0.3, 10, 10</td>
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<td>10, 1, 1</td>
</tr>
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<td>Tornio</td>
<td>ZV</td>
<td>5</td>
<td>0.3, 10, 5</td>
<td>0.1, 0, 0</td>
<td>10, 1, 1</td>
<td>10, 1, 1</td>
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<tr>
<td>Tana</td>
<td>LR(5)</td>
<td>11</td>
<td>ad(4)</td>
<td>0.3, 2.3, 2.0</td>
<td>0.1, 0.7, 1.1</td>
<td>27, 2, 2</td>
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</table>

Table 16. Tracking parameters for rivers.

Figures

Figure 61. Part of echogram (left) and position diagram (right) recorded in the River Tana. The horizontal lines probably originate from stones on the bottom. The position diagram shows the angular position of the echoes in the line seen at 44 m range. The echoes have been detected by the single echo detector.
Figure 62. Echogram from Lake d’Annecy (left) and from the River Tana (right). The tracks seen in the left echogram are believed to originate from fish. The framed track in the right echogram is probably from a fish. Both echograms present the output from the single echo detector.

Figure 63. Vertically recorded fish track from Lake d’Annecy (left) compared with two horizontally recorded fish tracks from the River Tana (right). Note the shape, track quality, and the noise echoes.
Figure 64. Testing the echo sounder’s reaction to water current in a pond. Current was introduced at a range of 6.4 m after ping 175. The 3D-echogram demonstrates an increase in intensity from the water layer with the current. At the same time the single echo detector started to detect scattered echoes within the current layer. An electric outboard engine produced the current. SV indicates volume backscattering strength.

Figure 65. Sound from two small stones knocked together under water, recorded with the echo sounder in passive mode.
Figure 66. Upper left corner: SED-echogram showing a fish track with low track quality $TQ=0.05$. Right: 3D Amp-echogram showing the same track. The advantage of applying the Amp-echogram is readily seen.
13 Paper III

Why single echo detectors tend to reject echoes from fish in shallow water

Abstract

Single echo detection and tracking is a common analysis method for sonar data recorded with mono, dual, and split-beam transducers. With sonar data horizontally recorded in shallow rivers, however, we have experienced problems with the single echo detector. Echoes from fish seem to be more often rejected than in open water applications. At the same time, echoes from bottom and scattered noise are accepted. Vertical and horizontal in situ recordings of fish are analysed and compared. It is demonstrated that echoes from single fish frequently take on multiple echo characteristics. Solutions are suggested.

Keywords

Single echo detection, SED, side-looking sonar, split-beam, multiple echoes.
Investigating why single echo detectors tend to reject echoes from fish in shallow water

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Introduction

During our first shallow river fieldwork, a standard Cu-sphere (23.0 mm, 120 kHz, \(-40.3\) dB) was dropped in front of the horizontally aligned transducer. We saw nothing. A larger target was tested with the same negative result. In the end we found ourselves rowing around on the river with a large rock hanging in a rope under the boat. Echoes were received from the target, but the single echo detector in the echo sounder still rejected most of these echoes. On the other hand, unwanted single echo detection (noise) was seen as thin lines at certain ranges, as clouds of scattered points and as thin arcs passing the beam.

This was in the River Tana in northern Norway summer 1998 at the west riverbank of the Polmak site. The observation led to the development of the fish track detector based on image analysis of the received echo intensity (Balk and Lindem, 2000). However, we wanted to find the causes for the rejections. Fish-echoes were recorded with vertically and horizontally aligned transducers and analysed. This article presents the results.

Soule et al. have published a series of articles about single echo detection in ICES Journal of Marine Science in 1995, 1996 and 1997. If two or more targets occur within the sonar beam's sample volume at the same time, the echoes from the targets will overlap and cannot be separated (Multiple-targets). The echoes might interfere constructively or destructively and thereby cause erroneous size estimates (Soule et al. 1996). By removing
all such echoes, it is possible to gain a more accurate size estimate. The SED does this by applying a set of discriminators testing for possible multiples.

There are other reasons for applying the SED as well. With split-beam systems, angular positions can be calculated for single echoes. Knowing the echo position enables the system to calculate the off-axis intensity loss and to compensate for this. It also enables calculations of movement and speed when echoes have been tracked. An important and appreciated feature with the SED is the high data compression ratios obtained when only echoes from single objects have to be stored.

In situations where echoes other than fish-echoes exist, it is important to identify and eliminate the echoes from the other sources in order to gain accuracy in the size estimates, and to obtain the correct number of fish. Tracking and classification can do this. However, missing detection in tracks from fish combined with high numbers of noise-based echoes can make tracking difficult.

Material and methods

Sonar data was recorded in the River Tana (northern Norway) and on the ice of Lake Semsvann (southern Norway). An EY500 echo sounder from Simrad AS equipped with an ES120, 4x10 deg. transducer was applied in these recordings. In the River Tana the transducer was mounted 40 m from the riverbank horizontally aiming 90 deg. to the water current. The transducer was tilted 2.1 deg. downwards. At the site, the river was 257 meter wide. The depth at the transducer was 2.75 m, slowly decreasing to 4.2 meter at a range of 40 meter from the transducer. The distance between the transducer’s centre and the surface was 50 cm. At Lake Semsvann, the transducer was mounted vertically 10 cm under the ice. Bottom was detected at a range of 33 m.

Data was recorded with a transmitting power = 63 W, ping interval = 0.3 s and transmitted pulse-length = 0.3 ms (medium pulse-length). Received power and angle data (telegrams) were sampled with 3 cm intervals by the EY500.

Sonar data recorded in other rivers was borrowed for checking whether the results found in the River Tana applied to other places and equipment. Files from the river Tornionjoki and the River Simojoki (northern Finland) were borrowed from the Finnish Game and Fisheries Research Institute (RKTL). Files from the River Numedalslå gen were borrowed from the Simrad AS. The River Tornionjoki files were recorded by an HTI
model 243 echo sounder while the other files were recorded with EY500. Sonar recordings from fish mounted on a carousel were used to test the echo length at all aspects.

The sonar data was studied by the application of the Sonar5 post-processing program from the University of Oslo. A sample data analyser and a single echo detector were implemented in order to do these tests. 768 echoes from 9 fish were selected from the River Tana files. 672 echoes from 5 fish were selected from the Lake Semsvann files. Fish tracks passing through the −3 dB sound beam were selected. All echoes from the selected fish tracks seen with echo intensities higher than 6 dB above the background reverberation level were applied in the tests.

Sonar5's sample analyser calculated the same single echo detector variables as used by the EY500. These variables were further analysed with Microsoft's Excel and Statgraphics PLUS 4.0 from Statistical Graphics Corp.

The SED in the EY500 applies 6 SED criteria. These are the Min. Value (MV), Min. Echo Length (-EL), Max. Echo Length (+EL), Max. Beam Comp. (MBC), Max. Phase Dev. (MPD) and the echo shape (SH). (Read + as maximum and - as minimum).

Min. Value defines the minimum fish size to detect. Min. Value is related to the beam compensation factor (BC) and forms a threshold as demonstrated in equation (1). This allows the echo sounder to detect the same minimum fish size in the centre and in the outer part of the beam. All echoes with intensities below the threshold are rejected by the SED.

\[ \text{Threshold} = MV - 6 - 2 \cdot BC \]  

(1)

Here, BC is the beam compensation factor and MV the Min. Value criterion. The constant 6 is applied in order to give a 6 dB signal to noise ratio. The factor 2 is applied in order to account for the two-way signal path.

The echo length is measured relative to the transmitted pulse-length. An echo from a well-defined single target should have the same length as the transmitted pulse. Hence the echo length should be 1. (Soule et al., 1995) demonstrated that echoes from two targets within the same sample volume could result in two echo-pulses shorter than 0.8 as well as one long pulse longer than 1.2 due to interference. The echo length is measured 6 dB below the echo peak as demonstrated in Figure 67.
MBC defines the cross-section width of the beam. Echoes detected outside the ellipse defined by the MBC in conjunction with the transducers opening angle will not be accepted as single echoes. The beam compensation factor that MBC works on is calculated by the application of a Bessel function as demonstrated in the following expression.

\[
BC = 2 \cdot 3.01\left(\alpha^2 + \beta^2 + 0.18 \cdot \alpha^2 \cdot \beta^2\right)
\]

(2)

\[
\alpha = \frac{Alo - aloOffset}{3dBBeamwAlo/2} \quad \beta = \frac{Ath - AthOffset}{3dBBeamwAth/2}
\]

Where BC = Beam compensation factor, \(\overline{Alo}\) = mean along-ship angle, \(\overline{Ath}\) = athwart-ship angle. The Alo and Ath offset parameter denotes the displacement of the transducers centre axis. Offset is measured in a calibration procedure. The 3dBBeamwAlo and the 3dBBeamwAth denotes the transducer opening angle (4x10 deg. respectively with the ES120 transducer).

Phase deviation (PD) is calculated as the sample deviation \(sAlo\) and \(sAth\) from the angular samples detected within each echo-pulse. With a pulse-duration of 0.3 ms, a sound frequency of 120 kHz and a sample rate of 24 kHz, 6 - 8 samples are normally found within the duration of a single echo. The EY500 measures electrical degrees in number of phase steps (ps) ranging from 0 to 64. PD is calculated from the variation in these phase steps and not from the mechanical degrees. PD reflects the axis with the maximum variation. The calculation is illustrated in equation (3),

\[
sAlo_{ps} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (Alo_{ps,i} - Alo_{ps})^2}
\]

\[
sAth_{ps} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (Ath_{ps,i} - Ath_{ps})^2}
\]

(3)

\[
PD = \text{Max}(sAlo_{ps}, sAth_{ps})
\]

where \(N\) is the number of samples in the pulse. Alo and Ath refers to the along-ship and athwart-ship axes defined for the Simrad transducer. Subscript ps is applied to indicate that the phase steps are used rather than the mechanical degree.
PD can be related to mechanical degree by applying the scaling factor between degree, phase steps and the electric to mechanical sensitivity factor.

\[ s_{\text{Ath}} = \frac{180}{64 \cdot \text{AngleSensitivity}_{\text{Ath}}} \cdot s_{\text{Ath}_{ps}} \]  

(4)

Due to the different sensitivities along the two angular axes, \( s_{\text{Ath}} \) and \( s_{\text{Alo}} \) have to be calculated separately.

The last discriminator in the EY500's single echo detector is the shape detector. The shape detector detects whether the echo-pulse is single or multiple peaked. Slicing the echo in -1.5 dB slices from the peak value and downward does this. If this slicing-procedure finds that the pulse has been cut in more than one area, the echo is defined as a multiple echo.

**Results**

The default SED parameter values recommended for the EY500 are -EL = 0.8, +EL = 1.2, MBC = 6 dB(two ways), MPD = 2 and SH = 1 peak. Figure 68, Figure 69, and Figure 70 shows the distributions of the echo lengths, the beam, compensation factors, and the phase deviations from horizontally recorded echoes. From these histograms it is clearly seen that a large proportion of the echoes will be rejected by the SED if the recommended parameters are applied. Table 17 gives the number of accepted echoes in the River Tana as a function of varying SED parameter setting. Figure 71 and Figure 72 compare rejection of echoes in vertical and horizontal applications as functions of increasing MBC and MPD criteria.

With the recommended parameter setting (Table 17 test 1h), a total of only 2% of the echoes from the River Tana were accepted. This explains our first experience with the fieldwork in this river. The MPD criterion gives the highest rejection rate (86% rejection) followed by the MBC criterion with 77% rejection. High rejection rates were also found with the -EL, the +EL, and the SH criteria.

The largest variation observed in the SED-criteria were: BC = [0..54], EL = [0.14..2.6], PD = [0..25] and SH = [1..3]. In the EY500, BC=12 (two ways), PD=10 and SH=1 are the maximum allowed criteria. The result of applying these maximum SED
criteria is seen in (Table 17 test 8h). The setting gives the highest acceptance rate possible with the EY500. As can be seen, 38% of the horizontally recorded fish-echoes are still rejected.

If similar SED parameter settings are applied to vertically recorded fish-echoes the results are different. With the default setting (Table 17 test 1v), 44% of the echoes are accepted and when the highest acceptance criteria are applied, 92% of the echoes are accepted. This is far more than with the horizontally recorded echoes. However, one might have expected even higher acceptance rates than those observed. Reasons for the relatively low acceptance rates are the BC parameter combined with the way the echoes have been detected. (See material and methods). When MBC was neglected, +EL, -EL and SH were kept as recommended and MPD set to 10, 100% of the vertically recorded echoes were accepted, while only 57% of the horizontally recorded echoes were accepted (Table 17 test 9 vh).

When testing whether it was the sAlo or the sAth that resulted in the rejection due to the MPD criteria, we found higher values in sAlo in 54% of the echoes from the horizontally recorded files. It was opposite in the vertical applications. Here only 11% of the sAlo measures gave higher values than the sAth. Data from a typical horizontally recorded fish-echo is seen in Table 18 and Figure 73. The along-ship angle samples take on variation of as much as 5.05 deg.

**Testing data from other rivers:** The sonar data recorded in the River Numedalslågen (southern Norway), the River Tornionjoki and the River Simojoki were checked in order to see whether the River Tana data differed from data recorded in other places and with other echo sounders. Tracks from fish were detected in these data and studied. The tendencies were the same for all detected tracks. Higher numbers of missing echoes in the tracks combined with high position variability among the actually detected echoes were observed (Figure 74).

**Discussion**

The basic differences between the horizontal shallow river and vertical open water application are the water current, the near bottom or surface alignment of the beam, the aspect of the fish and the general signal to noise level (SNR). Turbulent running water with thermal inhomogeneities can cause diffraction of the sound and result in multiple sound
paths. Multiple sound paths can also occur because a target re-radiates sound in many directions and the surface and bottom can reflect sound.

**Influence from the water current:** The water current might explain the observed increase in the phase deviation. Thermal inhomogeneities exist in the water and cause dispersion of the sound rays (Urich, 1983). Under the influence of turbulence, the dispersion will take on random shifts and multiple sound paths can occur. A difference of $x = d \sin(\Delta \alpha_0) = 1.2$ cm. in the travelled distance of the echo received at the two receiver elements is enough to cause the observed fluctuation seen in Table 18. (Assuming a transducer element displacement $d = 14$ cm). There are other ways that water current might influence the phase deviation. The transducer can vibrate in the current and the sound waves can drift along with the water. However, the effects from these phenomena are minimal and cannot explain the observed deviations. The transducer might vibrate as much as 1-2 deg. with a frequency of 10-20 Hz. This can result in erroneous in-between ping position estimates, but due to the short duration of the transmitted sound-pulse (0.3 ms) the vibration will not alter the angular position more than maximally 0.01 deg. With a water current of 0.5 ms$^{-1}$, a target range of 25 m and a sound velocity of 1500 ms$^{-1}$ the drift error will only be 1.6 cm sideways or 0.04 deg.

**Reflections from surface and bottom:** The observed position deviation during the echo in Table 18 and Figure 73 is 5 deg. along the vertical axis. With the target at a range of 24.5 m, 5 deg. corresponds to $y = 24.5m \cdot 2 \tan(\alpha_0/2) = 2.1m$ along the vertical axis. In this example, most samples are stable at a vertical position close to -1 deg. The dip that results in the high phase deviation goes down to -4 deg. At the same time the TS drops with 3-4 dB. This can indicate that sound might have been reflected from the bottom located at $y = 24.5m \cdot 2 \tan((4-1)^\circ/2) = 1.3m$ below the target. According to Figure 75, this reflection would come from a position outside the main –3 dB beam. A sandy bottom as found at the site in the River Tana is regarded as a good reflector, but at least we would have to expect a reflection damping of the signal of 4 dB or more (Urich, 1983). So if the deviation in the angular estimates should be explained as caused by one single reflection from the bottom alone, we should have observed a reduction in TS of 7 dB or more. This indicates that more than one phenomenon occurs at the same time and that the ray pattern in the river must be complex.

**The noise level:** If the noise level is high relative to the echo from the fish, additive and subtractive noise might blur the signal and cause elongation as well as truncation of
the echo pulse-length when measured at a fixed level below the peak. Figure 76 demonstrates this clearly with the 3D-pictures from fish-echoes in Tana and Semsvann.

**The fish aspect:** The cross-section area and the structure of a fish seen from the dorsal aspect are different than when seen from the side aspect. This might have an impact on the returned echo. To test this, data from carousel experiments were analysed. A 41 g roach was mounted with the side and the ventral aspects towards the transducer. We could not detect any differences between the echo-pulses returned from the two aspects from this fish. The situation might be different with a large salmon, however. We have observed that different types of targets result in different echo-signatures (Figure 77). A standard Cu-sphere builds up a characteristic "wall" of intensity before the actual target is detected and it continues to radiate sound with oscillating intensity some time after the sound-pulse has passed. Fish tracks from the River Tana are also often observed with a "tail" of sound after the pulse has passed. This tail might easily contribute to the measured echo length.

**Beam compensation:** One might consider whether the Max. Beam Comp. (MBC) is a single echo detection criterion or not. The uncertainty in the sonar estimates increases with increasing off axis position. By rejecting echoes far away from the acoustic axis, this uncertainty is avoided. MBC limitations also ensure a well-defined sample volume in accordance with the theoretical opening angle. However, in situations like the one in the River Tana, echoes from fish passing the transducer are observed "jumping in and out" of the well-defined beam. This results in unnecessary high numbers of missing echoes. Hence tracking becomes difficult.

### Suggestions

Single echo detection is a tempting analysis process in its simplicity and due to its high data compression capability. Single echo detection is also important in the process of gaining position estimates and accurate TS estimates. However, we have seen that echoes from fish in shallow rivers take on the characteristic of multiple echoes and that the traditional SED results in too high rejection rates.

To solve this problem we suggest a two step SED process. First echoes should be detected with echo length as the only criterion, accepting echoes up to 1.8 to 2.5 times the transmitting pulse. This ensures that we do not reject echoes from fish. This also increases the acceptance of noise-based echoes. In order to reduce these noise echoes we suggest
applying a low-pass filter before the actual SED. The output from this process will give a better basis for tracking than the traditional SED.

When the tracking and classification process hopefully has detected the tracks from fish and rejected other tracks, the second step of SED can be applied. Strict criteria now ensure that only the most accurate and well-defined single echoes are applied in the size estimates. We tested this method on some of the files from the River Tana. Figure 78 gives a demonstration of the results.

We also suggest a different method of calculating the angular position. Angular position is calculated as the mean value of the angular samples found within the received echo pulse-length. As seen from Figure 73, most samples take on stable values except for some few outliers. This situation was frequently observed and we would therefore suggest the application of algorithms like the $k$-nearest neighbours, median or sigma filters (Niblack, 1986). This has not been tested.

Conclusions

The reason as to why single echo detection in shallow rivers like the River Tana tend to fail is that echoes from fish have the characteristics of multiple echoes. High fluctuation in the phase estimates, high variations in echo lengths and multiple peaked echo-pulses are frequently observed. Applying traditional single echo detectors to such echoes does not work well, and can result in complete or partial rejection of the fish-echoes.

Acknowledgements

This work was supported in part by the County governor in Finnmark (northern Norway) represented by Kjell Moen, Simrad AS represented by Frank Reier Knudsen, and RKTL Finland. We thank Frank Reier Knudsen for help recording sonar data in the River Tana, Simrad AS, the County governor in Finnmark and RKTL for providing equipment and for providing sonar data from other rivers. Jan Kubecka and Jarka Frouzova from the Czech Republic provided us with the carousel data. Haakon Solli at Simrad assisted with information about the SED in the EY500.
References


### Tables

<table>
<thead>
<tr>
<th>SED criteria</th>
<th>Results in percent</th>
</tr>
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<tbody>
<tr>
<td>Test</td>
<td>MBC -EL +EL MPD SH</td>
</tr>
<tr>
<td>1 h</td>
<td>6 0.8 1.2 2 1</td>
</tr>
<tr>
<td>1 v</td>
<td>6 0.8 1.2 2 1</td>
</tr>
<tr>
<td>2 h</td>
<td>12 0.8 1.2 2 1</td>
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<tr>
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</tr>
<tr>
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<td>5 h</td>
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<td>9 v</td>
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<tr>
<td>Min. v</td>
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Table 17. Results of applying different values of the single echo detector criteria on the recorded fish-echoes. The "test" column indicates the test number. Here v denotes vertical and h denotes horizontal. MBC = Max. Beam Comp., -EL = Min. Echo Length, +EL = Max. Echo Length, MPD = Max. Phase Dev., SH = shape. The lower last rows display minimum and maximum observed values.
<table>
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<th>TS (dB)</th>
<th>Alo(deg)</th>
<th>Ath (deg)</th>
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<td>825</td>
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<td>-1.83</td>
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</table>

mean= -1.26  stddev= 1.03  Max.= 1.08  Min.= -3.97  Diff.= 5.05

Table 18 Typical echo recorded in the River Tana 19.07.99 17:06. Ping 230. For this echo the echo length was measured to 1.9 while the phase deviation was measured to 10.26.
Figures

Figure 67. Definition of an echo-pulse. a) peak TS.  b) A threshold is set 6 dB below the peak TS.  c) Pulse start is defined as the first sample after the threshold is passed with raising intensity.  d) Pulse stop is defined as the first pulse after the –6 dB threshold is passed with falling intensity.  e) Pulse width = Pulse stop - pulse start. (Here 7 = 10 - 3.)

Figure 68. Frequency distributions of echo length beam for 756 echoes horizontally recorded in the River Tana.
Figure 69. Frequency distributions of beam compensation factors for 756 echoes horizontally recorded in the River Tana.

Figure 70. Frequency distributions of phase deviation for 756 echoes horizontally recorded in the River Tana.

Figure 71. Number of accepted echoes due to changes in the Max. Beam Comp. criterion.
Figure 72. Number of accepted echoes due to changes in the Max. Phase Dev. criterion.

Figure 73. Angular position of all samples within an echo from a fish in the River Tana. Note the dip in Alo seen at sample 821. This dip is also seen in the target strength samples. Data for this graph is given by Table 18.

Figure 74. Angular position diagram from Sonar5. Left: Upstream migrating fish in the River Tana. Right: Fish passing the beam in Lake Semsvann. Note the smoothness of the tracks.
Figure 75. Multiple-path caused by reflections from the bottom.

Figure 76. Differences between vertically and horizontally recorded fish. Upper: Large fish passing the beam in the River Tana. Lower: Small fish entering the beam in Lake Semsvann. (3D-echograms from Sonar5)

Figure 77. Echo-signature from left: Cu-sphere, centre: vertically recorded fish in Lake Semsvann, right: horizontally recorded fish in the River Tana.
Figure 78. Testing single echo detectors on and echograms with echoes from an upstream migrating fish, scattered noise and lines of echoes from bottom. Left: SED with the most accepting criteria in EY500. Centre: removing all criteria except Echo length. (-EL = 0.4, +EL = 1.8) Right: applying a low-pass filter before applying SED from the centre echogram.
14 Paper IV

Development of a new single echo detector suited for fish detection in shallow rivers

Abstract

Analysing sonar data recorded with horizontally aligned transducers in shallow rivers has been recognised as difficult. With the commonly applied analysis method based on single echo detection and tracking, the single echo detector is recognised as the bottleneck. The detector tends to reject echoes from fish and to accept noise echoes. A new detector algorithm is designed and tested \textit{in situ} on recorded sonar data. Major improvement in detection probability and in noise suppression is demonstrated.

Keywords

Hydroacoustic, sonar, rivers, single echo detection, SED, tracking, split-beam.
Development of a new single echo detector suited for fish detection in shallow rivers

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Introduction

Sonars equipped with side-looking split-beam transducers are frequently applied in enumeration of migrating fish in rivers. (Ransom and Johnston, 1998), (Enzenhofer et al., 1998). A common method for analysing the resulting sonar data is the single echo detection and tracking method (STM) (Xie et al., 1997). STM was originally designed for open water applications. In commercially available equipment like the Simrad EY500 and EK500, the built-in single echo detector (SED) has been optimised to detect echoes from the fish dorsal aspect in low noise environments (Soule et al., 1995, 1996, 1997). Strict criteria are applied in order to gain high accuracy in the estimates of the position and target strength. However, when fish are monitored with side-looking sonar in a riverine environment, problems occur. Echoes from fish are frequently rejected in the SED while unwanted echoes from debris, stones and fluctuations in the background reverberation level often are accepted. This was clearly seen when analysis results from four rivers and three lakes were compared (Balk and Lindem, 2001a). Missing echoes in tracks from fish combined with frequent detection of unwanted noise made tracking difficult. With automatic tracking, tracks from fish were frequently split, not detected, combined with noise echoes or formed from noise alone. This could result in overestimates of fish in the order of up to 1:100 (Balk and Lindem, 2001e). The reason to why fish echoes from the rivers are rejected by the SED is that the echoes take on similarities with multiple echoes (Balk and Lindem, 2001c) such as multiple peaks and high variations in echo length (EL),
target strength, phase deviation, and off axis position. In order to adapt the STM to shallow rivers, the SED's ability to accept echoes from fish and to reject echoes from noise has to be improved.

**Traditional single echo detection**

A reason as to why a single echo detector is applied is that the sonar is not capable of detecting the angular position of more than one target (single target) at the same range. With two or more targets in the same distance from the transducer, interference from the two echoes will disable the phase algorithm from detecting the correct angular locations. The necessary target separation along the range domain is mainly defined by the duration of the transmitted pulse-length. If the sonar is still receiving the echo from one target when the echo from the next target arrives, the sonar will just observe one elongated echo. This echo may have two peaks and it may have a shift in position. It is therefore natural to apply the echo's length, shape and standard deviation in the position estimate as criteria for the single echo detector.

With a digitised echo-signal, these features are calculated from the sampled echo power and angles. Figure 79 demonstrates the echo definition applied by Simrad's EY500. In the EY500 the sample frequency is adjusted according to the sound speed so that each sample covers 3 cm of water along the range axis. Starting at the transceiver, peaks are searched for in the received signal. The first sample with a lower intensity at each side is noted as a peak, and a -6 dB threshold from this peak is applied to define the echo. To the left of the peak, the front edge of the first sample above the threshold denotes the echo start. To the right of the peak, the edge of the first sample below the threshold denotes the end of the echo. The echo range and the EL are determined from these points. The SED compares this EL with the transmitted pulse-length (PL). If the EL/PL ratio exceeds the user-defined limits, the echo is rejected as a multiple echo. Echo from single fish recorded in vertical applications will normally have EL/PL ratios between 0.8 and 1.2. With EY500's short pulse (0.1 ms), about 2 - 3 samples are received from a fish while the medium pulse (0.3 ms) results in single fish-echoes containing 7 - 8 samples.

Slicing the echo in 1.5 dB slices tests for multiple peaks. If a slice cuts the echo more than twice, the echo is said to be multiple peaked and thus rejected by the SED.

Each sample from the EY500 contains not only range and intensity estimates, but also the samples angular position. Standard deviation is calculated from the samples for the
two angular axes and the largest result is compared with a user-defined value called Max. Phase Dev. (MPD). Exceeding this value results in echo rejection. If not, the echoes’ angular positions are calculated as the mean sample value. MPD operates on electrical degrees measured as a number of phase steps. Equation (1) demonstrates the conversion between EY500’s internal angular format (phase step) and the mechanical angles. The conversion involves a transducer-specific angle sensitivity parameter, which gives the relationship between the transducers electrical and mechanical degrees.

\[
\text{Angle}_{\text{Mec}} = \frac{1}{e-d} \sum_{i=d}^{e} \text{PhaseStep}_i \cdot \frac{180}{64} \frac{1}{\text{AngleSensitivity}}
\]  

(1)

Here, \(d\) is the first sample while \(e\) is the last sample in an echo-pulse defined as a single echo, \(i\) the sample index, and \(\text{AngleSensitivity}\) the transducers electric to mechanical stiffness factor.

Two other SED-criteria are applied in the EY500. These are the angular limitation and the intensity criteria. The accuracy of the sonar’s ability to estimate position and intensity is reduced with increasing off-axis position. Echoes with high off-axis values are therefore rejected by the SED. Rejection is determined by comparing the user defined value in the Max. Beam Comp. (MBC) parameter with the calculated beam compensation factor (BC). The highest allowed MBC value in the EY500 is 6 dB. This is the one-way compensation.

\[
\begin{align*}
BC &= 2 \cdot 3.01 \left( a^2 + b^2 + 0.18 \cdot a^2 \cdot b^2 \right) \\
\frac{a}{\text{AthBeamWidth} / 2} &= \frac{Alo - AloOffset}{AloBeamWidth} \\
\frac{b}{\text{AthBeamWidth} / 2} &= \frac{Ath - AthOffset}{\text{AthBeamWidth}}
\end{align*}
\]

(2)

The above equation demonstrates calculation of BC, which is applied in compensating the target strength and the threshold criteria. The AloBeamWidth and the AthBeamWidth parameters denote the transducer’s –3 dB opening angle in the along-ship
(Alo) and the athwart-ship (Ath) direction. The names refer to a vertically mounted transducer on a ship.

The threshold parameter defines the smallest fish that can be detected and it separates fish-echoes from noise. The EY500 uses the SED parameter Min. Value (MV) to indicate that it is the minimum fish value and not the intensity threshold that forms the criterion. This ensures that if the operator has decided that the smallest detectable fish is a -42 dB fish, this will hold not only on the acoustic axis, but also at any at off-axis position. The relationship between threshold and MV is seen in equation (3). The EY500's SED are further explained in (Anon 1996).

\[ \text{Threshold} = \text{MV} - 6 - 2 \cdot BC \quad (3) \]

### Tracking

Tracking is the process that combines all echoes believed to originate from one and the same object passing the beam. This is important in order to enumerate fish correctly. It is also recognised that tracking improves the accuracy of the size distribution estimates (Ehrenberg and Torkelson, 1996). Tracking echoes detected by a single echo detector is based on a process that search for closely positioned echoes following a predicted trajectory. If echoes are missing along this course, the tracker might loose the track, define it as noise or combine it with echoes from another nearby track or from noise. It is therefore essential to detect as many echoes from a passing fish as possible and to avoid disturbing noise echoes. Tracking is described in (Blackman, 1986), (Xie, 2000) and (Balk and Lindem, 2001a).

### Material and methods

High-resolution test-data with echoes from fish and from artificial targets was recorded and analysed. Fish-echoes were recorded vertically on the ice of Lake Semsvann (southern Norway) winter 1999 and horizontally in the River Tana (northern Norway) in the summer of 1999. Echoes from fish mounted on a carousel and from artificial targets were recorded in the Rimov pond in the Czech Republic spring 2000.

The scientific echo sounder EY500 (Anon 1996) from Simrad AS recorded the data. The echo sounder was equipped with a 120 kHz, 4x10 deg. split-beam transducer. High range resolution was gained by storing the raw data. With the EY500, raw data are
stored in binary format as sample-power and sample-angle telegrams. Each telegram set contains the samples from one ping. The sample frequency in the EY500 is adjusted according to the sound speed so that each stored sample represents the echo intensity received from a 3 cm range bin of water. Raw data can be reprocessed by the EY500. This allows the SED-parameters to be altered later.

The sonar post-processing program 

Sonar5

was applied in the data analysis. 

Sonar5

has been developed at the University of Oslo in order to study data from commercially available echo sounders. 

Sonar5

has tools for visualising sonar data, for manual and automatic tracking and tools for analysing Amp-echograms and raw data. From raw data recorded by EY500, Amp-echograms with resolution down to 3 cm can be extracted.

Echoes from fish were first analysed by the 

Sonar5's raw data analyser to find optimal SED-criteria. These criteria were applied to the EY500's SED and the recorded data was replayed. The resulting echograms were used as references when testing new SED methods.

Two quantitative measures were defined to do the comparing. This was the track signal to noise ratio (TSNR), and the detection probability. TSNR was defined as the ratio between the number of SED-echoes in the tracks and the total number of SED-echoes on the echogram file. By normalising TSNR with the total number of ping (P) and the total number of fish tracks (F), this measure can compare echograms from different recordings. DP was defined as the ratio between the number of fish-echoes detected by the SED to the number of fish-echoes seen to exceed 6 dB above the background noise level on the Amp-echogram.

\[
\text{DP} = \frac{\sum_{i=1}^{F} (\text{SED-echoes in track}_i)}{\sum_{i=1}^{F} (\text{Amp-echoes in track}_i)} \quad (4)
\]

\[
\text{TSNR} = \frac{10000 \cdot \sum_{i=1}^{F} (\text{echoes in track}_i)}{P \cdot F \cdot \sum_{j=1}^{P} (\text{echoes in ping}_j)} \quad (5)
\]
Improving the SED

In the article (Balk and Lindem, 2001 c), rejection of echoes from fish was located to the strictness of the SED-criteria. Increased acceptance of fish-echo can thereby be gained by simply reducing this strictness. High uncertainty in the angular position estimates from fish-echoes resulted in frequent rejections by the SED's MBC and MPD parameter. These criteria were therefore removed. Two other criteria seen to cause fish-echo rejections were the MV and the shape criteria. Multiple peaks and ping to ping variations in the echo intensity caused the rejections, and both criteria were removed. This leaves the EL as the only remaining SED-criterion suited for river applications. Further, the strictness of this criterion has to be reduced to accept fish-echoes in rivers. In (Balk and Lindem, 2001 c) it was demonstrated that all echoes from vertically irradiated fish took on EL from 0.8 to 1.2 times the transmitted pulse. To gain the same acceptance of fish-echoes from rivers, the EL criterion had to accept pulses from 0.2 to 2.4.

The strictness of the EY500's SED-detection criteria cannot be reduced beyond certain values, and an SED algorithm based on EL as the only criterion could not be tested using this echo sounder. An alternative SED was therefore implemented in the Sonar5's source code. Detection by EL as the only criterion was seen to improve the DP relative to the results from the EY500's detector. However, the TSNR was reduced to an extent that made the method nearly useless (Figure 80).

In order to improve the TSNR, unwanted detection had to be removed. Two methods were tested. a) Filter techniques removing unwanted SED-detection on the SED-echogram and b) filter techniques removing high frequency components on the Amp-echogram before performing the SED.

By regarding the echogram as a two-dimensional sampled array, filtering can be applied by means of convolution. The original echogram is convolved with a filter array containing selected filter coefficients (Pratt, 1991). In the convolution equation, (equation \(6\)), \(Q(m_1, m_2)\) represents one sample in the resulting echogram while \(F(n_1, n_2)\) represents the sample at the row/column position \((m_1,m_2)\) in the original echogram. \(H\) is the filter array. The filter size is given by the number of rows (r) and columns (c). A filter size covering 11 rows and 3 columns is denoted 11x3. A filter with this size will cover 11 samples and 3 ping on the echogram. The effect of a 11x3 mean filter is seen in Figure 83.
\[ Q(m_1, m_2) = \sum_{n_1=-c/2}^{c/2} \sum_{n_2=-c/2}^{c/2} F(n_1, n_2) H(m_1 - n_1 + 1, m_2 - n_2) \] (6)

In (Balk and Lindem, 2001 b), four categories of echoes were identified on SED-echograms recorded in rivers. These were short-lived tracks from upstream and downstream moving targets, horizontal lines of echoes from time and range stationary targets like rocks or bottom reflections, and scattered noise echoes from fluctuations in the background reverberation level, air-bubbles, surface waves etc. Upstream moving targets mostly represent fish while downstream moving targets can be fish or other objects like debris. Separating fish and debris has not been a subject in this article.

In order to remove the scattered SED-echoes, morphological filters were tested. These filters use masks to identify echo patterns. Patterns recognised by a mask can be removed or transformed. Masks with different patterns and sizes were tested. A 3x3 dimensional mask with a 1 in the centre and 0 elsewhere was found capable of removing stand-alone scattered echoes (noise spikes). However, scattered noise was frequently observed with 2 or 3 successive echo detections in the range domain and an assortment of masks had to be defined to gain any notable effect. In many cases, fish-echoes were also removed and the method was therefore not found to be well suited.

In order to remove SED-echoes from stones and bottom reflections, histogram methods were tested. Frequency distributions of each range-bin defined by the sample interval were made. Bottom echoes seen as long horizontal lines on the SED-echograms resulted in high peaks in the frequency distributions. By detecting these peaks and removing all echoes related to them, a great portion of the unwanted echoes could be removed. It was difficult to find methods that automatically detected the correct peaks in the histograms, however. One reason for this was that the reflections where seen to produce semi-stationary lines of echoes. Shift in echo intensity, missing detection for some periods of time, and shift in range easily disturbed the detection of these echoes.

Better results were gained by applying low-pass filters to the Amp-echogram before performing the SED. Two low-pass filters, the median and the mean filters were tested. Mean filters were found to give the best result. Short-lived transients in the signal could be removed while echoes from fish remained. The filters were seen not only to remove noise, but also to improve the detection probability for fish.
This can be explained by the two-dimensional filter, smoothing ping-to-ping variations in the EL and in the echo amplitude. The combination of low-pass filtering with an SED, based on echo length, was found capable of reducing the number of unwanted noise echoes. At the same time, this improved the detection probability of fish relative to the reference result from the EY500's SED. For simplicity, the new SED-detector will be referred to as the filter echo length detector (FED).

Test results

The method was tested on recorded fish-echoes and on the echoes from the artificial targets. To measure the influence of the parameters on the FED a distinct fish track in data from the River Tana was selected (Figure 81). This fish was observed Sunday evening the 19 July 1999 at 7:46 pm. It was measured with TS = −22.19 dB, range = 22.4 m and velocity towards the current = 0.49 ms⁻¹. The track could be seen with 50 echoes on the Amp-echogram. Raw data analysis showed that suitable EY500-SED parameters were: MV = −45 dB, EL = [0.5..2.5], MBC = 6 and MPD = 10. The sonar file was replayed by the EY500 with these parameters. 100 ping from the resulting echogram containing the fish-echoes was stored as a separate echogram and reference TSNR and DP were calculated. Sonar5's FED processed this echogram repeatedly with varying parameters and stored the result on disk. The results were tracked manually. TSNR and DP were calculated and divided by the reference values. Results from this process are given in Table 19 and Table 20. Selected TSNR curves are seen in Figure 84.

From the tables, it is clearly seen that certain FED-parameter value results in echograms with higher quality than the reference echogram. This is marked with shaded cells in the tables. Increasing values in the maximum EL parameter is seen to improve the DP, but to reduce the TSNR. Increasing filter size is seen to give the opposite effect. Finding the optimal balance between TSNR and DP will depend on the applied tracker. An echogram with low DP, but with nearly none unwanted echo detection might give good results with one tracker while higher DP with more noise might suite another.

To test the method on other fish tracks, all the high-resolution data from the River Tana was manually tracked. 22 fishes were detected and the above described test procedure was performed for each track with one fixed FED parameter setting. (Filter size=13x3 EL 0.5..1.7). The result is given in Table 21. An overall mean DP-ratio of 1.2 and a TSNR-
ratio of 36 indicates that the FED is better suited to detect fish-echoes in the River Tana than the reference SED.

In order to test the FED in other situations, the method was tested on fish recorded vertically on the ice of Lake Semsvann and on echoes from a fish mounted on a carousel. Echoes from standard targets were tested as well. The Lake Semsvann recording contained traces of fish entering and leaving the beam. Echoes from the fish were frequently rejected by the EY500's SED as a result of high off-axis target positions and low intensity. Without being troubled with these criteria, the FED method naturally detected more echoes from the fish. This made it easier to track the fish movement in the beam. Due to the filtering, no disturbing SED-detection was obtained from the background reverberation.

In a pond at Rimov in the Czech Republic, a 41 g anaesthetised roach was mounted in a carousel with the side aspect towards a side-looking transducer. The pond measured 13x16x1.5 m. The carousel's mounting frame had a distance of 5.4 m. Monofilament fishing line was used for the mounting. Echograms resulting from the EY500's SED and from the FED are seen in Figure 85. Clear improvements in the DP and in the reductions of disturbing echoes can be seen on the echogram from the FED.

Two standard Cu-spheres (23.0 mm, 120 kHz, $-40.3 \text{ dB}$) were mounted on the acoustic axis at a range of 7.8 m from a horizontally mounted transducer in the pond. One of the targets was moved slowly towards the transducer. Interference and twin-peaked echoes disturbed the SED until the targets were well separated. By tuning the FED parameters it was possible to gain echograms with higher detection probability and lower noise than seen with the EY500's SED (Figure 86).

The Cu-spheres were recorded with two different transmitted pulse-lengths 0.1 ms and 0.3 ms. A clear relationship between transmitted pulse-length and filter range dimension was observed. The results given in Table 19 and Table 20 are therefore only valid for situations recorded with a transmitted pulse-length of 0.3 ms and sampled with 3 cm intervals.

**Discussion**

An important aspect, not tested, is the extraction of the angular estimates. In the EY500, taking the mean value of all angle samples returned within the defined echo-pulse does this. Due to the high variation in the ping to ping angular estimate often seen in river acoustics, alternative algorithms like selection of the centre sample, removal of outliers,
the $k$-nearest neighbour ($KNN$) or median should be tested. This also applies to the extraction of the echo intensity from a tracked fish.

The filter process changes the intensity of the resulting echo detection and the originally recorded intensity should therefore be looked up afterwards. Further, it has not been tested whether the variation in the intensity and in the angular estimates increase with the new detector. If so, this can be solved by applying two detectors as demonstrated in Figure 87. The developed FED-detector will locate the fish-echoes in order to gain better tracking possibilities. From the detected echoes, a second and strict SED-detector can select the echoes providing the highest TS and position accuracy. Instead of applying all echoes from a fish, only these echoes can be used in the calculation of statistics.

Because the threshold criterion is removed from in the FED, a relation between the fish size and range can occur in the resulting statistics. At short range where the signal to noise ratio is best, smaller fish can be detected than at other ranges. To avoid this bias, a threshold should be applied to the tracked fish instead. With the high variation in the ping to ping echo intensity observed in rivers, this might prove to be a better solution than to threshold the echoes before tracking.

**Conclusions**

The aim of this study has been to develop an alternative SED-detector suited for river applications. A solution was found by removing all the SED-criteria except for minimum and maximum the echo length criteria. This improved the detection probability. Applying a two dimensional digital low-pass filter before the detector was seen to of reduce the number of unwanted noise detections and to improve the detection probability.

A balance between noise and detection probability existed. This balance was influenced by the selected parameters. Optimal choice of parameters has to be made in accordance with the features of the selected tracker.

The results achieved in the tests have been promising. However, due to the amount of data produced when recording high-resolution raw data, the test material has been limited and more tests should be applied before accepting the method in riverine acoustics.
Acknowledgements

We thank Simrad AS, the County governor in Finnmark represented by Kjell Moen and the Finnish Game and Fisheries Research Institute (RKTL) for supporting the recording if the sonar data in the River Tana. Support was given by means of funds, equipment and labour. Frank R. Knudsen from Simrad assisted in the recording of the data in the River Tana and on the ice of Lake Semsvann. Haakon Solli from Simrad provided information about the EY500's SED not described in the manual. We also thank Jan Kubecaka and Jarka Froutzova (Cz) for providing equipment and for assistance with the recordings in the Rimov pond. Jarka Froutzova provided the "fish in carousel" data.

References


(Balk and Lindem, 2001c) Balk H., Lindem. T., 2001c. Investigating why single echo detectors tend to reject echoes from fish in shallow water. (In press)


Table 19. Ratio between TSNR measured from a fish detected by the FED with varying maximum EL and filter size parameters and the TSNR measured from the fish detected by the reference SED. Shaded values indicate situations where both the TSNR and the DP from the FED resulted in higher values than the reference SED.

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Table 20. Ratio between DP measured from a fish detected by the FED with varying maximum EL and filter size parameters and the DP measured from the fish detected by the reference SED. Shaded values indicate situations where both the TSNR and the DP from the FED resulted in higher values than the reference SED.

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Table 21. FED-detection results from 22 fish tracks detected in the River Tana. The applied FED parameters were filter size = 13x3 and EL = [0.5..1.7]. TSNR and DP-ratios are calculated with the FED result in the numerator so that values >1 is in favour of the FED method. Speed indicates the swimming speed against the water current. NrAE is the number of fish-echoes visible on the Amp-echogram.
Figures

Figure 79. Range/intensity diagram demonstrating the definition of a sampled multiple echo.

Figure 80. Single echo detection based on $EL=[0.2..2.4]$ as the only criterion.
Figure 81. A fish observed in the River Tana summer 1999. Left: Amp-echogram. Centre: SED-echogram produced by EY500’ internal SED. Right: Amp-echogram processed by the FED with filter size =11x3 and EL = [0.8..1.6]. (In the FED-processed SED-echogram, ping 51 relates to ping 2042 due to the extracting process).

Figure 82. 3D-echogram showing echoes from a fish sampled with 3 cm range resolution.
Figure 83. The result of filtering the echogram in Figure 82 with a 11x3 mean filter.

Figure 84. TSNR-ratios obtained by the FED and the reference SED method as a function of filter size and maximum EL. Values above 1 indicate improved TSNR results from the FED relative to the reference SED.
Figure 85. Side aspect of a rotating roach weighting 41 g. Left: SED-detection by EY500's SED with parameters $MV=-60$ dB, $EL=[0.5..1.5]$, MBC=3 and MPD=6. Right: Detection by the FED with filter size=9x5 and $EL=[0.5..1.5]$. Echoes from the carousel frame are seen as half-arcs when the fish approaches the head/tail aspect.

Figure 86. Echoes from two Cu-spheres slowly mowed away from each other along the sonar's acoustic axis. Left: SED-echogram processed by the EY500's SED. Right: SED-echogram processed with the FED. (Filter size = 11x5, $EL=[0.5..1.5]$)

Figure 87. Analysis method based on two SED-detectors. The FED-detects the fish-echoes while the strict SED selects the detected fish-echoes that is best suited for statistics.
15 Paper V

Improved single fish detection in data from split-beam sonar

Abstract

Hydroacoustic split-beam techniques have been applied to enumerate salmon migrating in the River Tana in northern Norway in the summers of 1998 and 1999. Analysing data by single echo detection and tracking was found difficult. Missing echoes in tracks from fish combined with noise in the output from the single echo detector was seen as reasons for this. An improved counting method is presented. Contours from moving targets are detected by image analysis. Then detected single echoes within these contours are combined into tracks. This procedure reduces problems related to noise and problems related to tracking fish with few accepted single echoes.

Keywords

Horizontally scanning sonar, split-beam, automatic tracking, neighbourhood tracking, fish detection, image analysis, single echo detection.
Improved single fish detection in data from split-beam sonar

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Introduction

Hydroacoustic split-beam techniques have been applied to enumerate adult Atlantic salmon (Salmo Salar) migrating in the River Tana in northern Norway in the summers 1998 and 1999. Data from the fixed, horizontally aligned transducer were analysed by single echo detection (SED) and tracking (Xie, Cronkite and Mulligan, 1997). Analysing data with this method proved more difficult than expected.

Two reasons for this were missing detection of echoes from fish and uncertainty in position estimates in echoes accepted by the SED. Another reason was noise. The SED accepted echoes from unwanted targets and from variations in the background reverberation level. Other scientists have reported similar problems. Noise from surface, bottom, and background reverberation has been treated by Kubecka, (1994). At the Riverine Sonar Workshop in Seattle Feb 15-17, Dawson et al., (1999) discussed variability in the split-beam angular measurements. Figure 88 and Figure 89 demonstrate differences between echo-signals from fish recorded in a lake and in a river. Figure 92a. demonstrates missing detection of fish by the SED.

The automatic tracking algorithm tended to generate fish-like tracks from noise echoes and to split tracks from fish. This resulted in overestimates. With manual analysis, SED-echoes are combined into tracks and counted by a person. This method was found labour intensive and subjective. It was difficult to detect echoes from fish when these were surrounded by noise, and different persons tracking the same data tended to get different results. Improving the automatic analysis method was seen as essential for further applications of hydroacoustics in the River Tana.
The split-beam transducer is composed of four separate units. These units are arranged geometrically so that both intensity and angles can be detected from the received echo-signal (Brede et al., 1990). The amplitude of the echo-signal from successive sound transmissions (pings) can be displayed in time/range diagrams (echograms). In order to detect echoes from single fish, a SED is often applied. Echo-pulses accepted by the SED are described with amplitude, time, and angular position. Such echoes can be displayed in echograms and position diagrams. In order to distinguish between the two types of echograms, SED and Amp will be used as prefix.

With split-beam echo sounders, a commonly used single fish analysing method is the method based on SED and neighbourhood tracking (Anon, 1999). The SED uses a set of criteria such as pulse-length and pulse-shape to decide whether a pulse originates from a single or a multiple-target. A fish passing the sonar will be hit by successive sound-pulses, resulting in a trace of echoes on the echogram. These echoes will be located close in time and position. Combining echoes based on such closeness is commonly called neighbourhood tracking or window tracking (Anon, 1999).

Image analysis is a field that has grown considerably during the past decade. Image processing has found a significant role in scientific, industrial, biomedical, and space applications (Pratt, 1991). In the field of hydroacoustics, image processing has been applied in ocean fisheries for detection and classification of fish schools (Lu and Lee 1995). In this paper, image analysis is applied to detect moving single targets that pass side-looking sonars in shallow rivers. This is done stepwise by a series of image enhancement and segmentation operators (Niblack, 1986).

**Materials and methods**

Test data has been recorded by an EY500 scientific echo sounder from Simrad AS. The main set of data was recorded in the River Tana northern Norway summer 1999. Here an ES120-4 split-beam transducer was mounted horizontally on a tripod equipped with a pan/tilt rotor. The rotor was built for this purpose at the University of Oslo. The tripod was placed 30 m from the west riverbank at a water depth of 2.8 m with the transducer 1.3 m above the bottom. The transducer was tilted 2 deg. down. On the selected site, the river was 257 m wide and had a sandy bottom with few stones. The bottom inclined smoothly within the transducer range from 2.8 m to 4.3 m within the 50 m range of the beam. The pan was adjusted so that the beam was pointing normal to the water current, which had a
measured speed of 0.19 ms\(^{-1}\). Ping rate was set to 5 ping per sec. The Amp-echogram resolution in the range domain was 9 cm. Video recordings show that nearly all upstream migrating fish were salmonids, mostly Atlantic salmon mixed with some trout.

Vertical sonar recordings were taken on the ice of the Lake Semsvannet (southern Norway) spring 1999 and used to compare signal and background noise levels (Figure 88). In order to get a broader test basis, data collected by other scientists was applied. Two vertically recorded files, one from Lake d’Annecy in France and one from a reservoir in the Czech Republic were selected. So was a horizontally recorded file from the River Numedalslågen in southern Norway.

A software program, "Sonar5" was developed with Borland's Delphi/Pascal compiler (Miller et al., 1997). Interactive and automatic methods for studying and tracking split-beam data were implemented.

### Single echo detection (SED)

The SED applied in these tests is the detector included in the EY500. The SED parameters used in the River Tana were: Min. Value = −40 dB, Min. Echo Length = 0.6, Max. Echo Length = 2.8, Max. Beam Comp. = 6, Max. Phase Dev. = 10, and one single peak. Transmitted echo length is 0.3 ms. The echo length values are given relative to the transmitted pulse-length. The echo length is measured at a 6 dB level below the maximum peak of a pulse. A single peaked echo is defined as an echo-pulse with no local minimum lower than 1.5 dB relative to the surroundings. The Max. Phase Dev. parameter relates to standard deviation in the electrical sample angles by a factor of 180/64.

### Neighbourhood tracking

The applied neighbourhood tracking algorithm worked like this: All SED-echoes found in the first ping were established as new tracks and noted in a list. Then a range of +/- 20 cm (neighbourhood) relative to the position of the last stored echoes was searched in the next ping. The closest echo found in this neighbourhood was added to the track in the list. If one echo was found within the neighbourhood of two different tracks, the echo was given to the closest track. Echoes not found within any neighbourhood were added to the list as new tracks. If no echoes were found within 6 following pings (max ping-gap) after the last echo in a track, this track was defined as completed. Tracks with less than 4 echoes (min track-length) were discarded as noise. These tracking parameters were found by studying the manually detected fish tracks from the test data. More sophisticated
algorithms applying angular positions, varying the neighbour region with missing ping and estimating expected positions for new echoes were tested. With low SNR, these algorithms did not track substantially different from the selected algorithm. It was therefore decided to apply the simplest method.

Developing a new counting method

In order to develop an automatic counting method suited for shallow rivers, the collected sonar data was studied. Amp and SED-echograms were compared. Two important observations were made.

1) The SED removes information from the sonar data. Background reverberation, bottom and multiple echoes are removed. With the EY500, also the width and shape of accepted single echoes are removed. By comparing Amp and SED-echograms from shallow rivers we found that it normally was easier to track fish on the Amp-echogram. Here fish tracks did not suffer from holes or ping-gaps due to missing detection in the SED. Noise pulses were found less disturbing to the human eye. Echoes from unwanted targets like stones and boat wakes could easily be identified when the complete echo-signal was available and not only limited to pulses accepted by the SED.

2) The second observation was that the horizontally recorded echo-signal could be divided into three main groups. Each group appearing with significantly different intensity/shape signatures. These groups were a) echoes from passing objects, b) echoes from stationary phenomena and c) echoes from stochastic noise.

Echoes from passing objects could be seen as short tracks in the time domain, often with characteristic changes in range related to the geometry of the beam. Stationary phenomena generated thin horizontal lines on the Amp-echogram. These lines changed with changing transducer tilt and were believed to originate from bottom reflections. The last group is seen as clouds of scattered noise pulses. The number of these pulses increased during periods of rain and wind and they where more frequent at longer ranges. Sources might be air bubbles, reflections from the surface or sound generated directly in the river. It is reasonable to assume that only fish should be associated with the first group and it is therefore not important to find the causes for the echoes in the two latter groups. Examples of all three echo groups can be seen in Figure 92 a, b.

The first observation suggests that the Amp-echograms should be applied in the analysis. The second observation indicates that it could be worth trying to detect echoes
from the first group and to suppress echoes from the other two. Regarding the Amp-echogram as an image, techniques from the field of image processing can be applied. Filter operators and segmentation algorithms was implemented in the Sonar5 program and tested against the recorded Amp-echograms. A combination of routines capable of detecting the perimeter of passing targets was found by repeated tests.

A SED was applied to find the movement of the detected targets. Angle data from accepted single echoes within the detected regions were then used to calculate direction and speed. Targets seen with upstream movement were counted as fish.

Results

Two basically different image analysing methods were tested, the edge method and the level method. With the edge method, the echograms are treated with high-pass filters. Applying these filters detect changes in the intensity. With low fluctuations in the background level and in the inner parts of the objects, the bounds of the object should be detected. We found that the general level of fluctuations in the sonar data was too high for this type of operators. Most high-pass filters produced echograms that could not be read with the human eye. One exception was the gradient filter that managed to highlight some tracks (Table 22).

Level based segmentation methods seemed to work better. This method uses low-pass filters and threshold techniques to separate tracks from the background noise level. The dimension of the filters was found to be important. In the test data, most tracks from passing objects were observed with more or less horizontal orientation. Using a wide, but short filter (e.g., 7 ping x 3 sample) on these tracks removed noise without removing tracks (Figure 90). Using a narrow, but tall filter (e.g., 1 ping x 15 sample) was seen to remove both noise and tracks.

The noise level in the test data varied strongly with time and range. The application of a constant threshold level did not manage to separate tracks from the background noise level. An adaptive threshold method measuring the noise level locally and adjusting the threshold according to the changing background noise was found to work quite well. Regions with intensity 6 dB above the surroundings were found in this way (Figure 91). Most of the resulting regions proved to contain echoes from moving and static objects, but some regions with scattered noise were also detected.
Analysing the shape of these objects revealed differences between the groups. Regions with noise were found to have shorter perimeter, smaller areas and larger height/width ratios than the two other groups. Static objects were seen with longer perimeters than moving objects. The application of a filter removing regions having short or long perimeters was seen to differentiate the three echo classes well. Perimeter is here measured as the number of samples found along the border of a detected region. The meaning of long and short varies depending on the range and time resolution on the echograms and on the average transit time for passing objects. Moving objects in our data were well detected with perimeter lengths between 20 and 500 samples.

Cracks in the detected regions were a problem, but the application of a growing operator, i.e., increasing the size of each region, proved to close most of the observed cracks. A similar effect was seen with low-pass filters.

Qualitative evaluation of the responses from the tested image operators on echograms is given in Table 22 while Figure 92 demonstrates detection of a fish surrounded with scattered noise and echoes from bottom structures. In this example both a mean and a median filter was applied in different stages of the process. Generally, the following set of operations was found to work well with the recorded sonar data. a) Low-pass mean filter with dimension 1 x 3, b) adaptive threshold, c) perimeter filter accepting perimeters between 20 and 500 samples, and d) growing operator increasing regions horizontally with 6 ping and vertically by 2 samples. Combined with SED and movement calculations, this set of operators was applied to count fish in the collected sonar files. The steps in this procedure are demonstrated in Figure 92. Manual count was applied as reference for the "true" number of detectable fish. The files were also analysed by the SED/neighbourhood method to show the performance relative to the manual and the image method. Count results are shown in Table 23.

Manual count resulted in 198 fish tracks. The result from the image count was 210 fish and the neighbourhood method detected 6743 tracks. Relative to the results from the manual count an accuracy of 94% was achieved by the image analysis method. The SED/neighbourhood method achieved 3% accuracy.
Discussion

The application of manual counting as a reference for the accurate number of detectable fish tracks is somewhat speculative. Manual counting is regarded as subjective and inaccurate due to variation in the counter's concentration and interpretation of the echograms. Fish tracks with low signal to noise ratio can easily be overlooked. However, with small data sets and with the benefit of using both the Amp and SED-echograms, manual counting can be quite accurate. It is possible to maintain a high and steady concentration during a short counting time. The test data was counted three times, each time giving the same result. It is also important to note that the manual counting does not necessarily reflect the actual number of fish having passed the site where the transducer was placed. This does not interfere with our results because we are evaluating different data analyse methods and not the overall performance of the hydroacoustic method.

In Table 23, we see high correlation between the manual and image count in all files. This shows that the image-based method is capable of analysing both vertically and horizontally recorded sonar data. This is different with the SED/neighbourhood method. The method seems to apply fairly well to vertically recorded data with high SNR. Good results were achieved with the file from Lake d’Annecy. With the Czech file, the overestimate is caused by fractionated fish tracks. With the horizontally recorded files, the overestimates were caused mostly by generation of noise-based tracks. Reducing the ping-gap parameter reduced the overestimate, but then tracks from fish were overlooked.

In this study, fish tracks were separated from drifting objects simply by checking the movement relative to the water current. Only targets moving upstream were classified as fish. Down moving targets will therefore probably be a mixture of fish and drifting debris. Differentiating objects with the same movement is difficult and has not been an objective in this study.

Image analysis is a broad subject. With the many different operators available, it is not possible to test all combinations. During this study we have seen that many different operators and combinations of operators give interesting results. It is essential to underline that the presented method represents one possible way only, not necessary the best. The availability of the many image analysis operators provides a high degree of flexibility and makes it possible to adapt the method to many kinds of sonar data. A disadvantage with
this flexibility is that it becomes time consuming and difficult to tune the method. Care has to be taken when selecting types and dimensions of operators.

**Conclusion**

Image analysis was found to be an effective tool when working with split-beam sonar data. The application of filtering techniques was seen to improve the readability of the recorded echograms. Noise could be suppressed and fish tracks could be made easier to see for the human eye. Image analysis was also found capable of detecting passing single targets. In combination with traditional SED, this could be used to form an automatic counting method. When applied to the recorded sonar data, good agreement with the fish count from manual analysis was achieved.

**Acknowledgements**

This work was supported in part by the County governor in Finnmark (northern Norway) represented by Kjell Moen, Simrad AS represented by Frank R. Knudsen, and RKTL Finland. We thank Frank R. Knudsen for help recording sonar data in the River Tana, Simrad AS, the County governor in Finnmark and RKTL for providing equipment. We also want to thank Martin Cech (Cz), Nathalie Gaudreau (Ca), and Simrad AS for lending us sonar data from other sites.

**References**


# Tables

<table>
<thead>
<tr>
<th>Operator</th>
<th>Type</th>
<th>Eval.</th>
<th>Our comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean filter</td>
<td>Low-pass</td>
<td>+</td>
<td>Well suited for noise reduction in echograms before segmentation. Some success with ping-gap filling after segmentation.</td>
</tr>
<tr>
<td>Pyramid filter</td>
<td>Low-pass</td>
<td>-</td>
<td>Same results as the mean filter, but weaker and more difficult to use. Pyramid filter is a weighted mean filter.</td>
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<tr>
<td>KNN filter</td>
<td>Low-pass</td>
<td>-</td>
<td>Difficult to find parameters and dimensions that manage to treat a wide range of track types. The filter algorithm replaces the output echo value with the mean value found from the $k$-nearest neighbours. ($k$ is a user given integer)</td>
</tr>
<tr>
<td>Sigma filter</td>
<td>Low-pass</td>
<td>-</td>
<td>Difficult to find parameters and dimensions that manage to treat a wide range of track types. The filter algorithm replaces the output echo value with the mean value calculated from the echo values found within a range around the filter matrix centre value.</td>
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<tr>
<td>Gradient filter</td>
<td>High-pass</td>
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<td>Seen to remove time range variations in the background reverberation level. Vertical gradients seen to highlight horizontal tracks. Produce interesting results, but seems difficult to use. The filter detects the first-order derivatives.</td>
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<tr>
<td>Laplace filter</td>
<td>High-pass</td>
<td>-</td>
<td>Not well suited. Seems to be too much variation in the reverberation level for this operator to work. The filter detects the second-order derivatives.</td>
</tr>
<tr>
<td>Segmentation</td>
<td>Edge-based</td>
<td>-</td>
<td>Too much variation on the echograms. Method not well suited. Works by linking parts of edges detected by</td>
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</table>
high-pass filters.

<table>
<thead>
<tr>
<th>Operator Type</th>
<th>Description</th>
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<tr>
<td>Segment Threshold</td>
<td>Well suited to separate tracks from the background noise level. Based on low-pass filters and adaptive threshold.</td>
</tr>
<tr>
<td>Hit and remove Morphologic filter</td>
<td>Can be used to remove short noise pulses. Searches a predefined pattern and removes echoes when found.</td>
</tr>
<tr>
<td>Hit and add Morphologic filter</td>
<td>Can be used to fill ping-gaps in tracks from fish. Searches a predefined pattern and adds echoes when found.</td>
</tr>
<tr>
<td>Grow Morphologic operator</td>
<td>Well suited to fill ping-gaps in segmented echograms. Increases the size of detected regions by adding echoes along the border.</td>
</tr>
<tr>
<td>Shrink Morphologic operator</td>
<td>Can be used in combination with growing operators to gain more distinct tracks when filling ping-gaps. Reduces the size of detected regions by removing echoes along the border.</td>
</tr>
<tr>
<td>Perimeter filter Morphologic operator</td>
<td>Well suited to remove small regions with echo-pulses from stochastic noise and bottom-structures. Should be used in combination with growing operators. The filter removes regions with short and long perimeters. “Short” and “long” is defined by the operator.</td>
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*Table 22. Qualitative evaluation of the image operators effect on echograms.*
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<th>Recorded</th>
<th>Man. count</th>
<th>Image count</th>
<th>Neighbourhood count</th>
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<td>100%</td>
<td>94%</td>
<td>3%</td>
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Table 23. Counting results from manual tracking, image tracking and neighbourhood tracking.
Figures

Figure 88. Echogram showing a fish entering the beam. Vertical recording in Lake Semsvann southern Norway spring 1998.

Figure 89. Fish passing the horizontally aligned beam in the River Tana northern Norway summer 1999. This echogram demonstrate the lower signal to noise ratio, the higher fluctuation in the reverberation level and the less stable target strength in the echoes from the river compared with the situation in the lake.
Figure 90. Result of filtering the horizontally recorded echogram from figure 1 b with a 3x7 mean filter.

Figure 91. Segmenting the filtered echogram from figure 1 c.
Figure 92. Image processing used to detect a fish with low signal to noise ratio.  

- a) SED-echogram.  
- b) Amp-echogram  
- c) Output from a mean 1x3 filter and adaptive threshold.  
- d) Output from a median 3x3 filter followed by a growing operator. Note the reduction in the ping-gaps and the reduction of noise regions.  
- e) Output from the perimeter filter.  
- f) Contour detection.  

Filter dimensions in c and d are noted as height x width. This fish passed the sonar in the River Tana 19 July at 5:06 p.m at a mean range of 44 m.

Figure 93. Counting method using image analysis operators. This method was used to produce the results shown in figure 91.
16 Paper VI

Application of linear discriminant function analysis to the classification of echo-tracks detected by split-beam sonar in shallow rivers

Abstract

Automatic fish detection applied to split-beam sonar data recorded in shallow rivers, can produce large overestimates. Overestimates in the order of 1:100 are not uncommon when automatic counts are compared with manual counts. Reasons for this are low signal to noise ratio and unwanted targets in the river. In order to reduce the labour intensive work of checking the tracking results, automatic classification based on Fisher’s linear discriminant function analysis is tested. 49 descriptive feature variables from the tracks were applied in the analysis. 93% reduction in the work needed for manual checking was gained without overlooking any fish track.

Keywords

Hydroacoustics, split-beam, sonar, shallow rivers, classification, fish counting, discriminant function analysis.
Application of linear discriminant function analysis to the classification of echo-tracks detected by split-beam sonar in shallow rivers

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Introduction

Hydroacoustic fish detection methods are frequently applied to estimate escapement in shallow rivers (Ransom and Johnston, 1998). A common method is to apply one or more side-looking split-beam sonar systems aimed across the river. The recorded data are analysed by a single echo detector, followed by manual or automatic tracking of individual fish. Manual tracking is very time consuming and automatic tracking is therefore preferable. However, due to noise and echoes from objects other than fish, automatic tracking may produce high overestimates. In this article, automatic classification methods are tested in order to reduce this overestimate.

A variety of phenomena and objects can cause sound reflections in a shallow river. Single fishes, shoals of fish, and drifting debris that cross the beam may be seen as short lived tracks on the echogram. Stones and reflections from bottom structures produce range stationary echo-signals, while surface waves, air bubbles, turbulence, and boat wakes produce clouds of random scattered noise. Active sound sources exist as well. Even rattling stones on the river bottom can produce sound picked up by the transducer. Phenomena such as lightning can produce electric noise resulting in false echoes in an echo sounder. When signals and noise are passed through the single echo detector, the result is detection of fish, debris, and stones, mixed with stochastic detection of echo-pulses from the other sound and echo sources (Figure 94). Due to this process and to fluctuations in the echo-signal, detected objects are frequently observed with ping-gaps (missing detection) and
variations in position estimates. E.g., an upstream migrating fish is not detected with a smooth track. On the other hand, echoes from a stone on the bottom can produce tracks looking like upstream migrating fish. In the River Wye crossing from Wales into England, aquatic weed is reported to produce upstream tracks with echo intensity similar to adult salmon (Nealson and Gregory, 2000). The combination of ping-gaps in tracks from solid objects, and a high number of surrounding noise echoes, can result in false noise-based tracks being generated by an automatic tracking algorithm. With interactive analysis methods, the operator performs both the tracking and the classification. The operator may hopefully correctly identify clusters of echoes from fish, stones, drifting objects and noise so that only fish are counted. With automatic tracking this is different. The tracking algorithm will produce all types of tracks. A classification algorithm is therefore needed as a post processor to the tracker in an automatic fish counting system. Xie et al., (1997) suggested a method based on successive filters for individual track features (e.g., TS), to reduce the overestimate. In this article we are testing a classification method that uses many track features concurrently.

In general terms, the objective of classification is, given a set of objects, to assign each object to one of a set of classes. Classification can be divided into “supervised” and “unsupervised” methods (Niblack, 1986). With “unsupervised” methods, a computer algorithm tests the objects for similarities. Such methods are referred as cluster analysis (Tryon, 1939). With “supervised” methods, the operator selects training sets from the data and teaches the system to distinguish objects from the different classes. Neural networks, Bayesian maximum likelihood, and discriminant function analysis are examples of “supervised” classification methods.

Linear discriminant function analysis (DFA) does not assume normal distributed variables and it is simple to implement. This method was introduced by Fisher, (1936) and has become popular in many professions. In 1982 Ezquerra and Harkness, (1982) published an article about classification of radar signals. In 1986 Chen, (1986) applied linear discriminant functions to classify seismic data and Vray et al., (1990) applied discriminant function analysis to recognise fish species by their echo-signature.

Split-beam echo sounders provide echo position estimates. When two or more echoes are combined into a track, a variety of variables like track velocity can be calculated (Table 24). A linear discriminant function (DiF) can transform these variables into a single variable so that the classes are maximally separated. Figure 95 illustrates this
for two variables, \( x_1 \) and \( x_2 \), and two classes “a” and “b”. It is obviously simpler to study the observations in a univariate distribution than in a multivariate, especially if more than two or three variables have been measured. If there are more than two classes, the DFA will result in more than one discriminant function. However, the functions will be ordered with descending explanatory power. Hence, studying the transformed observations in one or two-dimensional transformed scatter-plots will give a clarified picture of the observations.

**Linear discriminant function analysis**

The multivariate distribution \( \mathbf{x} = x_1, x_2, \ldots, x_p \) can be linearly transformed into the distribution \( \mathbf{y} = \mathbf{u} \mathbf{x} \) (Johnson and Wichern, 1992). In order to gain maximal separation between different distributions we would like to find the \( \mathbf{u} \) that maximises the distances between the classes and at the same time minimises the variances within the classes. Maximising the ratio does this:

\[
r = \frac{\text{Sum of squared distances from the total mean } \mathbf{y}}{\text{Total of variance } \mathbf{y} \text{ in all classes}}
\]  

(1)

Letting \( n_i \) be the number of objects in class \( i \), \( g \) the number of classes, and defining the between class \( \mathbf{B} \) and the within class \( \mathbf{W} \) cross product matrixes in the following way,

\[
\mathbf{B} = \sum_{i=1}^{g} (\bar{x}_i - \bar{x})(x_i - \bar{x})'
\]

(2)

\[
\mathbf{W} = \sum_{i=1}^{g} \sum_{j=1}^{n_i} (x_{i,j} - \bar{x}_i)(x_{i,j} - \bar{x}_i)'
\]

the ratio \( r \) can be expressed as \( r = \frac{\mathbf{u}' \mathbf{B} \mathbf{u}}{\mathbf{u}' \mathbf{W} \mathbf{u}} \). Maximising \( r \) can then be done by expressing \( \mathbf{u} \) in the form of eigenvectors \( \mathbf{e} \) of the matrix \( \mathbf{W}^{-1} \mathbf{B} \).
\( \mathbf{W}^{-1} \mathbf{B} \mathbf{e} = \lambda \mathbf{e} \)

(3)

where \( \mathbf{e} \) is found from the characteristic equation

\[ | \mathbf{W}^{-1} \mathbf{B} - \lambda \mathbf{I} | = 0 \]

(4)

With \( \mathbf{S}_{\text{Pooled}} \) being the total normalised sample covariance matrix, let \( \lambda_1, \lambda_2, \ldots, \lambda_s > 0 \) denote the \( s \leq \min(g-1, p) \) nonzero eigenvalues of \( \mathbf{W}^{-1} \mathbf{B} \) and \( \mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_s \) denote the corresponding eigenvectors scaled so that \( \mathbf{e}' \mathbf{S}_{\text{Pooled}} \mathbf{e} = 1 \). Then the coefficient \( \mathbf{u} \) that minimises the ratio \( r \) is given by \( \mathbf{u}_1^{\prime} \mathbf{S}_{\text{Pooled}} \mathbf{e}_1 = 1 \). The linear combination \( \mathbf{u}_1 \mathbf{x} \) is called the sample first discriminant. \( \mathbf{u}_2 \mathbf{x} = \mathbf{e}_2 \mathbf{x} \) is called second and so on. The discriminant functions are given by the linear transformation from the original variable space \( \mathbf{X} \) to \( \mathbf{Y} = \mathbf{u} \mathbf{X} \). The first two discriminant functions are given by:

\[
\begin{align*}
\mathbf{f}_1 (\mathbf{u}_1 \mathbf{x}) &= e_{11} x_1 + e_{12} x_2 + \ldots + e_{1p} x_p \\
\mathbf{f}_2 (\mathbf{u}_2 \mathbf{x}) &= e_{21} x_1 + e_{22} x_2 + \ldots + e_{2p} x_p
\end{align*}
\]

(5)

**Applying the discriminant functions for classification**

The linear transformations based on calculating the eigenvectors result in a new variable space \( \mathbf{Y} = \mathbf{u} \mathbf{X} \). The components of \( \mathbf{Y} \) have unit variances and zero covariances. This space has a lower dimensionality than the original space, it is orthogonal and is organised with decreasing explanatory power with the higher dimensions (Johnson and Wichern, 1992). Euclidean metrics applies in this space and we can calculate the distance from a new observation to all the different classes.

The observation can then be assigned to the closest class with the decision rule:

Allocate the new observation \( \mathbf{x} \) to the class \( k \) if:

\[
\sum_{j=1}^{r} (y_j - \bar{y}_{kj})^2 = \sum_{j=1}^{r} [\mathbf{u}_j (x - \bar{x}_k)] \leq \sum_{j=1}^{r} [\mathbf{u}_j (x - \bar{x}_i)] \text{ for all } i \neq k
\]

(6)
where \( r \) represents the number of derived discriminant functions and \( i, k \) are class indexes.

The distance can be regarded as proportional to inverse probabilities. Decreasing distance between the observation and a class, increases the probability for the observation to belong to that class. Functions giving higher scores for smaller distances are called classification functions (CiF). Like the DiF’s, the classification functions can also be expressed as a linear transform of the original variables. Statistical software programs frequently output the classification factors as well as the discriminant factors.

**Material and methods**

Five sonar files, recorded in the River Numedalslågen (southern Norway), were analysed. The nature of these files is seen in Figure 94 and Figure 96. Each file covered 40 minutes. Three files were selected to form a training set and two files were selected for verification. Descriptive classification variables were defined and calculated from the training set. Automatic tracking, followed by automatic classification, was tested first on the training set and then on the verification set. The best classification method was then tested on data recorded in other rivers in order to see whether the derived decision rules applied to other data sets.

The *Sonar5*\(^5\) post-processing program developed at the University of Oslo was applied for handling sonar data, tracking, extracting track variables and for classifying tracks from the verification set. Statgraphics PLUS 4.0 from Statistical Graphics Corp. was used to analyse selected variables, identify the most significant variables, and to calculate the discriminant and classification function weights.

Simrad AS recorded the sonar data from the River Numedalslågen in 1996. An EY500 split-beam echo sounder equipped with an elliptical side-looking ES120-4 split-beam transducer was used. Some important parameters for this set-up were: Sound frequency = 120 kHz, transducer opening angle = 4x10 deg., transmitted pulse-length = 0.3 ms and transmitted power = 63 W.

\(^5\) Demo version of *Sonar5* are available at the internet page www.fys.uio.no/~hbalk
Single echo detection

The data was analysed by the EY500’s internal single echo detector. This detector applies 6 different parameters in the detection. The Min. Value specifies a threshold for the uncorrected echo level (TS). Echoes below this threshold are not evaluated. Min. and Max. Echo Length specifies limits for the relative echo duration, which is given by the echo length between the -6 dB points, divided by the transmitted pulse-length. The Max. Phase Dev. parameter limits the phase deviation, which is calculated from the detected electrical phase steps within the echo sounder. It relates to the deviation in mechanical degrees by a parameter dependent conversion factor. The Max. Beam Comp. (MBC) parameter is calculated from the detected angles by a Bessel function. Echoes with MBC less than this parameter, are discarded. Also twin peaked echo-pulses are discarded. Twin peaks are defined to have local min. points lower than −1.5 dB in between. The single echo detection parameters were: Min. Echo Length = 0.8, Max. Echo Length = 1.2, Max. Phase Dev. = 2, Max. Beam Comp. = −3 dB and Min. Value = −40 dB.

Tracking algorithm

Sonar5’s SED/tracking algorithm was applied in order to produce tracks for classification. This tracker is a multiple-target tracker (MTT) based on elements as described by (Blackman, 1986) and (Balk and Lindem 2001). It has an association algorithm based on evaluation of echo closeness, a track supporter testing on max. ping-gap (MPG) and min. track-length (MTL), a four dimensional gate and a predictor algorithm. Echo closeness is estimated by a weighted Euclidean distance formula taking into account the spatial distances and the echo intensity. The track supporter applies stepwise constant functions in order to evaluate when a track has left the beam and whether the track is too short to be regarded as a track from a solid object. The gate limits the region for the search for new echoes. Because the data has been recorded in advance, time as well as the traditional spatial dimensions can be applied in the gating. This allows the tracker to overlook an echo if there is a better-positioned echo available in the next ping. Sonar5 has 4 predictors. These are zero velocity, weighted mean, linear regression and Alpha-Beta predictors. Full description of the tracker is given in (Balk and Lindem 2001). For the present tracking task, Sonar5 used:
- Association’s closeness evaluation factors: \( t = 2 \) ping, \( R = 1 \) m, \( Alo = 1 \) deg., \( Ath = 1 \) deg.
- Track supporter: \( MPG = 11 \) ping, \( MTL = 5 \) echoes. (Range = 5 to 65 m)
- Predictor: Linear regression based on the 5 last echo positions.
- Gate size: \( t = 3 \) ping, \( R = 0.4 \) m, \( Alo = 10 \) deg., \( Ath = 10 \) deg.
- Gate expansion per ping: \( 0.1 \cdot R, 0 \cdot Ath, 0 \cdot Alo \) (no expansion of time, Ath and Alo)

\[ R = \text{range in meter, } t = \text{time in number of ping, } Alo = \text{along-ship, and } Ath = \text{athwart-ship in deg. For side-looking sonars, Alo defines the vertical angle axis while Ath defines the horizontal axis.} \]

The choice of algorithms and parameters for the single echo detector and tracker are important, especially when the sonar data are characterised by low signal to noise ratio. Even small changes can result in major changes in the resulting tracks and it has therefore been necessary to give a description of the applied methods.

**Range limitation**

The River Numedalslå gen echograms have been recorded with a maximum range of 100 m. However, at a range of 70 m the average reverberation intensity exceeds \(-20 \) dB and fish detection at longer ranges is difficult. In order to avoid the nearfield, transducer ringing, and extreme reverberation levels, ranges shorter than 5 meter and longer than 65 m have been excluded from the tracking. Distribution of echo intensity as a function of range is seen in Figure 97.

**Defining echo classes**

Defining the optimum number of classes can be important. Some classes are often given in advance. In a fish counting system, “fish” and “not fish” are obvious classes. In order to derive well working decision rules, subclasses might be needed as well. With the two classes, “fish” and “not fish”, it is possible that a particular track derives the same probability of belonging to both classes. Splitting up the class “not fish” into subclasses like "bottom" and "debris" might result in a better identification of the tracks.

From studies of echograms recorded in the River Numedalslå gen, the River Tana, the River Tornionjoki, and the River Simojoki (Norway and Finland) different echo patterns common to echograms from all four rivers were identified. The most striking patterns were the long thin lines seen at particular ranges (Figure 96). These lines can be
generated from stationary objects and originate most likely from reflections from bottom structures and stones. The single echo detector frequently detects these echoes, and the tracker combines the detection into tracks. It is therefore natural to define “stones” as a subclass for unwanted tracks. The second most striking phenomenon is the thin arcs of echoes seeming to follow the water current. The origin of these tracks can be downstream migrating fish or drifting objects like debris. Because these tracks look similar independent of their origin, we assign them to the class debris. Separating echoes from downstream migrating fish and other drifting objects is extremely difficult and will not be attempted here. The third sub-class of “not-fish” is the type of tracks that seem to be generated without a solid object in the beam. These are believed to originate from occasional detection of fluctuations in the background reverberation level and from the detection of air bubbles and surface reflections. The number of these echoes seems to increase in periods of rain, wind/waves or in regions containing boat wakes. Also weak signals from bottom are seen to generate this type of tracks. We assign these echoes and tracks to the class “noise”. The last and most obvious class to define is the upstream migrating fish. This gives a total of four classes. Examples are given in Figure 98 and Figure 99.

**Extracting training and verification data**

In a supervised classification system training and verification data are important. It is also essential that the training set contains representative tracks. Hence, the sonar data was analysed manually by viewing all tracks generated by *Sonar5*. Five files were then selected, two of them for the training set and three for verification. The training set contained totally 594 tracks while the verification set contained 984 tracks. All tracks in these sets were manually studied in the *Sonar5*’s SED-echogram window, in the two and three dimensional amplitude echogram, and in the position diagram windows. Sequences of echoes seen with a general upstream movement, with echoes stronger than the surroundings, and with changes in range were assigned to the class “fish”. Similar tracks, but with downstream movement was assigned to the class “debris”. Tracks detected with stable range in layers seen to contain stones in the amplitude echograms were registered as stones. Tracks generated from echoes without distinct reflections found in the amplitude echograms were registered as noise. In all cases the tracks were accepted as they were generated from the tracker. Long tracks split up in two shorter tracks by the tracker were accepted as two tracks. Noise echoes, combined with tracks from solid objects were accepted as solid objects. In order to see whether the number of subclasses were important,
two, three and four classes were tested. The fish was always present. In the two-class test all other tracks were regarded as noise. In the three-class test, debris was taken out of the noise as a separate class.

**Deriving explanatory variables from the tracks**

When an operator evaluates tracks, a variety of features are considered. Many of these can be expressed by numerical variables like track-length and speed. Inter-relations with other tracks and with the background are also important to a human operator, but are difficult to express numerically. If a track is observed close to other tracks already classified as fish, then this can increase the probability that the track in question will be classified as fish. On the other hand, if a track is seen in a region with noise from bottom reflection, this can reduce the chance for the track to be classified as fish. Such relations can be defined and implemented in a computer program. This is not a trivial task, however, and in this experiment only variables extracted from singular tracks were tested.

*Sonar5* extracts 66 different variables for each track including track number, file name, track time, etc. Other variables are defined from the number of registered echoes, the echo intensity and the echo positions. Moment, aspect, velocity, smoothness, number of changes in direction, and axis crossing are examples of variables calculated from the echo position estimates within the tracks. Table 24 gives a list of the variables we have applied for the classification. 49 variables were selected for further significance testing while variables like filename, track number, time, and date were omitted.

Some of the variables are correlated or they contain low explanatory power. Applying all the available variables in the discriminant analysis gave the highest achieved classification accuracy with the test data (81.2%). However, when testing the derived classification functions on the verification set, only three tracks were classified as fish. Of these, only one track was actually believed to originate from fish while one was identified as noise and the others as debris. In the other extreme, when only one variable was applied for the classification, far too many tracks were classified as fish.

In order to select the most significant variables from the 49 possible, three methods were tested.

a) Manual dual-class selection  
b) Automatic dual-class selection and  
c) Automatic all-class selection.
With dual-class selection, the fish class was compared to one of the variable distributions from the unwanted classes at the time. With manual selection, the variable distributions in the training set were compared manually, and variables seen to distinguish fish were selected. With automatic all-class selection, all variables were considered at the same time. Automatic selection was done by the application of Statgraphics PLUS’s stepwise forward multivariate F-test. The F-test gives a measure of a variable's significance in separating the classes. High scores indicate high significance. The stepwise test builds up a variable set by first testing all variables and then selecting the one variable that has the highest F-value. Then the second variable is selected among the remaining variables. Two thresholds, one for F-to-enter and one for F-to remove, control the selections. Only variables with higher F-value than the F-to-enter threshold are added. Adding a variable to the set might reduce the significance of other variables. Variables seen to fall below the F-to-remove threshold are withdrawn from the set. When no more variables are entered or withdrawn, the selection process stops.

Two ways of applying discriminant classification

When the original variable space $X$ is transformed into the orthogonal space $Y$, a reasonable classification rule is to calculate the Euclidean distance from a new observation to all class centroids and then assign the observation to the closest class. We did this by means of the classification functions shown in equation (7). However, with two classes, a single DiF maps the multivariate variable space to a univariate space. This makes it easy to study the observed distributions and to manually control the decision rules. By selecting a threshold, ensuring that all fish tracks in the training set are detected, high probabilities of detecting all fish in the verification set are obtained. The two decision rules are shown in equation (7) and (8). Both methods were tested.

\[
CiF_{Fish} = -2.68x_{14} + 0.46x_{24} + 39.72x_{28} + 0.66x_{39} - 59.86 \\
CiF_{NotFish} = -3.30x_{14} + 0.68x_{24} + 14.8x_{28} + -1.34x_{39} - 84.97
\]

If $CiF_{Fish} > CiF_{NotFish}$ then fish else NotFish

The classification function (CiF) in equation (7) derived for the two-class problem demonstrates optimal decision rules. Variables were selected by forward automatic all-class selection. Both F-to-enter F-to-remove thresholds equal 10. The factors are the weights as described in the introduction.
Equation (8) demonstrates a discriminant function (DiF) derived for the two-class problem. Again, variables have been selected by forward automatic all-class selection and F-to-enter F-to-remove thresholds equal 10.

Results

Table 25 gives the results of the tests. It is seen that classification can improve hydroacoustic fish counting in shallow rivers. All methods reduced the overestimates from the tracker. The reduction was from 6 to 41 times, dependent on the selection of variables and the classification method.

For the verification data, most tests resulted in overestimates. Erroneously detected tracks were mainly found in a period of high noise level believed to originate from a rain shower. The number of tracks generated in this period increased dramatically. This also increased the statistical probability of producing fish-like tracks. Other tracks detected as fish were clearly identified as downstream moving objects and stones.

Variable selections and selection methods

Variable selection was found to be important. Too many or too few variables resulted in an increase in erroneous fish track identification. With two classes, 4 to 5 variables seemed appropriate for good detection. With three classes, 8 to 13 variables worked well and four classes demanded between 10 and 16 variables. Dual-class variable selection was found slightly better than all-class selection, but it can be discussed whether this is significant or not. Manual selection gave both higher overestimates and higher number of detected fish than the other selection methods when applied to the four classes. Again it can be discussed whether the number of detected fish was significant.

The significance of variables changed when changing the number of classes, selection method, and number of selected variables. Results from applying automatic selection by F-to-enter = F-to-remove = 10 are given in Table 26. The least important variables with 2 classes were the standard deviation in the athwart-ship angles. With three
and four classes, the Euclidean 3-dimensional mean track distance and the uncompensated target strength were seen as most significant.

**Deciding the number of classes**

Four different kinds of echo patterns were observed in the data, fish, stones, noise and debris. It was assumed that dividing the training data into these four classes would give a more accurate classification than with the two classes fish and not-fish. An example of a four-class separation is seen in Figure 100. We found that applying two classes resulted in higher overestimates than when the training set was divided into 3 or 4 classes. With two classes, more downstream moving objects were classified as fish than with 3 and 4 classes. There were indications in the test results that four classes gave the best results, the tendency was not significant, however, and further tests are needed.

**Applying the derived classification function to data from other rivers**

It was hoped that the derived classification functions would have general validity for shallow rivers. This was found to be partly true. Tracks from two other rivers were classified. Fish in the River Simojoki (northern Finland) were recognised, but with quite high overestimates (140/70). Fish in the River Tana (northern Norway), were only partly recognised. This suggested that a classification function has to be derived from the data to be classified.

**Classification of tracks from the River Simojoki (northern Finland)**

The data were recorded for the Finnish Game and Fisheries Research Institute (RKTL) by Juha Jurvelius 30 June 1999 from 18:56 to 00:43 next day. The application of an EY500 echo sounder equipped with an ES120-4x10 transducer recorded the data. A total of 69229 ping were recorded. In the range from 4 to 43 m, the tracker generated 290 tracks. The 4-class classification function derived in the River Numedalslågen was applied to these tracks. This resulted in 140 fish, 46 noise, 120 stones and 10 debris. 70 of the 140 fish tracks were believed to originate from fish. The other halves of the classified fish tracks belonged to the other classes.
Classification of tracks from river Tana (northern Norway)

The authors recorded the file 6 July 1999 from 07:43 to 12:06. An EY500 equipped with a split-beam ES120-4x10 deg. split-beam transducer was used. Manual tracking resulted in 48 fish tracks in the range 5 to 46.5 m. The auto tracker produced 9661 tracks in the same range. Inspection confirmed that the auto-tracker actually detected the 48 fish tracks. However, some tracks were combined differently. Splitting of tracks and combinations of tracks with noise-based echoes occurred. Applying the 4-class classification function derived in the River Numedalslå gen resulted in 7 fish tracks, 307 stones, 0 noise, and 9344 debris being detected. Only 1 of the 7 classified fish tracks was actually believed to originate from a fish.

Applying a garbage collector

A common technique with classification is to apply a garbage collector. A garbage collector is an additional class for objects with low probability for belonging to any class. Unfortunately the mean score value for correctly and incorrectly classified fish were nearly the same. A garbage collector would therefore reduce the accuracy in the detection of fish. A garbage collector could also be applied in situations where the scores were fairly equal in each class. This was not tested.

Discussion

The aim of applying a classification algorithm was to reduce the number of unwanted tracks detected by an automatic tracker. The linear discriminant function method seemed to do this quite well. As expected, accurate classification was not achieved. In most tests 2 - 4 fish tracks in the verification data were not recognised while about 14-20 unwanted tracks were always detected as fish. It was nearly the same wanted tracks that were not identified, and the same unwanted tracks that were identified in each test. It was seen that most of the unwanted tracks had strong similarities with fish tracks and a human tracker would have to study the data carefully in order to reveal that these tracks were not representing fish. At the same time, the undetected fish tracks were seen as abnormal fish tracks with similarities with noise and stones. Figure 98 demonstrates tracks that are easy to misclassify while Figure 99 demonstrates tracks typical for each class. Not all mis-classifications were obvious to the human eye. Three examples are seen in Figure 101. The
reason why these tracks were classified in a specific way, must be found in the selection and weighting of the variables applied in the tests. From Table 27 it is seen that the most important variables were the mean total track distance (mDxyz), the sample deviation in the athwart-ship angle (sAth) and the number of changed direction along the z-axis (CDz).

In order to improve the classification further, two different approaches should be tested.

a) Develop better descriptive variables and
b) Filter out tracks from the classes stones and noise.

Better descriptive variables might be found by image analysis and by extracting inter-track relations. Filtering out tracks from the classes “noise” and “stones” before applying discriminant function classifications can be done by the application of image processing (Balk and Lindem, 2000) or by histogram and morphological filter techniques.

The number of fish tracks applied in the training set was rather small compared with the number of other tracks. The assumption of equal covariance in the classes was therefore probably violated. Increasing the number of fish tracks might increase the classification accuracy.

Stratification of the data by range, might be another way of improving the classification. Tracks generated at short range are bound to differ from tracks observed at long range due to the geometry of the beam and the declining signal with increasing range.

Conclusion

Classification based on discriminant function analysis was seen to improve the analysis of sonar data from the River Numedalslågen by a substantial reduction in the overestimate from the tracker. 100 % classification accuracy was not achieved and a manual check of the results might still be needed.

Classification functions derived from data recorded in one river gave only partly successful classifications in other rivers indicating that training sets have to be derived from the actual classification data.

Dividing the unwanted tracks into the subclasses debris, noise and stones gave better results than classification with the two classes fish and not-fish.
Dividing the data into more classes demanded more variables in order to maintain the classification accuracy. A number of variables between 4 and 16 were seen to work well. Too many or too few resulted in low classification accuracy and high overestimates.

Selecting variables automatically based on forward F-tests worked well. Significant class-separation was achieved with these variables. Variable selection by testing one class after the other against the fish class, did not improve the selection compared by testing all classes at the same time.

In order to detect all fish, higher overestimates must be expected than if losing a few fish could be accepted.

Acknowledgements

We thank Simrad AS (Norway) and the Finnish Game and Fisheries Research Institute (RKTL) for the use of their sonar data in this article.

References


## Tables

<table>
<thead>
<tr>
<th>#</th>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>NrE</td>
<td>Number of detected echoes in a track</td>
</tr>
<tr>
<td>5</td>
<td>MPG</td>
<td>Max. Ping-Gap. Largest successive number of missing ping in the track.</td>
</tr>
<tr>
<td>6</td>
<td>suMP</td>
<td>Sum of missing ping within a track.</td>
</tr>
<tr>
<td>7</td>
<td>suP</td>
<td>Sum of ping. Total numbers of ping from the first to the last detection.</td>
</tr>
<tr>
<td>8</td>
<td>TTT</td>
<td>The tracks transit time through the beam. = TCP/Pingrate.</td>
</tr>
<tr>
<td>12</td>
<td>mTSc</td>
<td>Mean off-axis-compensated target strength.</td>
</tr>
<tr>
<td>14</td>
<td>mTSu</td>
<td>Mean TS before beam compensation.</td>
</tr>
<tr>
<td>18</td>
<td>VOL</td>
<td>Volume of the beam surrounding the track.</td>
</tr>
<tr>
<td>19</td>
<td>cvTSc</td>
<td>Coefficient of variability in mTSc.</td>
</tr>
<tr>
<td>20</td>
<td>cvTSu</td>
<td>Coefficient of variability in mTSu.</td>
</tr>
<tr>
<td>21</td>
<td>BC</td>
<td>Off-axis beam compensation factor.</td>
</tr>
<tr>
<td>22</td>
<td>mAth</td>
<td>Mean athwart-ship position.</td>
</tr>
<tr>
<td>23</td>
<td>mAlo</td>
<td>Mean along-ship position.</td>
</tr>
<tr>
<td>24</td>
<td>mR</td>
<td>Mean range of the track.</td>
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<tr>
<td>26</td>
<td>sAth</td>
<td>Sample deviation in the Ath estimates.</td>
</tr>
<tr>
<td>27</td>
<td>sAlo</td>
<td>Sample deviation in the Alo estimates.</td>
</tr>
<tr>
<td>28</td>
<td>sR</td>
<td>Sample deviation in the range estimates.</td>
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<td>29</td>
<td>aspect</td>
<td>Angle between track and the transducer centre axis.</td>
</tr>
<tr>
<td>30</td>
<td>tilt</td>
<td>Angle between track and the beam’s Ath-axis.</td>
</tr>
<tr>
<td>31</td>
<td>SM1</td>
<td>Smoothness 1. Distance ratio between the 3 dim. Euclidean first-last echo distance and the sum distance normalised by log10(NrE)</td>
</tr>
<tr>
<td>32</td>
<td>SM2</td>
<td>Smoothness 2. Mean angles between two and two echoes in the xy-domain.</td>
</tr>
<tr>
<td>33</td>
<td>SM3</td>
<td>Smoothness 3. Sample deviation ratio = sx/sy The track is first rotated so that the xy regression line through the track is parallel with the x-axis.</td>
</tr>
<tr>
<td>34</td>
<td>CDx</td>
<td>Number of times the track changes direction along the x-axis</td>
</tr>
<tr>
<td>35</td>
<td>Cdy</td>
<td>Number of times the track changes direction along the y-axis</td>
</tr>
<tr>
<td>36</td>
<td>CDz</td>
<td>Number of times the track changes direction along the z-axis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>37</td>
<td>NrCx</td>
<td>Number of times the track crosses the x-axis (y=0)</td>
</tr>
<tr>
<td>38</td>
<td>NrCy</td>
<td>Number of time the track crosses the y-axis (x=0)</td>
</tr>
<tr>
<td>39</td>
<td>flDx</td>
<td>Distance between the first and the last echo along the x-axis</td>
</tr>
<tr>
<td>40</td>
<td>flDy</td>
<td>Distance between the first and the last echo along the y-axis</td>
</tr>
<tr>
<td>41</td>
<td>flDz</td>
<td>Distance between the first and the last echo along the z-axis</td>
</tr>
<tr>
<td>42</td>
<td>Dfl abr</td>
<td>Distance between the first and the last echo along in spherical domain.</td>
</tr>
<tr>
<td>43</td>
<td>suDxyz</td>
<td>Sum of Euclidean distances between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>44</td>
<td>mDxyz</td>
<td>Mean Euclidean distance between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>45</td>
<td>flSxyz</td>
<td>Speed between the first and the last echo in the xyz domain.</td>
</tr>
<tr>
<td>46</td>
<td>mSxyz</td>
<td>Mean speed between all echoes in the xyz domain.</td>
</tr>
<tr>
<td>47</td>
<td>flVx</td>
<td>Velocity along the x-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>48</td>
<td>flVy</td>
<td>Velocity along the y-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>49</td>
<td>flVz</td>
<td>Velocity along the z-axis calculated from the first and the last echo.</td>
</tr>
<tr>
<td>50</td>
<td>suAVx</td>
<td>Sum of all absolute velocities along x-axis</td>
</tr>
<tr>
<td>51</td>
<td>suAVy</td>
<td>Sum of all absolute velocities along y-axis</td>
</tr>
<tr>
<td>52</td>
<td>suAVz</td>
<td>Sum of all absolute velocities along z-axis</td>
</tr>
<tr>
<td>53</td>
<td>mVx</td>
<td>Mean of all the &quot;between echo x-components&quot; of the velocity.</td>
</tr>
<tr>
<td>54</td>
<td>mVy</td>
<td>Mean of all the &quot;between echo y-components&quot; of the velocity.</td>
</tr>
<tr>
<td>55</td>
<td>mVz</td>
<td>Mean of all the &quot;between echo z-components&quot; of the velocity.</td>
</tr>
<tr>
<td>56</td>
<td>svx</td>
<td>Sample deviation from all the x components of the velocity.</td>
</tr>
<tr>
<td>57</td>
<td>svy</td>
<td>Sample deviation from all the y components of the velocity.</td>
</tr>
<tr>
<td>58</td>
<td>svz</td>
<td>Sample deviation from all the z components of the velocity.</td>
</tr>
<tr>
<td>65</td>
<td>nsuP</td>
<td>suP normalised by dividing on number of echoes.</td>
</tr>
<tr>
<td>66</td>
<td>vMP</td>
<td>Variation in the detection probability of a track.</td>
</tr>
</tbody>
</table>

*Table 24. Track variable definitions. D=Distance, V=Velocity, N=Number, S=Speed, A=Absolute, su=Sum, fl=first last, m=mean s=sample deviation, v=sample variance, x,y,z =Cartesian co-ordinates, abr=spherical co-ordinates.*
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Vx&gt;0</td>
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<td>--</td>
<td>1</td>
<td>76/12</td>
<td>156/12</td>
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<tr>
<td>2</td>
<td>DiF &gt;1.54</td>
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<td>4</td>
<td>10</td>
<td>39/21</td>
<td>64/12</td>
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<td>23/7</td>
<td>44/1</td>
</tr>
<tr>
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<td>All</td>
<td>1</td>
<td>15</td>
<td>23/18</td>
<td>31/7</td>
</tr>
<tr>
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<td>4</td>
<td>10</td>
<td>23/17</td>
<td>31/8</td>
</tr>
<tr>
<td>2</td>
<td>CIF</td>
<td>All</td>
<td>5</td>
<td>7</td>
<td>24/17</td>
<td>34/9</td>
</tr>
<tr>
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<td>8</td>
<td>6</td>
<td>26/17</td>
<td>30/8</td>
</tr>
<tr>
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<td>26/17</td>
<td>30/8</td>
</tr>
<tr>
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<td>All</td>
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<td>4</td>
<td>26/19</td>
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</tr>
<tr>
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<td>37/8</td>
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<tr>
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<td>2</td>
<td>38/11</td>
<td>44/8</td>
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<td>18</td>
<td>23/18</td>
<td>1/1</td>
</tr>
<tr>
<td>3</td>
<td>CIF</td>
<td>All</td>
<td>4</td>
<td>13</td>
<td>22/17</td>
<td>27/9</td>
</tr>
<tr>
<td>3</td>
<td>CIF</td>
<td>All</td>
<td>5</td>
<td>10</td>
<td>21/16</td>
<td>25/8</td>
</tr>
<tr>
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<td>CIF</td>
<td>All</td>
<td>8</td>
<td>8</td>
<td>21/16</td>
<td>24/8</td>
</tr>
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<td>CIF</td>
<td>All</td>
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<td>4</td>
<td>18/12</td>
<td>24/7</td>
</tr>
<tr>
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<td>CIF</td>
<td>All</td>
<td>40</td>
<td>4</td>
<td>18/12</td>
<td>24/7</td>
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<td>CIF</td>
<td>All</td>
<td>60</td>
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<td>38/6</td>
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<td>CIF</td>
<td>All</td>
<td>10</td>
<td>7</td>
<td>22/17</td>
<td>25/8</td>
</tr>
<tr>
<td>3</td>
<td>CIF</td>
<td>Dual</td>
<td>4</td>
<td>13</td>
<td>21/16</td>
<td>24/8</td>
</tr>
<tr>
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<td>CIF</td>
<td>Dual</td>
<td>5</td>
<td>10</td>
<td>21/16</td>
<td>25/8</td>
</tr>
<tr>
<td>3</td>
<td>CIF</td>
<td>Dual</td>
<td>8</td>
<td>8</td>
<td>21/16</td>
<td>24/8</td>
</tr>
<tr>
<td>3</td>
<td>CIF</td>
<td>Dual</td>
<td>10</td>
<td>7</td>
<td>22/17</td>
<td>25/8</td>
</tr>
<tr>
<td>4</td>
<td>CIF</td>
<td>All</td>
<td>2</td>
<td>27</td>
<td>21/17</td>
<td>1/1</td>
</tr>
<tr>
<td>4</td>
<td>CIF</td>
<td>All</td>
<td>4</td>
<td>16</td>
<td>23/17</td>
<td>25/8</td>
</tr>
<tr>
<td>4</td>
<td>CIF</td>
<td>All</td>
<td>5</td>
<td>14</td>
<td>21/16</td>
<td>24/8</td>
</tr>
<tr>
<td>4</td>
<td>CIF</td>
<td>All</td>
<td>8</td>
<td>10</td>
<td>22/17</td>
<td>23/8</td>
</tr>
<tr>
<td>4</td>
<td>CIF</td>
<td>All</td>
<td>10</td>
<td>9</td>
<td>22/17</td>
<td>24/8</td>
</tr>
<tr>
<td>4</td>
<td>CiF</td>
<td>All</td>
<td>20</td>
<td>6</td>
<td>19/14</td>
<td>22/7</td>
</tr>
</tbody>
</table>
Table 25. Classification results. First column displays number of training classes. Second column displays the classification method. Vx is the velocity parallel to the flow of the river. DiF is the discriminant function and CiF the classification function. The third and fourth columns display the variable selection method. “All” indicates that all available variables were applied initially while the number in the fourth column gives the significance threshold applied in the forward F-to-enter (Fe), F-to-remove (Fr) test. Fe and Fr were always kept at the same threshold. Dual indicates that two and two classes were tested with the F-test. One class then always being fish. The “No. var.” column displays the number of variables applied in the test while the two last columns give classification results in the format of total-fish divided with actual fish for the training and the verification data set.

<table>
<thead>
<tr>
<th>No. Classes</th>
<th>Variable number</th>
<th>Variable names</th>
<th>Fe</th>
<th>Fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-</td>
<td>26, 14, 39</td>
<td>sAth,</td>
<td>mTSu, flDx</td>
</tr>
<tr>
<td>3</td>
<td>all</td>
<td>44, 26, 14</td>
<td>mDxyz, sAth, mTSu</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>dual</td>
<td>44, 26, 14</td>
<td>mDxyz, sAth, mTSu</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>all</td>
<td>44, 26, 36</td>
<td>mDxyz, sAth, CDz</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>dual</td>
<td>14, 39, 24</td>
<td>mTSu, flDx, mR</td>
<td></td>
</tr>
</tbody>
</table>

Table 26. The three most significant variables sorted with descending significance. Result of automatic variable selection based on F-to-enter = F-to-remove = 10.
<table>
<thead>
<tr>
<th>Variable no.</th>
<th>name</th>
<th>Debris</th>
<th>Fish</th>
<th>Noise</th>
<th>Stones</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>x_6</td>
<td>suMP</td>
<td>0.022</td>
<td>0.016</td>
<td>0.021</td>
<td>0.042</td>
<td>0.055</td>
</tr>
<tr>
<td>x_14</td>
<td>TSu</td>
<td>-4.099</td>
<td>-3.468</td>
<td>-4.045</td>
<td>-3.925</td>
<td>7.784</td>
</tr>
<tr>
<td>x_18</td>
<td>VOL</td>
<td>0.003</td>
<td>0.030</td>
<td>0.001</td>
<td>0.001</td>
<td>0.030</td>
</tr>
<tr>
<td>x_24</td>
<td>mR</td>
<td>1.545</td>
<td>1.304</td>
<td>1.558</td>
<td>1.601</td>
<td>3.013</td>
</tr>
<tr>
<td>x_26</td>
<td>sAth</td>
<td>23.409</td>
<td>24.253</td>
<td>21.207</td>
<td>20.477</td>
<td>44.780</td>
</tr>
<tr>
<td>x_36</td>
<td>CDz</td>
<td>8.988</td>
<td>11.820</td>
<td>8.746</td>
<td>15.124</td>
<td>22.929</td>
</tr>
<tr>
<td>x_39</td>
<td>flDxyz</td>
<td>-0.047</td>
<td>3.030</td>
<td>0.337</td>
<td>0.522</td>
<td>3.093</td>
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<tr>
<td>x_44</td>
<td>mDxyz</td>
<td>-52.797</td>
<td>-52.921</td>
<td>-49.241</td>
<td>-50.642</td>
<td>102.847</td>
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<tr>
<td>x_47</td>
<td>flVx</td>
<td>-1.312</td>
<td>1.228</td>
<td>1.567</td>
<td>3.666</td>
<td>4.373</td>
</tr>
<tr>
<td>CONST</td>
<td></td>
<td>-150.964</td>
<td>-124.178</td>
<td>-142.819</td>
<td>-143.148</td>
<td>281.245</td>
</tr>
</tbody>
</table>

Table 27. Classification function for four classes, Debris, Fish, Noise and Stone.

Variables selected by F-to-enter = F-to-remove =10. All variable selection. The importance column is the Euclidean distance of the four class components from each variables. High numbers indicate high importance in the classification function. As seen, mean total track distance mDxyz has highest importance followed by the sample deviation in the athwart-ship angle (sAth), number of changed direction along the z-axis (CDz).
Figures

Figure 94. Amplitude echogram from the River Numedalslågen demonstrating a boat wake, track from fish, drifting debris and echoes from stones on the bottom.

Figure 95. Linear transform of variable space from multivariate to a univariate space. Left: scatter-plot of the observations measured by $x_1$ and $x_2$. Simple decision rules like all observations with $x_1 > c_1$ and $x_2 > c_2$ where $c_1$, $c_2$ are constants are bound to result in low classification accuracy. However indicated by the line $m$, it is possible to improve the classification. Right: The observation is transformed into a univariate space. Now the simple decision based on the constant $m$ will result in optimal classification.
Figure 96. Echogram from the single echo detector recorded in the River Numedalslå gen. Three fish are believed to be seen at ping 7050 and range 42 m. A layer containing echo detection from a stone is seen at about 54 m. Remaining echoes are believed to originate from drifting objects, reverberation, air bubbles, etc.

Figure 97. Increasing reverberation level seen in the recording from the River Numedalslå gen. The file has been recorded with a TVG of 40log(R).
Figure 98. Examples of tracks. Upper left: fish close to the transducer looking like noise. Upper right: fish track mixed with noise makes the track turn downstream. Lower left: Stone track looking like fish. Lower right: noise track looking like fish.

Figure 99. Examples of typical tracks. Upper left: fish, upper right: debris, lower left: stone, lower right: noise.
Figure 100. Scatter plot demonstrating separation of the four classes by the two most powerful discriminant function.

Figure 101. Typical tracks that would be frequently mis-classified as fish.
17 Paper VII

Discrepancy between expected and measured sound field in shallow waters

Abstract

A strange hydroacoustic phenomenon was observed in the River Tana in the summer 1998, 1999. A similar phenomenon was observed in a pond at Rimov in the Czech republic summer 2000. In all cases a split-beam transducer was placed horizontally in shallow water. Beam mapping revealed high deviation between the theoretical and actual beam. In the River Tana, the sound seemed to fill the entire river cross-section from surface to bottom at all measured ranges between 6 and 50 meters. In Rimov a second shadow beam was seen under the main beam. The phenomenon can cause serious problems in fish monitoring projects resulting in lost control of the sample volume and in vertical position estimates. As a result, area expansion and target strength estimation became difficult or impossible.

Keywords

Hydroacoustics, sound beam, split-beam, sonar, shallow water, sound phenomenon, beam breakdown.

Note! This paper has not been submitted. The reason is that we recently have been told about an experiment indicating that the targets mounting line could have played us some trick. It is difficult to believe that we have observed echoes from the thin monofilament mounting line in these experiments. Especially when the target was lying stable on the river bottom with slack line in the current. However, we cannot prove that the fishing line did not cause the echoes and before submitting the paper we want to test this.
Discrepancy between expected and measured sound field in shallow water

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Introduction

During hydroacoustic fieldwork in the River Tana, a strange sound phenomenon was observed summer 1998 and 1999. The River Tana is a sub-arctic river situated in the north east part of Norway (70°N, 28°E) The upper part of the river forms the border between Norway and Finland. It is Norway’s and Finland’s largest salmon river. Enumeration of migrating salmon was the aim of the study. In order to check the behaviour and placement of the acoustic beam, beam mapping was carried out (Figure 102). A standard Cu-sphere (23.0 mm, 120 kHz, −40.3 dB) was lowered from a boat. To our disbelief the target was visible on the echo sounder from the moment it touched the water-surface and it was still visible when it was resting on the sandy bottom (Figure 103). This was observed at 6.5, 12, 27, 42, and 52 m ranges. With a transducer opening angle of 4 deg. and a water depth between 2.25 and 4 m, this should not be possible. In 1999 the phenomenon was observed again at the same site. Early summer 2000 a similar phenomenon was observed in a shallow pound at Rimov in the Czech Republic (Figure 104). Here carousel measurement of fish target strength was the aim of the study. Lowering a standard Cu-sphere from the surface to the bottom revealed that a second beam existed under the main beam at short range. This second beam “melted” together with the main beam at longer range. Later in the summer the phenomenon disappeared and could not be detected in the pond.

A different, but perhaps related phenomenon was seen at the opposite riverbank in the River Tana. At this place the beam did not cover more of the water cross-section than
expected, but it was found to “bend” down in a trench in the river. The Finnish Game and Fisheries Research Institute (RKTL) has made similar observations in the River Tornionjoki (northern Finland). The River Tornionjoki project is described in (Romakkaniemi et al., 2000), but this particular observation has not been officially reported.

We have not been able to explain the phenomenon. The problem was first presented and discussed at the 22th Scandinavian Symposium on Physics Acoustics at Ustaoset (Norway) February 1999 and later at the Shallow Water Fisheries Conference (SWFC) in Seattle September 1999. We have discussed the phenomenon with specialists in our own Department and with other scientists. Refraction due to thermal inhomogeneities and reflections from surface and bottom has been hinted. However, by studying the experimental results, we are not convinced that the phenomenon can be explained in these ways. The observations are presented here of two reasons, a) to warn other users of the hydroacoustic fish detection methods and b) to encourage other scientist to look for the phenomenon and for explanations.

Various sound phenomena can occur in shallow water. Thermal inhomogeneities can give rise to reflection, refraction and dispersion with multiple path and interference effects as results. The water-surface or bottom can act like mirrors of varying quality and reflect the sound. Spatial changes in sound speed due to thermal inhomogeneities will occur and cause refraction. Multiple sound paths and interference phenomena such as formation of caustics can then occur. Special phenomena like dipole effects and image interference can occur when the source and target is close to the reflecting boundary.

Multiple layers with different or slowly changing sound speed can form channels trapping the sound. Thermal layers can form such channels. The SOFAR channel (Urich, 1983, p 159) used by whales for communicating over large distances is an example. The temperature in the upper region and the temperature and pressure in the lower region forms this channel. In such channel caustics and convergence zones can be observed in which relatively high sound intensities occur (Brekhovskikh, 1980, pp. 388-408).
Material and methods

In the River Tana an EY500 scientific echo sounder from Simrad, equipped with an ES120-4x10 split-beam transducer was applied in the surveying. The transducer was mounted on a tripod 40 m out in the river, aiming normally to the water current. The water depth at the transducer was 2.25 m and the transducer was mounted with its centre 50 cm below the water-surface. The river bottom consisted of sand and declined smoothly from 2.25 m at the transducer stand down to 4.2 meter 50 meter further out. The transducer was tilted 2.1 deg. downwards. The ES120-4x10 transducer operates at a frequency of 120 kHz with an opening angle of 4x10 deg. The transducer was mounted with the 4 deg. axis in the vertical direction.

Sound-pulses were transmitted three times per sec. with a power of 63 W and a duration of 0.3 ms. Beam mapping was carried out from a canoe-like river-boat anchored in the current. A standard Cu calibration sphere (23.0 mm, 120 kHz, −40.3 dB) mounted with a thin 0.35 mm monofilament fishing line was lowered trough the sound beam 1.5 m from the boat side towards the transducer. Beam mapping was carried out under good weather condition with sun, no wind and smooth river surface.

In the pond at Rimov, an EY500 was applied. Two transducers were tested, one ES120-4x10 and one ES120-7x7. The 4x10 transducer was tested with the main angular axis aligned both horizontally and vertically. The pond measured 13x6x1.5 m. The transducer was aiming along the apex of the 13 m pond side. Various values for tilt and depth were tested. Sound-pulses were transmitted three time per sec. with a power of 63 W. 0.3 ms and 0.1 ms pulse-duration were tested. Beam mapping was carried out from a movable bridge crossing the pond. A standard Cu-sphere (23.0 mm, 120 kHz, −40.3 dB) was used in the mapping. The weather when the observations were taken was warm with no wind. (32° Celsius in the shadow).

Recorded sonar data was analysed by the Sonar5 post-processing program from the University of Oslo and with Microsoft’s spreadsheet Excel.
Observations

Table 28 gives an overview of the observations in the River Tana and Rimov.

Observations in the River Tana

Beam mapping from a boat in a river is not a trivial task. Keeping the boat steady in the current is not easy and the target will not hang still in the water current. Data from beam mapping under such circumstances are, therefore, not reliable. However, some information can still be deduced. Figure 105 gives a geometrical description of the experiment. Each measure sequence was initiated with the target situated on the sandy river bottom. The recording was started and the target was lifted slowly until it reached the surface (Figure 106). As seen from Figure 107 and Figure 108, both TS and angle estimates are “messy” and one needs imagination to see trends. What one clearly can read from the graphs is: a) The target can be observed when it is resting on the bottom at all tested ranges. b) The target is detected with near random position and target strength estimates when lifted slowly through the beam. c) At all ranges except at the 6.5 m the target was detected all the way through the water until it touched the surface. At the 6.5 m range the target disappeared from the echo sounder screen about 14 cm before it reached the surface, but it was detected at all other depths.

Figure 107 demonstrates the observation at 6.5 m range. With the target situated on the bottom, the sonar detects the target closer to the surface. When the target is lifted, the sonar first detects that the target is lowered. At the same time target strength increases from $-44$ to $-30$ dB during the first 150 ping or ca. 25 cm. Higher in the water something similar to the expected intensity behaviour is observed around ping 1500. The angular estimates seem corrupted at most positions. It is also worth noting that the acoustic size of the $-40.3$ dB target is observed with TS values as high as $-30$ dB in positions far below the theoretical beam. The TS is also seen to increase with increasing range. At 12 m, a maximum of $-18$ dB is seen, at 26 m, $-15$ dB, at 42 m, $-13$ dB, and at 52 m, $-10$ dB is observed.

Figure 109 displays the first echoes from the target from the moment it is being lifted from the river bottom at the 6.5 meters range. The echoes are registered clear and distinct, but with an echo length 1.5 times the 0.3 ms transmitted pulse-length. The same was observed at the other ranges.
The general impression is that no actual beam is present and that most of the water-column one way or another is filled with sound.

Summary of the River Tana observations

- Target observed far outside the theoretical beam
- Target strength observed to increase with range
- Stronger target strength readings than expected
- No clear beam pattern was found at any tested range
- Vertical phase reading seemed corrupted
- Horizontal phase reading seemed fine
- Returned echo length observed to be 1.5 times the transmitted pulse-length

Observations in the Rimov pond

In the small pond, the working situation was much simpler and the target could be positioned with high accuracy. The sonar was mounted in mid-water with zero tilt as demonstrated in Figure 110. The target was first placed on the bottom of the pond under the centre of the beam. In this position, the target could be readily seen on the echo sounder screen. Figure 111 shows the received echoes when the target was lifted through the beam at a rage of 5 m. Two sound beams are observed. First the target passes a shadow beam close to the bottom. Intensity raises and falls as expected from a normal beam. The vertical angle measurement also behaves normally except that the angular sensitivity is reduced. The beam then passes through a transit region with low, fluctuating echo values and position estimates. Higher up in the water the target passes through the ordinary expected beam.

We measured the size of the three regions from the first and last ping seen in the near linear angular regions. This gave an under beam thickness of 115 ping, a transit region of 135 ping and a main beam of 218 ping. A total of 745 ping was transmitted during the target lifting from bottom to surface. With 745 ping/1.5 m, we calculate the thickness of the three regions. Shadow beam = 0.23 m or 2.6 deg., transit region = 0.27 m or 3.0 deg. and main beam 0.44 m or 5 deg. The centre of the main beam is seen at ping 358 or at a depth of 0.72 m from the bottom. This is 0.08 m below the expected centre.

The echo sounders single echo detector was set to accept echoes with off-axis positions out to the -6 dB beam. The theoretical, the measured, and the estimated main beam seem thereby to be in acceptable agreement. Observed and sonar-estimated opening
angles of the shadow-beam are also fairly in agreement, except for the fact that the shadow beam should not been there in the first place. The target is observed through a 2.6 deg. beam while the echo sounder reports position estimates from −0.5 to 1 deg.

**Echo characteristics:** Figure 112 displays 40 echoes from the target resting on the bottom in the Rimov pond. At all ranges and depths, the returned echo length was measured to 0.3 ms. No difference was seen between the echoes in the main beam and the echoes from the shadow beam. Reducing the transmitted pulse-length from 0.3 ms to 0.1 ms did not alter the detection of the shadow beam.

**Other transducer positions:** In order to test whether the shadow beam depended on the transducer position, the transducer was placed in a position 30 cm under the surface (Table 28 test R9) and at a position 30 cm. from the bottom, tilted upwards (Table 28 test R4, R5). There was no significant evidence of the shadow beam in these positions.

**Other transducer opening angles:** In order to test the influence from the opening angle, the transducer was rotated 90 deg. (Table 28 test R6). An ES120-7x7 transducer was tested as well. (Table 28 test R7). With the rotated transducer, the target was visible from the surface to the bottom. Weak indications of a second beam could be seen. With the 7x7 deg. transducer, the indications were more distinct.

**Summary of Rimov observations**
- Target observed outside the theoretical beam
- The target behaved normally within the position of the theoretical beam
- A second beam was observed under the first beam
- The under beam’s intensity show the same profile as the main beam, but with weaker echo intensity
- The under beam’s angle estimates show a narrower opening angle than the main beam
- A transition region was observed between the two beams at shorter range. At longer range the two beams melted together into one wide beam
- Echo-pulse-length did not differ from the transmitted pulse-length
- The transducer depth and tilt influenced the phenomenon
- The phenomenon depended on the transducers opening angle
- The phenomenon varied with range
Testing the observations against known phenomena

It is natural to relate the observations to known phenomena as described in the introduction. Refraction in thermal layers and reflections from surface and bottom or influence from side-lobes can often explain strange sound phenomena.

**Refraction:** Snell’s law is frequently applied in order to describe refraction of sound paths due to spatial changes in the sound speed.

\[
\frac{\cos(\theta_1)}{c_1} = \frac{\cos(\theta_2)}{c_2} \quad (1)
\]

The relationship between sound speed and temperature is found from empirical formulas given by e.g. (Medwin, 1975)

\[
c = 1449.2 + 4.6T - 5.5 \cdot 10^{-2} T^2 + 2.9 \cdot 10^{-4} T^3
\]
\[
+ (1.34 - 10^{-2} T)(S - 35)
\]
\[
+ 1.6 \cdot 10^{-2} D \quad (2)
\]

where \( c \) = sound velocity in ms\(^{-1} \), \( T \) = temperature in degree Celsius, \( S \) = salinity in ppt and \( D \) is the depth in meter.

We can assume a thermal layer just under the transducer, refracting the lower edge of the beam downwards. This might explain how the target could have been detected on the bottom far below the theoretical beam. In the River Tana with an initial transducer tilt of 2.1 deg. and a vertical opening angle of 4 deg., the lower -3 dB beam edge had a tilt of -4.1 deg. In order to observe the target at the river bottom at a horizontal distance of 6.5 m, the lower beam edge would have to be refracted an additional 11.9 deg. downwards. From Snell’s law, this represents a sound speed ratio of:

\[
\frac{\cos(4.1)}{c_1} = \frac{\cos(11.9)}{c_2} \iff \frac{\cos(11.9)}{\cos(4.1)} = \frac{c_2}{c_1} = 0.981 \quad (3)
\]

The water temperature was measured to 16°C 50 cm below the surface. Applying the empirical sound speed formula given by equation (2) results in a sound speed of \( c_1 = \)
1468.6 ms\(^{-1}\). The lower water layer would have to be colder with a sound speed \(c_2 = 1440.7\) ms\(^{-1}\). In order to predict this sound speed at a depth of 1 m we have to apply a temperature of 8.53\(^\circ\)C in equation (2). This is a thermal difference of 7.47\(^\circ\)C. Such a strong and stable thermal difference is unlikely in the middle of the water current in a river.

Another observation, not explained by refraction, is the inverted phase reading at the 6.5 m range. When the target was lifted from the bottom, the detected angular positions show that the target was lowered. This indicates reflection from the surface and not refraction.

One or a few of the side-lobes could have been reflected from the surface. The first side-lobe along the vertical axis has an offset angle of 7 deg. from the main lobe. The second side-lobe is measured 13 deg. to the side. With the transducer placed 50 cm below the surface and tilted 2.1 deg. downwards, the 7 deg. side-lobe will hit the surface at a horizontal distance of 5.8 m. It will be reflected downwards with the same gracing angle and pass the depth of the target at a horizontal distance of 5.8 + 26.2 = 32.0 m. This is far beyond the actual target position. It can be possible for some of the higher side-lobes to reach the target, but there is another factor that eliminates side-lobe reflection as an explanation. This is the target strength. The first side-lobe is damped with \(-28\) dB relative to the main lobe. The higher side-lobes are all damped more than \(-30\) dB. Echoes from the side-lobes would have caused a week reading of the target, but the target is actually detected with a stronger signal than expected.

**Dipole effect:** If the transducer or the target is mounted close to the surface, a dipole can be formed by reflection from the surface. This dipole will focus the sound downwards. (Urich, 1983, p.134). However, the distance between the source and the target has to be less than the wavelength for the phenomenon to occur. This will normally not be a problem with high frequency sonars. At 120 kHz, 1500 ms\(^{-1}\) the wavelength will be \(\lambda =\frac{1500}{120000} = 0.0125\) m, which was not the case in our observations.

**Image interference:** Also known as Lloid’s Mirror. If sound propagates by a direct and a surface reflected path, interference can occur. The received echo will be the sum of the two pressure-waves. Three zones are formed depending on the source and target depth, distance, and wavelength. At a short distance, a nearfield zone is observed followed by an interference zone, and at long range, a far field zone (Medwin and Clay, 1998, p. 34).
The pressure at the target position from two sound paths can be calculated as the sum:

\[ P = \frac{P_0 R_0}{R_1} e^{i(\omega t - kR_1)} + \frac{P_0 R_0}{R_2} e^{i(\omega t - kR_2)} \]  \hspace{1cm} (4)

where \( P_0 \) and \( R_0 \) are the initial pressure at the unit range, \( R_1 \) and \( R_2 \) the distances along the direct and indirect path, \( k \) the wave number \( (2\pi/\lambda) \), and \( t \) the time. If the source depth \( d << R_1 \) and the target depth \( h << R_1 \) then \( R_1 \approx R_2 = R \) and equation (4) can be rewritten

\[ P = \frac{2iP_0 R_0}{R} \sin\left(\frac{khd}{R}\right) e^{i(\omega t - kR)} \]  \hspace{1cm} (5)

The amplitude decrease following \( R^{-1} \) is modified by a pressure doubling with peaks at

\[ \frac{khd}{R} = \frac{\Pi}{2}, \frac{3\Pi}{2}, \frac{5\Pi}{2} \]  \hspace{1cm} (6)

and with minimum points in between. At long range were \( R >> khd \) the pressure decreases normally as \( R^{-2} \).

In the Rimov pond, sweeping the target from the narrow end to the far end at a depth of 0.3, 0.8, and 1.3 m with the transducer at 0.8 m depth should have revealed evidence of surface imaging effects. Sweeping at 0.3 m depth, the target was not observed at all. If sound energy were reflected from the surface, we would have expected at least some observations of the target at some ranges. At 0.8 m all ranges except very close range gave the correct target strength of \(-40.3 \text{ dB}\) when compensated with the traditional \( 40\log(R) \) spherical spreading model (Figure 113). No evidence of surface imaging was seen. Sweeping with the target at a depth of 1.3 m resulted in a steady increase in the target strength with increasing range (Figure 114). A steady increase is reasonable because the target is approaching the beam with increasing range. However, the angular estimates behaved strangely in this sweep. Approaching the beam should have resulted in a decrease in the angular position estimates, but the opposite was observed (Figure 114 upper graph).

**Sound channels and waveguides:** A shallow lake or river can form a waveguide, trapping sound between surface and bottom. Propagation goes by repeated reflections from
the boundaries. This can be described by ray theory and by mode theory. With ray theory, the resulting sound pressure observed at the target position builds up as if the sound originates from a series of image sources with increasing grazing angle. The total pressure can be described as a sum

\[ P = P_0 \sum_{m=0}^{\infty} R_m e^{ikr_m} \]

where \( P_0 \) is the initial pressure, \( R_m \) the amplitude reflection coefficient appropriate for the \( m \)th image reflection, \( r_m \) the distance of the \( m \)th image and \( k \) the wave number given by \((2\pi/\lambda)\).

In Tindle et al., (1987), sound-pulses are emitted in a shallow water wedge not unlike the river profile in Tana. The wedge was built with a sandy bottom stretching from 0.1 to 1.5 m at a range of 10 m. It is demonstrated that single modes could be emitted into the entire water cross-sections and that these modes would stretch with the declining bottom. The modes were generated by a source array filling the water cross-section in the shallow end of the wedge. The generated sound was bursts of 4 cycles at 80 kHz.

The observations in the River Tana indicated that the total water-column was filled with sound. The sound leaves the transducer and spreads out in the entire water cross-section propagating without producing reflections from the boundaries. Only distinct targets produced backscatter. During beam mapping, we tried to lower a target from the surface on the acoustic shadow side of the long riverboat. The boat was clearly visible on the echogram at a range of 30 m. The target was detected in the acoustic shadow of the boat from the moment it passed the surface. This behaviour indicates that the sound propagates in a sort of waveguide. The intensity profile from the beam mapping in the River Tana is similar to the 1-mode transmission while the intensity profile in Rimov has a similar profile as the 2-mode propagation in Tindle’s experiment.

The differences between our situation and Tindle’s experiment were that we used a point source with a higher frequency in a wedge and with a much deeper initial wedge depth. While Tindle’s initial depth was 10 cm or ~5.5 wavelengths, our initial depth was 2.25 m or ~186 wavelengths. Although the sound transmission behaves in similar ways, it is difficult to explain how our point source can produce this sound field.

**Related phenomena in the River Tana and in the Rimov pond:** An important question is whether the observations in Tana and Rimov are related. Similarities have been
mentioned, but there are also differences like the clear main and shadow beam with valid angular estimates and expected echo length in Rimov towards the total water cross-section coverage, the elongated echo length, and the corrupted angular estimates as observed in the River Tana. However, corruption of the beam was also seen at the 10 m range in Rimov. Here, the water-column was covered in a similar way as in the River Tana with reflections from the target in most positions and angular position estimates stabilising just below 0 deg. when the target reaches the bottom. The high echo lengths seen in the River Tana could be a result of multiple paths, but this should have led to a mixture of constructive and destructive interferences when the target was lifted. Figure 109 demonstrates that the echo intensity and the echo length are fairly stable when the target is lifted from the bottom. This does not indicate multiple paths. Due to the differences in the experiments it is difficult to give a definite conclusion as to whether the phenomena are related.

**Avoiding spherical spreading:** A spherical R^{-4} spreading model has been assumed. This should be correct when the beam is submerged in the media. However, in the River Tana the sound is distributed in the entire water cross-section, indicating that a cylindrical spreading damped by R^{-3} or 30\log(R) would be correct. In Table 29, the arithmetic mean TS observed at each measured range has been calculated according to the two models. Both models result in values that are too high according to the -40.3 dB target, but the cylindrical model gives a more stable target size. The “too high” TS values can be a result of constructive interference. There is an ongoing debate whether mean TS should be calculated as the arithmetic or the logarithmic mean (Lilja et al., 2000). The mathematical correct way is to convert to the linear domain, finding the mean value and then converting back to the logarithmic domain. This procedure will, however, focus on the few strongest echoes. Treating TS as a linear variable when finding the average is often used. If we calculate the mean TS directly from the logarithmic values, a mean TS of -42 dB is found in the 6.5 m range. This is close to the actual -40.3 dB that the target should have. Calculating the accurate target strength is not possible without any acoustic axis and without reliable off axis position estimates.

In Rimov, the -40.3 dB target was mounted on the acoustic axis and calibrated by adjusting the gain until correct estimates were detected (Figure 111). At 5 and 7 meters this worked fine, but problems occurred at 10 meters (Figure 115). Here it is seen that the target strength continues to increase with decreasing angular position and reaches a maximum at 1 meter or at -1 deg. If intensity contours are drawn between the indicated
vertical intensity profiles in Figure 110, it is seen that the shadow beam becomes narrower and approaches the main beam with increasing range. The effect at 10 meter can be described as the two beams melting together.

Discussion

The Tana and Rimov measurements clearly demonstrate that the theoretical sonar beam can be corrupted under certain conditions. Common factors for both sites during the observations were a) observations of the target outside the theoretical beam b) warm and nice weather, c) shallow water and d) at least fairly smooth and hard bottom. In Rimov, it was found that the phenomenon depended on the transducer’s opening angle, depth, and tilt. A third and unknown factor must exist because the phenomenon could not be repeated later in the Rimov pond. It is tempting to assume that this factor is the temperature. Thermal inhomogeneities and thermal layers could exist both in the River Tana and in the Rimov pond, causing dispersion and thereby multiple sound paths.

Conclusions

The River Tana and the Rimov measurements clearly demonstrate that the theoretical sonar beam can be corrupted under certain conditions and that this leads to an unexpected increase in the sample volume. The phenomena can also cause erroneous target size and position estimates.

Loosing control of the beam and the sample volume is a serious threat to the hydroacoustic monitoring method. It is important to find out what causes the phenomenon and when it is likely to occur. It is essential to test the influence of water depth, bottom substrate and temperature.

In order to avoid erroneous estimates of fish stocks, it is important to test the behaviour of the beam. With fixed positioned sonar, this can be done by beam mapping, and by placing known reference targets within and under the beam during surveying.

The phenomena in Tana and Rimov seem related. This cannot be concluded from the observations, however. Future experiments need to check for the possibility of two different phenomena.

If the phenomena can be controlled, the increase in sample volume could improve the hydroacoustic fish detection method. It is tempting to be able to detect all targets from
surface to bottom. Size distribution could be detected by an additional system working under normal conditions.

Acknowledgements

Simrad AS, the Finnish Fish and Game Research Institute RKTL, the County governor in Finnmark represented by Kjell Moen and the River Tana Salmon Fishing Rights Owner Association made the fieldwork in the River Tana possible by providing equipment and manpower. We want to thank all involved persons for making this fieldwork possible. Especially we will like to thank Frank R. Knudsen from Simrad who took part in the actual measurements.

We thank Jan Kubecka and his Institute the Hydrobiological Institute, Academy of science of the Czech Republic, Ceske Budejovice. Kubecka and the Institute provided equipment and accommodation during the one week long survey in Rimov. Kubecka also assisted and gave advice during the work. We thank Jarka Frouzova from the Hydrobiological Institute for her assistance during the survey.

References


### Tables

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<td>tilt</td>
<td>(m)</td>
<td>rvd</td>
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<td>4x10</td>
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<td>R1</td>
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<td>0</td>
<td>5</td>
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<td>0</td>
<td>7</td>
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<td>0</td>
<td>7.8</td>
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<td>R7</td>
<td>7x7</td>
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<td>0</td>
<td>5.2</td>
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<td>Two beams. Second beam 10 dB weaker.</td>
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<td>R8</td>
<td>4x10</td>
<td>0.8</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>Sweeping range with target depth =1.3 m. Detection at all ranges from 0.9 to 10.86 m.</td>
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<td>R9</td>
<td>4x10</td>
<td>0.34</td>
<td>0</td>
<td>7.2</td>
<td>Partly</td>
<td>Observing one normal beam with centre at 0.8 m depth. Echo intensity increases again when target approaches bottom.</td>
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*Table 28. Observations. T = Tana. R = Rimov. Column 2 indicates transducer type and rotation. 4x10 is the ES120-4x10 mounted with the narrow opening angle in the vertical plane. 10x4 indicates that the transducer is rotated 90 deg. with the 10 deg. opening angle in the vertical plane. 7x7 refers to the ES120-7x7 transducer.*
<table>
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<td>-10</td>
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Table 29. Correcting the target strength according to spherical and cylindrical damping.

Figures

Figure 102. Photos from Tana. Left: The assistant Gry V. Haraldsson demonstrating the beam-mapping rod with the measure wheel and target. Working boats are seen in the background. Right: Picture taken from the equipment caravan giving an overview of the river during beam mapping. Cables for the transducer's pan, tilt rotor and the sonar signals are seen in the foreground.
Figure 103. Photos from Tana. Left: Part of river bottom photographed late in the season when water had withdrawn. The bottom at the actual site was verified to be similar by observations from divers. Right: Transducer mounting with rotor and tripod. The camp with equipment and accommodation caravans is seen in the background.

Figure 104. From Rimov. Left: Overview of the pond with the movable bridge and the equipment caravan. Right: Transducer stand with rotor and the transducer.
a) meter  6.5  12  27.  42  52   m.
b) Depth  2.25 2.7  3.0  3.5  3.5  m.
c) beam  0.45 0.84 1.89 2.93 3.63 m.

Figure 105. Geometry and observation positions for the River Tana beam mapping. 
a=range, b=water depth, c=beam thickness. Small circles indicate target positions. 
Transducer is drawn in the upper left corner with the 4 deg. beam increasing to the right. 
Bottom is drawn as an ideal slope not unlike the real bottom. The arcs indicate the 
measured echo intensities with increasing intensity to the right.

Figure 106. Compressed SED-echogram from beam mapping at 52 meter in the River Tana 
at range of 52 m. Threshold set at –25 dB. The target is seen as the upper line. The target 
is lifted slowly from bottom to surface during ping 1 to ping 1390, taken out of the water, 
and then dropped down to the bottom again. At ping 1 and ping 1597, the target is resting 
on the bottom. Drifting of the boat causes changes in the range.
Figure 107. Beam mapping in the River Tana at a range of 6.5 m. Echoes from a standard Cu-sphere lifted slowly from bottom to surface. TS has been compensated for geometrical spreading loss ($40\log(R)$), but not for off-axis loss. (Beam compensation)

Figure 108. Beam mapping in the River Tana at range of 52 m. At ping 0, the target is lying on the sandy bottom. The target is then lifted through the water-column until it reaches the surface at ping 990. Water depth at this range was 4 meter giving a ping to depth rate of 248 ping per meter. The upper figure gives the along-ship angle estimates in degrees. The lower figure gives the target strength (TS). TS have been compensated for geometrical spreading loss ($40\log(R)$), but not for off-axis loss.
Figure 109. 3D-echogram from the River Tana. The target is just being lifted up from the river bottom far below the sonar beam at 6.5 m range. Clear and distinct echoes are seen. The mean echo length of the displayed echoes were 1.55 times the transmitted pulse-length.

Figure 110. Experimental set-up in the Rimov pond. ES120-4x10 transducer mounted mid-waters with the 4 deg. opening angle describing the vertical axis. Circles indicate some of the target test positions and test lines. The arcs at 5, 7 and 10 meter indicate measured intensity when the target was lifted through the water-column.
Figure 111. Single echo detected echoes from a standard Cu-sphere lifted from bottom to the surface in a shallow pond. Range = 5.14 m. The target passed the surface at ping 745 giving a lifting speed of 499.3 ping per meter. The upper figure shows the uncompensated target strength while the lower figure shows the measured angular positions. File: 06211350.dg0

Figure 112. Echo-signal from the target resting on the bottom of the Rimov pond 10 m from the transducer. The strong echo starting at sample number 410 is from the back wall of the pond.
Figure 113. Single echo detected echoes from a standard Cu-sphere moved from the close end to the far end of the pond at a depth of 80 cm. ES120-4x10 transducer mounted mid-waters with 0 deg. tilt.

Figure 114. Single echo detected echoes from a standard Cu-sphere moved from the close end to the far end of the pond at a depth of 130 cm. ES120-4x10 transducer mounted mid-waters with 0 deg. tilt.
Figure 115. Single echo detected echoes from a standard Cu-sphere lifted from bottom to the surface in the pond. Range =10.7 m. Target measured in steps. Each point represents the mean value of 50 echoes.
18 Paper VIII

Influence from water current on hydroacoustic measurements

Abstract

Hydroacoustic fish detection methods for fish stock assessments have for some years been tested in shallow rivers. One or a few fixed-location side-looking transducers are common. Many problems not known from vertical open water hydroacoustics can occur. In order to develop methods better suited for shallow rivers, it is important to learn how this new environment influences the sound. The influence from water current on the sound beam is tested in this article. This is done in a shallow pond with the application of an electric outboard engine. The engine produced a current normal to the sound beam at a range of 6.4 m. A standard Cu-sphere (23.0 mm, 120 kHz, $-40.3$ dB) was mounted at a range of 9 meters. The current was observed to influence the background reverberation level significantly in the current region and on the detection of the target.

Keywords

Hydroacoustic, sonar, split-beam, water current, pond experiment

Note! The paper has not been published. The experiment has to be repeated with better control of water current and water quality before we want to publish the results.
Influence from water current on hydroacoustic measurements.

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Introduction

For some years we have worked with hydroacoustic fish monitoring techniques in shallow rivers. We are using a side-looking split-beam sonar with a narrow opening angle. The method is promising, but we have experienced many difficulties. Sonar data recorded in shallow rivers have proved more difficult to analyse than data recorded with vertical sonar in lakes. Noise-based detections from the single echo detector and missing echoes in tracks from fish have been major reasons for this. One difference between the two applications is the water current. When a transducer is placed in a river, the water current can influence the recording in different ways. There are practical problems related to the mounting of the transducer. The current may force the transducer to vibrate and thereby introduce uncertainty in the angular position estimates. The water current can make stones and other objects produce noise by forcing them to rattle. Silt, debris and air bubbles in the water will pass the beam and influence on the echo-signal.

The turbulent water current might also interfere more directly with the sound waves. The main aim of this study has been to test for such interference.
Refraction caused by thermal inhomogeneities

According to (Urich, 1983) inhomogeneities exists in the sea as well as in the atmosphere. Inhomogeneities in temperature result in different indexes of refraction at different positions. A propagating sound wave will be scattered and refracted, causing the sound wave to split into multiple paths. Interference between the different paths can occur. In situations with current and turbulence, this interference will result in a time varying signal at the receiver. With a split-beam echo sounder transmitting short sound-pulses, these time variations in the signal will cause both sample-to-sample and echo-to-echo variability.

Displacement of the sound-beam

Sound waves can be explained as interactions between molecules in the medium. If the molecules move, this should also influence on the propagation of the waves that are carried by the molecules.

If a rod is placed in a water channel and set to vibrate, waves will start to spread out in circles on the water surface. The wave front will first reach the closest channel wall at a point on the normal from this wall to the rod. A pair of sensors mounted symmetrically to each side of this point will soon after and simultaneously be reached by the wave.

This will change if a water current is introduced in the channel. The vibrating rod will still produce a circular wave pattern, but the circles will drift along with the current. The first meeting point between the wave front and the channel wall will no longer be at the normal, but further downstream. The downstream sensor will be reached first. If signals from the sensors were our only source of information, we would believe that the rod had moved in the direction of the current.

This is illustrated in Figure 123. If the sensors are the elements of a split-beam transducer and the rod radiates sound waves, the downstream transducer element will detect the wave before the upstream element. On the echo sounder's angle position screen it will look like the rod had moved in the direction of the current.

When the sound beam and the water current are normal to each other, the horizontal displacement $d$ can be calculated from equation (1). From the numerical example, it is seen that a target will be estimated with a horizontal displacement of 3.78 mm per meter water current.
\[ d = \frac{v \cdot 2 \cdot R}{c} = \frac{2.8 \cdot 2 \cdot 1}{1480} = 0.00378 \]

Where \( d \) is the displacement in meter, \( v \) = water speed in \( \text{ms}^{-1} \), \( c \) = sound speed in \( \text{ms}^{-1} \) and \( R \) is the range or the distance that the sound has to travel in the water current. The factor 2 is applied because the sound passes the region twice.

**Material and method**

The experiment was carried out in a test pond at Rimov in the Czech Republic (Figure 116). The pond is 13 m long, 6 m wide, and 1.5 m deep. A Simrad EY500 echo sounder equipped with an ES120-4x10 transducer was used in the test. The transducer was mounted at one end of the pond, aimed horizontally along the pond’s centre axis. An electric outboard engine of the type WonderTroll 909 generated the water current. The engine was mounted on a bridge 2.65 m to the side of the sound-beam’s acoustic axis with the propeller aiming normal to the beam. The engine was mounted so that the current should cross the sonar beam at a range of 6.4 m. A standard copper target of \(-40.3 \text{ dB}\) was mounted at a range of 9 m. The depth of the transducer centre, the propeller and the target were all 0.70 meter. The set-up is sketched in Figure 117.

**The experiment**

The transducer pan and tilt was adjusted until the target was seen in the centre of the position window of the EY500. The TS gain was adjusted until the target was detected with \(-40.3 \text{ dB}\). The sonar recording was started before the engine was turned on. After having recorded 430 ping without water current, the engine was started. No noise was observed on the echogram when the engine was turned on, but later, random single echo detections and an increase in reverberation level was observed at the range where the current was expected to pass the beam. The current could not be seen on the surface of the pond, but turbulent water was up welling at the pond wall opposite the engine.

With a 4x10 deg. transducer, the 1/2 beam width at the range of the engine is 0.22x0.56 meter. The engine was thus mounted far away from the theoretical beam. The distance from the upper \(-3 \text{ dB}\) beam to the surface was \(0.70 - 0.22 = 0.48 \text{ cm}\) while the distance from the lower edge of the \(-3 \text{ dB}\) beam to the bottom was 0.58 cm. With the present transducer mounting, the beam would have hit the surface at a range of 20 m.
The echo sounder’s transceiver parameters were set to: Transmitted pulse-length = 0.1 ms, Ping per sec. = 7.6, Frequency = 120 kHz, Power = 63 watt, 3 dB Beamw. along = 4.3 deg., 3 dB Beamw. Athw = 9.1 deg., 2-Way Beam Angle = -21.70 dB. Angle Sens. Along = 38.0, Angle Sens. Athw = 15.0

The single echo detector parameters were: Min. Value = -55 dB, Min. Echo Length = 0.8, Max. Echo Length = 1.5, Max. Beam Comp. = 6 dB, Max. Phase Dev. = 10. The Min. and Max. Echo Length parameters are given relative to the transmitted pulse-length. Max. Beam Comp. is the maximum target strength compensation factor calculated from the off-axis position of the echo. When set to 6 dB, only echoes within the -6 dB beam will be accepted by the single echo detector. The Max. Phase Dev. parameter expresses the standard deviation in the angular samples within each echo-pulse. The parameter is calculated from the EY500's internal phase step detector and not from the mechanical angles. It is always the angular axis with the largest deviation that is tested against the parameter. The relationship between phase deviation and mechanical standard deviation can be expressed as:

\[
MaxStdDev = \left(\frac{180}{64 \cdot AngleenSitvity}\right) \cdot MaxPhaseDev \tag{2}
\]

**Software and data post-processing**

The EY500 was set to record sample power, sample angle and single echo detector (trace) data. The *Sonar5* post-processing program from the University of Oslo was applied in the data analysis and to create the presentations. Microsoft Excel and Statgraphics PLUS 4.0 from Statistical Graphics Corp. was applied to the analysis of echo information extracted by *Sonar5*. 
Results
When the water current was introduced in the pond, the following was observed:

- The reverberation level increased in the region where the current passed.
- The single echo detector (SED) started to detect echoes from the water current.
- The Cu-sphere behind the current was less frequently detected by the SED.
- The estimated horizontal position of the target was changed.
- The standard deviation in the angular estimates of the Cu-sphere increased.

Increased reverberation level
A significant increase in the reverberation level was observed after the engine had been turned on. The increase was limited to the region where the current crossed the beam. The result is demonstrated in Figure 118, Figure 119 and Figure 120. Figure 118 shows the increase relative to the size of the target. The sonar equation for spherical spreading and point sources (TVG of 40log(R)) has been applied in this figure. Figure 119 shows the echogram before and after the current is introduced. Figure 120 shows parts of the echogram in 3 dimensions.

It is clearly seen that the water current changes the reflection properties of the water. Before the current was introduced, the average reverberation level was $-50 \text{ dB}$. When the water current was introduced the reverberation level at the centre of the current increased with $9 \text{ dB}$ to an average $S_v$ level of $-41 \text{ dB}$. Peaks in $S_v$ were found as high as $-36 \text{ dB}$ in the centre of the current.

According to mixture of thermal inhomogeneities, an increase in the reverberation level was expected. However, an increase of $9 \text{ dB}$ is more than we would have expected.

Another explanation for the measured increase in reverberation level could be that the engine "dragged" particles form the nearby surrounding water and thereby increased the amount of particles in front of the beam. There were some algae, water bugs, and organic dust in the pond that could have been focused by the current. However, these particles should have caused more track-like detection than the scattered echoes seen on the Amp and SED-echogram.
Increased noise in the output from the single echo detector

At the same time as the increase in reverberation level was observed, the SED started to detect single echoes (SED-noise) from the water current layer. This noise is seen in Figure 121. The detection occurs randomly at all angles as demonstrated in Figure 122. The arithmetically averaged target-strength of the detected noise-echoes was calculated to $-42.5$ dB while the logarithmic average was calculated to $-50$ dB.

Influence from the current on the echoes from the target

The influence from the water current on echoes from the Cu-sphere is seen in Table 30. There are no significant influences on the target strength (a decrease of 0.16 dB). However, the horizontal angular position, the standard deviation in the angular positions, and the number of detected echoes seems to be influenced. Echoes are more often rejected by the SED when the sound has to pass through the turbulent current layer. The percentage of missed echoes increases from 23% to 27%. The position estimate of the target is moved 0.25 deg. in the same direction as the current. The standard deviations in both the angular estimates increase.

Increased echo rejection

To find the causes for the increased number of missing detections, sample data was analysed. 300 echoes from the situation without current and 300 echoes from the situation with current were analysed. The single echo detection parameter and the criteria applied by the EY500 are described in the material and method. We let the Sonar5 program calculate these parameters directly from sample data. The result is presented in Table 31. It can be seen that the echo length and the target strength are approximately the same, but there is a change in the phase deviation. Phase deviation reflects the highest of the phase step sample standard deviations in the angular measurements. By checking each ping rejected by the EY500' SED, we found that 100% of the rejections were caused by high values in the phase deviation. High values in the phase deviation parameter were most frequently found with samples from the vertical axis. 74% with water current and 68% without. In the rest of the cases, single echo rejection was explained by deviations along the horizontal axis.
Changed horizontal position estimate

When the water current was turned on, the sonar's horizontal position estimate of the target was altered. The target appeared as if it had been moved 0.25 deg. in the direction of the current. At a range of 9 m, this constitutes a displacement of 4 cm. The significance of this change in position was tested with a t-test. The test gave the t-value of \( t = 4.96 \) with a P-value = \( 9.2 \times 10^{-7} \). The hypothesis that the mean position estimates were equal in the two situations was thereby discarded. Position estimates from 200 SED-echoes with and without current were applied in the test.

From the recorded echogram, the thickness of the layer disturbed by the water was measured to 1.5 m. With a displacement of 3.78 mm per meter with water current, this gives a displacement of 5.67 mm, which is 7 times less than the measured value. For the observed displacement to be in accordance with the current, the current would have to be:

\[
\begin{align*}
\frac{\nu}{\text{m/s}} &= \frac{0.04 \cdot 1480}{2 \cdot 1.5} = 19.7 \text{m/s} = 71 \text{km/h}\n\end{align*}
\]

The actual water current was not measured, but 71 km/hour is far more than we could expect from a small electric outboard engine. We can therefore not explain the measured displacement.

Conclusions

The experiment demonstrates that phenomena connected with water current can influence on an echo sounder in various ways. The reverberation level increased in the layer where the current crossed the sound beam, and the single echo detector started to detect echoes from this layer when the current was turned on.

The current was seen to disturb the detection of a standard target positioned behind the current layer. The targets TS estimate was not significantly changed, but the number of single echo detections was reduced. This was related to an increase in the variability in the echo sounder’s sample-to-sample angular estimates.

Whether the observed effects were caused by particles in the water, by air dissolved in the water and released by the sudden stir of water, or by mixing of thermal layers cannot be stated from the data. All these elements might occur in a river, and the observation from the experiment fits well with what we see when we compare vertically recorded sonar data.
from lakes with horizontally recorded data from rivers. However, before drawing
c oncussions to whether the causes are the same, the experiment should be repeated with
better control of the water quality and the current.

References
Inc. USA, 423 p.

Acknowledgements
We thank Prof. Jan Kubecka and his Institute the Hydrobiological Institute,
Academy of science of the Czech Republic, Ceske Budejovice. Kubecka and the Institute
provided equipment and accommodation during the one week long survey. Kubecka
assisted and gave advice during the work in Rimov.

Tables and figures

Table 30. Statistics from echoes accepted by the single echo detector. N= total number of
analysed echoes. NA= not accepted echoes, TSc = mean compensated target strength. Ath
and sAth is the mean and standard deviation in the angle measured along the athwart-ship
or horizontal axis, Alo and sAlo is the mean and standard deviation in the angle measured
along the along-ship or vertical axis. R=range.

<table>
<thead>
<tr>
<th>Current</th>
<th>N</th>
<th>NA</th>
<th>TSc</th>
<th>CV (TSc)</th>
<th>BC</th>
<th>Ath</th>
<th>Alo</th>
<th>R</th>
<th>sAth</th>
<th>sAlo</th>
<th>sR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>300</td>
<td>68</td>
<td>-40.77</td>
<td>95.45</td>
<td>-0.12</td>
<td>-0.1</td>
<td>0.05</td>
<td>8.97</td>
<td>0.6</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>On</td>
<td>300</td>
<td>80</td>
<td>-40.61</td>
<td>63.89</td>
<td>-0.13</td>
<td>-0.34</td>
<td>0.02</td>
<td>8.97</td>
<td>0.61</td>
<td>0.25</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 31. Sample analysis. Mean values of parameters calculated from sample data. 300
echoes have been analysed in each situation. Without current, the EY500 detected 237
single echoes. With the current present, only 220 single echoes were detected.

<table>
<thead>
<tr>
<th>Current</th>
<th>Mean</th>
<th>Peak</th>
<th>R/Tx</th>
<th>Mean</th>
<th>Mean</th>
<th>Max</th>
<th>sTS</th>
<th>sAlo</th>
<th>sAth</th>
<th>Phase</th>
<th>Dev</th>
<th>Peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample</td>
<td>TS</td>
<td>Ratio</td>
<td>Ath</td>
<td>BC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off</td>
<td>2.9</td>
<td>-42.42</td>
<td>1.17</td>
<td>-0.02</td>
<td>-0.05</td>
<td>0.44</td>
<td>2.37</td>
<td>0.53</td>
<td>1.03</td>
<td>7.15</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>On</td>
<td>2.88</td>
<td>-42.25</td>
<td>1.17</td>
<td>-0.01</td>
<td>-0.26</td>
<td>0.55</td>
<td>2.34</td>
<td>0.60</td>
<td>1.07</td>
<td>7.99</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Table 32. Statistics from horizontal angular position estimates in echoes detected by the single echo detector. Ath is the athwart-ship or horizontal angles measured in degrees.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Ath (no current)</th>
<th>Ath (current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Average</td>
<td>-0.08</td>
<td>-0.33</td>
</tr>
<tr>
<td>Variance</td>
<td>0.43</td>
<td>0.33</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.66</td>
<td>0.58</td>
</tr>
<tr>
<td>Minimum</td>
<td>-1.70</td>
<td>-1.90</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Range (max, min)</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Stnd. skewness</td>
<td>-0.65</td>
<td>2.11</td>
</tr>
<tr>
<td>Stnd. kurtosis</td>
<td>-1.94</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Figures

Figure 116. Three pictures showing the pond at Rimov in the Czech Republic. Left: Overview showing the pond, the equipment caravan and the working bridge. Centre: Transducer mounting. Right: Mounting of the electric engine and the rod holding the target. When the experiment was carried out, the rod was mounted at the other end of the pond in order not to be disturbed by vibrations from the engine. The engine was oriented parallel to the bridge. (During the tests the outboard engine was aimed parallel with the bridge and not as seen on the picture)
Figure 117. Experimental set-up. A = transducer, B = outboard engine, C = bridge and D = standard copper target. Transducer mounted horizontally at 0.8 m depth. Distance between engine and acoustic axis = 2.65 m.

Figure 118. The left graph shows TS as a function of range before the water-current was introduced. The right graph is made with the water current turned on. The echo from the Cu-sphere is seen at 9 m range in both graphs. The effect of the water current is seen in the right graph around the 6.4 m. The graphs have been created by calculating the mean values from 150 ping at each range bin. Range resolution is 3 cm. per sample. TS with 40 log R is applied in order to show the correct size of the Cu-sphere.
Figure 119. Amp-echogram showing the $S_v$ values. The increase in reverberation level from the water current is clearly seen.

Figure 120. Three-dimensional echogram showing the $S_v$ values. The increase in reverberation level caused by the water current entering the beam at ping 175 is clearly seen. The 3D-echogram has been created from sample data with a range resolution of 3 cm per sample. The echogram has been smoothed with a mean filter. The filter dimension was 5 ping x 7 sample. (Ping number 150 refers to ping 290 in the original file.)
Figure 121. SED-echogram showing SED-detection from the water current.

Figure 122. Position diagram showing the angular distribution of the SED-noise.

Figure 123. Displacement of a target in the beam due to the effect of a water current.
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21\textsuperscript{th} Scandinavian Symposium on Physics Acoustics
Ustaoset 2-4 February 1998

Hydroacoustic fish counting in rivers and shallow waters, with focus on problems related to tracking in horizontal scanning sonar
21\textsuperscript{th} Scandinavian Symposium on Physics Acoustics  
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Hydroacoustic fish counting in rivers and shallow waters, with focus on problems related to tracking in horizontal scanning sonar.

by
Helge Balk and Torfinn Lindem\textsuperscript{6}.

Introduction

The increased interest in managing fish stocks in river systems makes it important to develop a new hydroacoustic fish detection method for fish counting.

Fish stock assessment is a well-established method with vertically mounted echo sounders. In this exercise we have modified and tested the method on a horizontally mounted split-beam system. An elliptic transducer with an opening angle of 4x10 deg. was mounted in shallow water close to the riverbank, looking out into the deeper part of the river. The goal was to verify if existing hardware and software could be used in this new environment.

With a split-beam echo sounder, fish are measured with target strength (TS) and spatial position in the beam. Echoes close in time and range, are connected into tracks,

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possibly from fish. This provides information on size, speed, time, and depth from the passing fish.

When the transducer is horizontally mounted in a river, new problems arise. First, the noise level increases. Second, the sonar's co-ordinate system is changed. Different echo-signals from bottom, surface, and drifting objects (Ehrenberg and Torkelson 1996) have to be separated from the fish-echoes.

![Diagram](image1.png)

*Figure 124. Changed co-ordinates as a result of changed transducer alignment.*

When the transducer’s alignment is changed from vertical to horizontal, the meaning of the co-ordinate system changes (Figure 124). While the delta-range (dR) parameter in the vertical situation describes a horizontal layer, it now describes a vertical layer.

Because fish are more likely to move horizontally in the water-column, this is an important change to the tracking algorithm. To deal with this change, we have tested a three-dimensional «Neighbour-region», calculating a dX and dY parameter from the angular measurements.

![Graph](image2.png)

*Figure 125. Counting-response.*

To test this arrangement we have measured the counting response with different shape and size of the neighbour-region. This has been done in both horizontally and vertically recorded files. The main conclusions from these tests are that a) the use of a one dimensional layer defined by the range parameter, produced the best tracking results both in the horizontal and the vertical case. b) The size of the dR parameter should be set close
to the system range resolution. c) The resolution in the range measurement was shown to be much better than the resolution of the angular measurement.

**Tracking in regions with high echo density**

Due to the increased noise level and the multiple object problem, the echo density increased. This led to situations with more than one echo in the neighbour-region of a track. The tracking algorithm has to solve this problem. Different solutions can be implemented in a tracking algorithm such as: a) Select the closest echo in space. b) Select the echo with the closest target-strength. c) Select the echo producing the smoothest track.

By testing these different solutions, we found that selecting the closest echo in space gave the most correct tracking.

**Suppressing unwanted objects**

It is essential to find a way to sort out echoes from unwanted targets. We have tested two different methods: a) Defining a «Movement-vector», MV, moving the Neighbour-region a specified distance in a defined direction. b) Defining an «Illegal-region» inside the Neighbour-region. The first method suppresses echoes following other trajectories than the one described by the Movement-vector. The second method suppresses echoes from fixed and very slow moving objects.

![Expected echo position](image1)

*Figure 126. Left: Movement vector Right Illegal region.*

To test the methods we have used a vertically recorded file with fish from the Lake d’Annecy and a horizontally recorded file with stones from the River Tornionjoki. The counting-response, mean track-length, and the track-smoothness were measured with varying length of the Movement-vector and Illegal region.
Figure 127 shows how using the Movement-vector influences the counting response for fish and stones. For stone-tracks the smoothness increases, indicating that we are producing fish-like tracks from the stone echoes. With $|MV| = 2$ m, all the stones are removed, but at the same time, the fish track-lengths are reduced, indicating that the fish tracks are fractionated. We must conclude that the method does not manage to separate echoes from fish and stones.

The second method using an Illegal-region does not produce fish tracks from stones when the region is increased, but it fails because it fractionates the fish tracks.

**Conclusions**

The established vertical counting method was not well suited in the new environment. The main reason was that the tracking-algorithm did not manage to suppress echo-signals from the unwanted objects.

Restrictions in positions and target strength tended to break up long tracks into smaller segments (Xie *et al.*, 1997) or it lead to the creation of imaginary fish tracks.

It is obvious that the tracking algorithm should only connect echoes into tracks. It should not try to separate or suppress tracks from different types of objects. This encourages us to propose a new counting model, adding a separate classification process after the tracking. To remove fixed objects, a noise filter should be inserted in front of the tracking process. See Figure 130.

**Figure 128. Model for fish counting in shallow water.**
Acknowledgment

This work was supported in part by Nathalie Gaudreau, RKTL Finland, Simrad AS and Hydroacoustic Technology Inc (HTI). We thank Natalie Gaudreau for sonar data from Lake d’Annecy, RKTL for sonar data from the River Tornionjoki, Simrad for equipment, technical support and sonar data from the River Numedalslå gen, and HTI for technical support.

References


20 Proceeding II

22\textsuperscript{nd} Scandinavian Symposium on Physics Acoustics
Ustaoset 2-4 February 1999

Fish tracking in shallow water by applying image processing
22\textsuperscript{nd} Scandinavian Symposium on Physics Acoustics  
Ustaoset 2-4 February 1999 

Fish tracking in shallow water by applying image processing  

by  
Helge Balk and Torfinn Lindem. 

Introduction 

Today, there is an increased interest in shallow water fish-stock assessment, and improved monitoring techniques are essential. Hydroacoustic fish detection methods seem promising, but for shallow water the equipment has to be easy to carry, use little power, and be inexpensive. For these reasons, we are working with the split-beam sonar. Applying one or a few horizontally aligned elliptical narrow-beam transducers, most of the river cross-section can be covered. 

Figure 129 describes the traditional split-beam monitoring method. Recording the echo-signal on four independent recording units, the phase and amplitude information can be extracted. The single echo detector uses this information to sort out echoes believed to originate from multiple-targets. The amplitude of the remaining single echoes can then be beam-pattern corrected, according to the estimated off-axis position of a target in the beam. The tracking algorithm then combines the single echoes into tracks (Balk and Lindem 1998), (Xie \textit{et al.,} 1997), (Ehrenberg and Torkelson 1996). These tracks can be counted and statistics such as size, speed, and migrating pattern can be extracted.
Problem definition

When a split-beam sonar is horizontally applied in shallow water, noise level and fluctuations in amplitude and phase measurements tend to increase. This results in the rejection of echoes from fish by the SED and in the creation of artificial noise-based fish-like tracks by the tracking algorithm.

Improving the method by applying image analysis

One way to improve the accuracy in this counting method is to use the sonar data in a more efficient way. We have observed that the SED removes important information from the signal such as echoes without valid phase measurements, echoes below a specific threshold and the shape of the tracks. (See Figure 130)
By applying image analysing elements to the raw data, we have managed to extract and use this information in an improved counting system. We applied a 3x15 median-smoothing filter to reduce high frequency components, region based segmentation to separate the foreground information from the background, and a contour detector to find the perimeters of the detected regions. Only the echo-signal located within these regions were then used by the SED and tracking algorithm to form SED-based tracks.

Numerical features can now be extracted both from the SED-based tracks and from the regions were the tracks were located. This can improve the ability to differentiate fish tracks from noise.

Figure 131. Fish-echo tracking method combining image analyzing tools with elements from the established method.

Figure 132. Examples of three fish migrating up-streams the River Tana summer 1998. Raw-echogram (left), followed by the result of applying a 3x15 median filter (center), and a region segmentation (right).
Conclusion

Combining echogram image tracking with the traditional SED and tracking method seems promising. More research has to be done on applying automatic segmentation methods, feature selection, and classification algorithms. We have, however, shown that this method manages to extract and use important information lost by the SED, reduce the creation of noise-based fish tracks, and suppress noise in the raw echogram. The overall ability to trace fish in sonar data with low signal-to-noise ratio is improved by this method.

Acknowledgment

This work was supported in parts by the County governor in Finnmark represented by Kjell Moen, Simrad AS by Frank R. Knudsen, the Finnish Fish and Game Research Institute (RKTL) in Finland and Fritz Albregtsen from the Institute of Information technology at the University of Oslo. We thank Frank R. Knudsen for help on collecting sonar data from the River Tana, Simrad AS, the County governor in Finnmark, and RKTL for providing equipment, and Fritz Albregtsen for advises on image analysis.
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