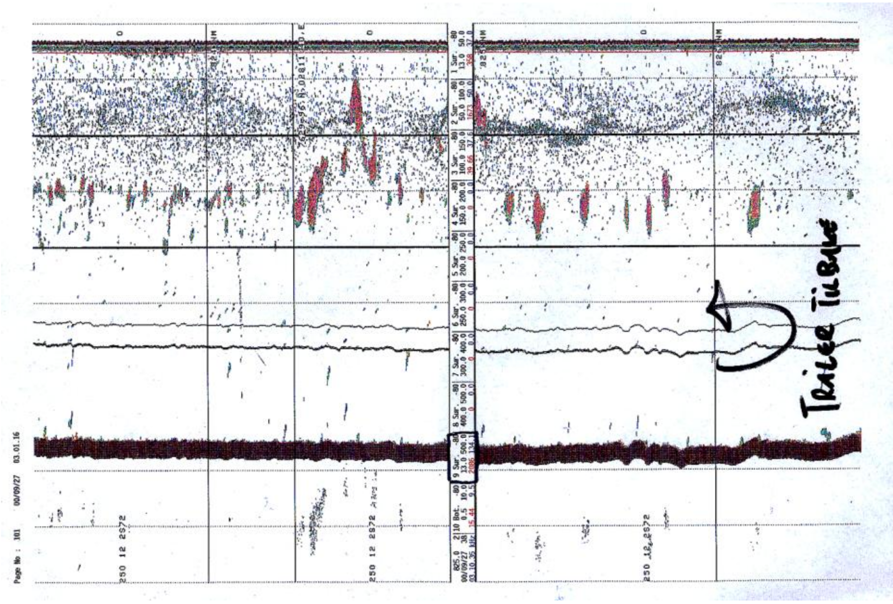
Hydroacoustic fish abundance estimation

Kjell Kr. Olsen and Roar Jørgensen
(translated to English and slightly modified in 2007 by Asgeir Aglen)



Institutt for Akvatisk Biologi
Norges Fiskerihøgskole
Universitetet i Tromsø

2006

1. The development and use of hydroacoustic methods

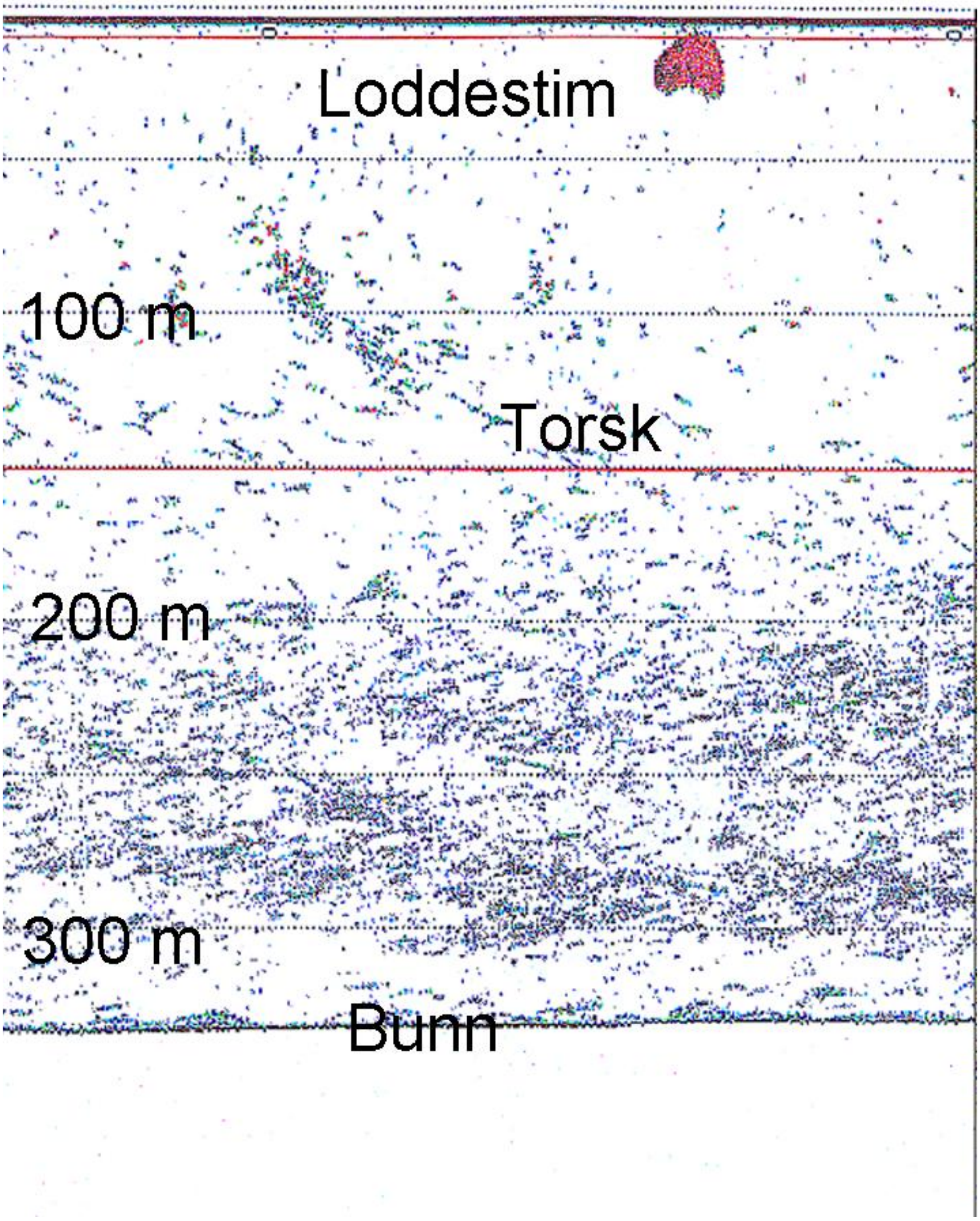


Figure 1: Echo records of capelin school and single fish traces of cod at the coast of Finnmark, March 2001.

As early as 1876 J. D. Colladon from Switzerland measured the sound velocity in water. He found that the velocity varied with salinity, temperature and pressure, and calculated an average sound speed of 1490 m/s (Tangen 2002). When knowing the sound speed, the travel time between two positions can be used to calculate the distance between the positions (distance=speed*time). The first known use of a self recording echo sounder (for measurement of bottom depth) was by a German named Breme in 1912. He detonated explosives at surface. A time recording unit measured the time lag between the detonation and the received echo from the bottom (Olsen, 1981).

During first world war underwater acoustic was used more widely. The development was driven by the military, but the trawler fleet soon discovered the usefulness of echo sounders and they became rather wide spread in the early 30-ies. In the beginning the trawlers mainly used the echo sounders for finding suitable bottom conditions for bottom trawling. Finding fish with echo sounders came later.

In 1934 echo sounder was for the first time used on a Norwegian fishing vessel. Since Norway had not yet developed a trawl fleet, this firts echo sounder was on a purse seiner. It was the sprat purse seiner, ”Signal III”, which used it for locating the fish. Rather soon a number of herring purse seiners also installed echo sounders. (Tangen, 2002).

The Research Vessel ”Johan Hjort” was in 1935 equipped with a 16 kHz echo sounder. The same year this was used in the Lofoten area during the spawning fishery for cod. ”Johan Hjort” reported to the fishers where the found cod recordings and at which depths the fish was observed. Later maps showing the cod distribution was produced from the research vessel measurements. Those were also included in the annual reports for the Lofoten fishing season (Sund, 1939). This was the first systematic mapping of fish based on echo sounder.

During the second world war there came a break-through for the so-called ”**ASDIC**” (**A**nti-**S**ubmarine **D**etection **I**nvesttigation **C**ommittee) or ”**SONAR**” (**SO**und, **NA**vigation and **R**anging), in later terminology. While the echo sounder just was able to record targets just below the vessel, the ”asdic” could also search for targets horizontally. ”Asdic” became a very important tool for hunting sub-marines.

Every year from 1950 onward the fishery scientist Finn Devold had a survey with ”G. O. Sars” in the Norwegian Sea to find the herring. By use of acoustic equipment he could follow the herring during its spawning migration towards the Norwegian coast. Now he was not limited by the use of echo sounders. He wrote “with the echo sounder we only observe the schools just below the vessel” (Olsen, 1981; Tangen, 2002). Now he could also use the sonar. In the late 50-ies sonar was also installed on the purse seiners.

In 1949 Simonsen Radio (Simrad) launched the first Norwegian produced echo sounder, after some military licences were released by the Military Research institute. Soon their products dominated the Norwegian market (Tangen, 2002). Much of the success for Norwegian scientists using acoustic instruments is owing to the good cooperation with Simrad. This cooperation made it possible for Simrad to have some governmental funding for the development work. Both fishermen and scientist could as a result have high quality products available.

Modern equipment gives new opportunities for the science; for quantitative abundance estimation of fish and zooplankton. Norway is in the front of this research. Acoustic abundance estimation is now used in a number of countries. In Norway it is used both for abundance estimation of pelagic stocks like capelin, blue whiting, sprat and herring and for some demersal stocks like cod, haddock and saithe. Acoustic methods are also used for investigations of o-group and zooplankton.

Acoustic equipment is used for a number of purposes as remote control of ROVs, and acoustic sensors on fishing gears. **ADCP** (**A**coustic **D**oppler **C**urrent **P**rofilers) are used to measure current velocity and direction.

2 Construction, how it works and calibration

Construction

A modern echo sounder system consists of
-Transceiver (transmitter and receiver) unit
-Transducer
-PC, both for running the echo sounder and exporting data to storage unit
-PC for logging and post processing of data
-Navigation instruments
-Printer

The brain in the echo sounder is a PC that both records the received echoes and triggers the transmission of pulses. A graphical presentation (echogram, similar to the old paper recordings) is shown on the screen. The echo strengths are visualised by use of colours (figure 3). The echo data and navigation data (position and log) are logged at chosen intervals. The data are normally exported to another computer for storage, scrutinising and post processing.

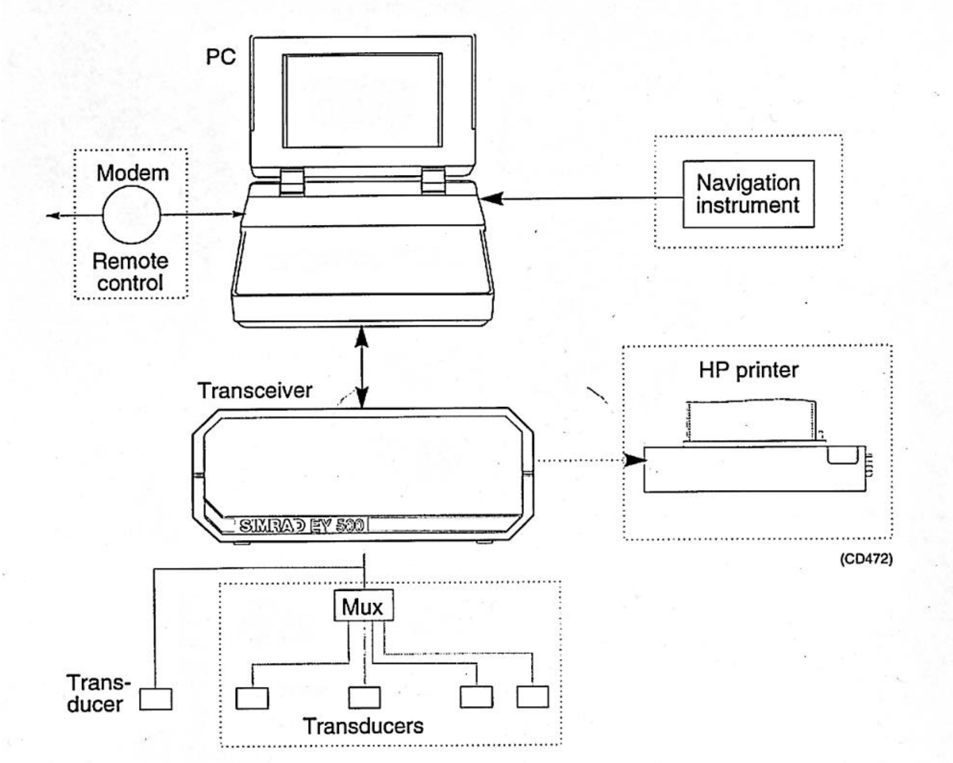


Figure 2. The pc-based echo sounder system EY500. From SIMRAD (1999)

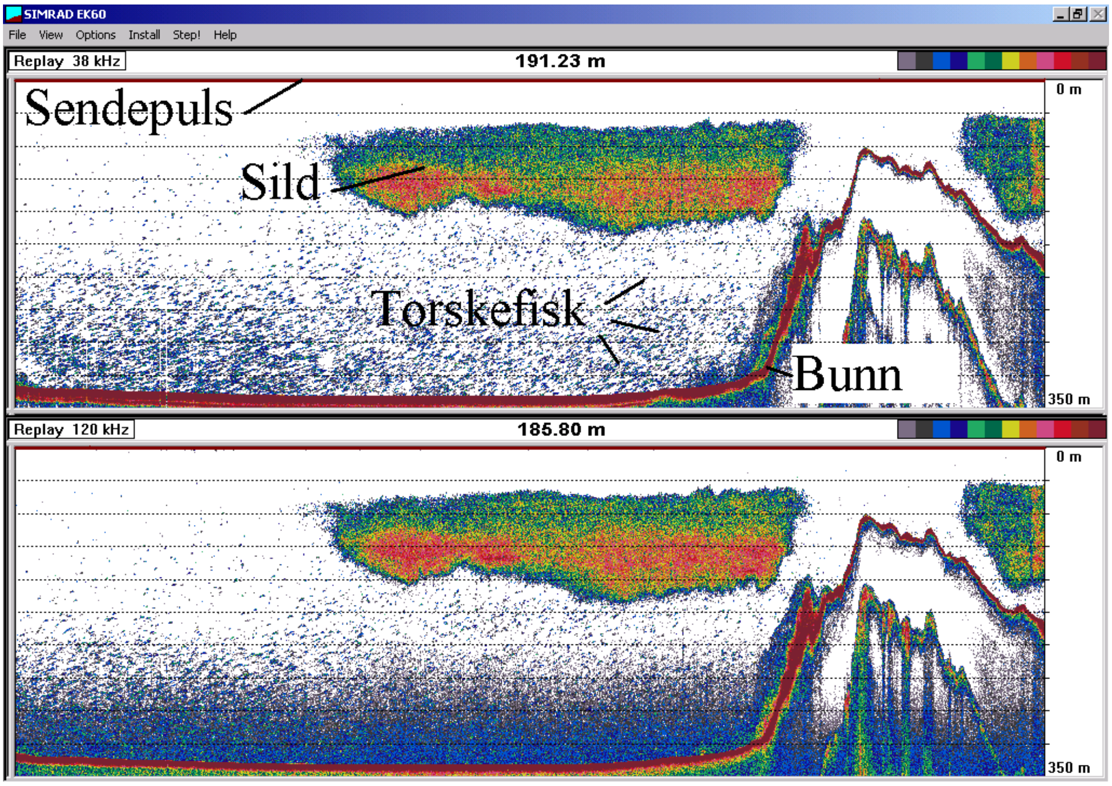


Figure 3 Echogram of herring shoal and scatter single fish of gadoids. Replay from a SIMRAD ER60 sounder.

The receiver has large dynamic range (160 dB), which means that small targets can be recorded at large depths. The measurements of signal amplitudes are quite precise and the system noise is low. This makes it possible to make precise measurements both from small and large targets at the same time (SIMRAD, 1999)

The receiver unit contains a module for attachment of PC and printers, an analogue module containing the transmit and receive unit, and a digital module for analogue/digital converting. The transceiver unit also make the amplitude measurements and for split beam measurements it also performs the phase measurements. In the transmitter unit the sound pulse is formed and amplified and implied on the transducer elements. The transducer work both ways; it transform the electrical transmitting pulse to a sound pulse, and any sound in the appropriate sound frequency, hitting the transducer is transform to electrical pulses that are recorded as echoes or noise. The algorithms for range compensation, bottom detection, echo integration and target strength calculations are parts of the pc software.

The echo sounder transmits a pulse of acoustic energy vertically towards the sea floor and measures the total time down and up again until the bottom echo is received. If it takes 1 sec and the sound speed is 1500 m/s the depth is 1500m/s*1s/2= 750 m.

The sound speed is particularly influenced by the salinity and the temperature of the water. In our waters sound speed variations are not very big, and fairly precise depth measurements can be obtained by setting a fixed sound speed (say 1470 m/s) for the entire water column. Modern echo sounder can be set up to read ctd data and apply the most realistic updated sound speed at depth. Modern sounders are also able to adjust the pulse repetition rate according to the bottom depth or the depth range of interest (for instance by transmitting a new pulse as soon as the bottom echo is received). Alternatively it can be set at a fixed rate.

The pulse is composed of a number of sound waves and has a fixed duration (τ), for instance 1 millisecond. The time for transmitting one single wave (the period) is inverse to the sound frequency (f):
$t=1/f$

At a frequency of 38 kHz we get $t=1/38000=26*10^{-6}$ seconds = 26 µs.
This means that a 38 kHz pulse of 1 ms must consist of 38 waves (periods).

At a sound speed of 1500 m/s the pulse length in water is 1500 m/s *0.001 s = 1.5m.

The calculation can be simplified by introducing the wave length (λ): n waves of length λ has an extension of $l_p=n*\lambda=n*c/f$ (Karlsen et al., 2001).

The pulse length is an important parameter in fisheries acoustics because:
- it determines the depth resolution for separating targets, both between individual fish and between fish and bottom. The radial distance from transducer to target has to differ by more than half a pulse length ($c/2$) to obtain non-overlapping echoes from the targets. This is illustrated in Figure 4. The shorter pulse length, the better resolution.
- On the other hand the signal/noise ratio and thereby the detection range increases with pulse length, because of the larger pulse energy in a longer pulse.

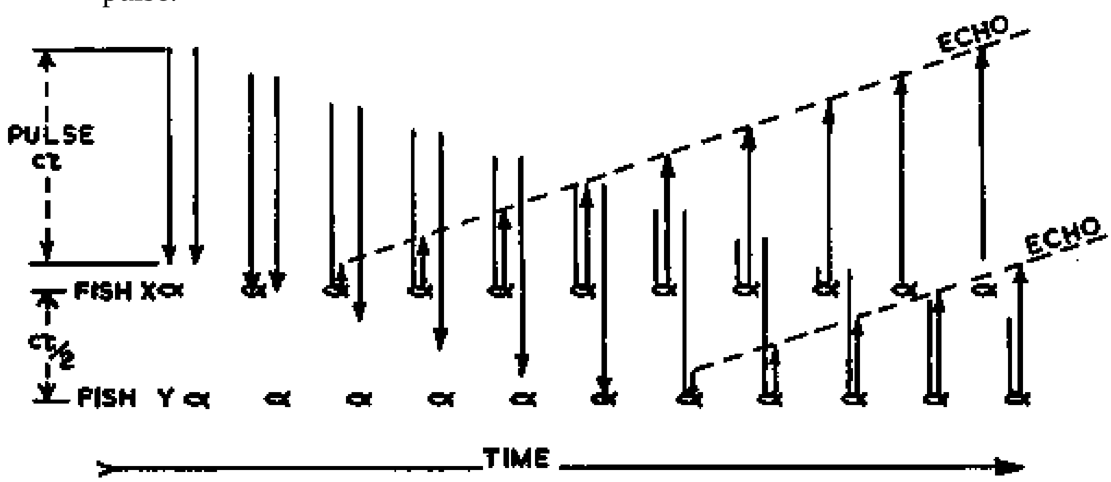


Figure 4. How the resolution is determined by the pulse length. From Johannesson and Mitson (1981).

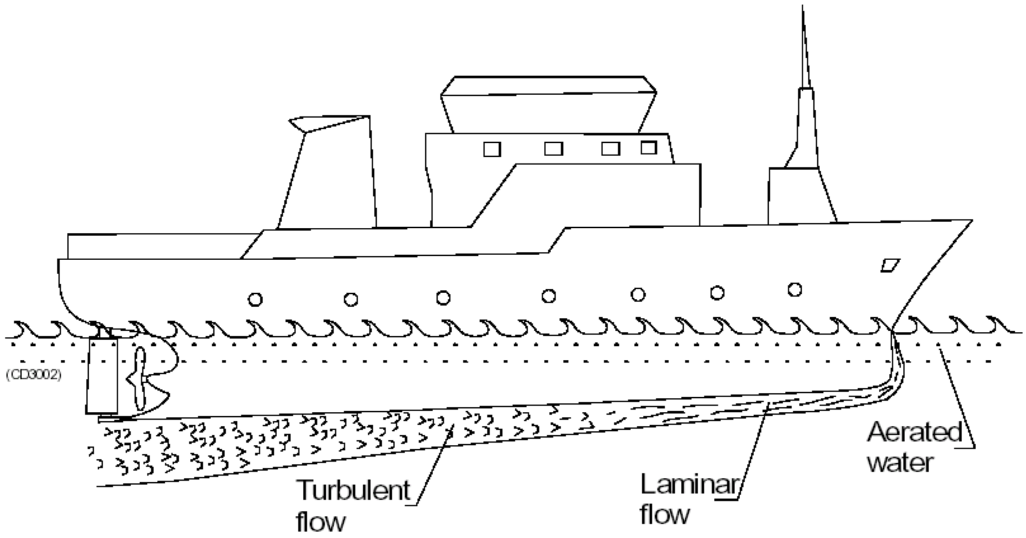


Figure 5. Water flow below the hull of a vessel. From SIMRAD (1999).

Conditions influencing sound transmission

Vessel based sensors like echo sounder transducers and sonars are mounted on the hull of the vessel. They should be mounted in a way that minimizes the influence of noise and air bubbles (Karlsen et al., 2001). Such noise is mainly induced by the vessel (sound from engine and other activities onboard, propeller noise and noise genreted by the movement of the vessel in the waves. Noise is mainly a problem for the reception of echoes, because it limits how weak echoes that can be detected above the noise level.

It is important that the transducer is mounted in the foremost 1/3 of the vessel where the water flow is laminar. This to reduce the amount of air bubbles in front of the transducer surface. Bubbles attenuate the sound and causes errors in the measurements. Bubbles may either derive from air brought down by the movements (pitching and rolling) in bad weather, or it can be generated by cavitation caused by pressure changes along the hull. In addition, in bad weather, patches of bubbles are brought several meters down below surface by breaking waves. The conditions for sound transmission are thereby reduced during bad weather. One way of reducing this effect is to reduce the vessel speed or change coarse. Many modern research vessels have the transducers mounted on a protrudable centre-board, that can be lowered 2-4 m below the hull. This improves conditions significantly (see figure 6).

Transducers and sound beams

Even if the transmitting and receiving circuits are separate in echo sounders, the same transducer is normally used both for transmitting and receiving the sound. A modern transducer is composed of a number of ceramic elements. When sound is transmitted, electrical energy is transform to acoustic energy. The electric signal cause the transducer surface to vibrate at a certain frequency for a certain duration and a sound pulse is generated. When sound (echo) is received, the opposite happens. The sound wave causes the transducer surface to vibrate and an electrical pulse is generated. The transmitter is sometimes referred to as a projector and the receiver as a hydrophone. The transducer acts as a projector when the electrical alternating current causes the elements to change size (pulsate) and thereby causing pressure waves on the water side of the transducer. This pressure waves have the same frequency as the electrical oscillations in the transducer. The opposite happens when pressure waves from an echo hit the transducer surface; The size of the elements pulsate and generate electrical voltage varying with the same frequency as the pressure waves. Figure 7 shows the construction of a transducer, and an experimental transducer mounted on an aluminium frame.

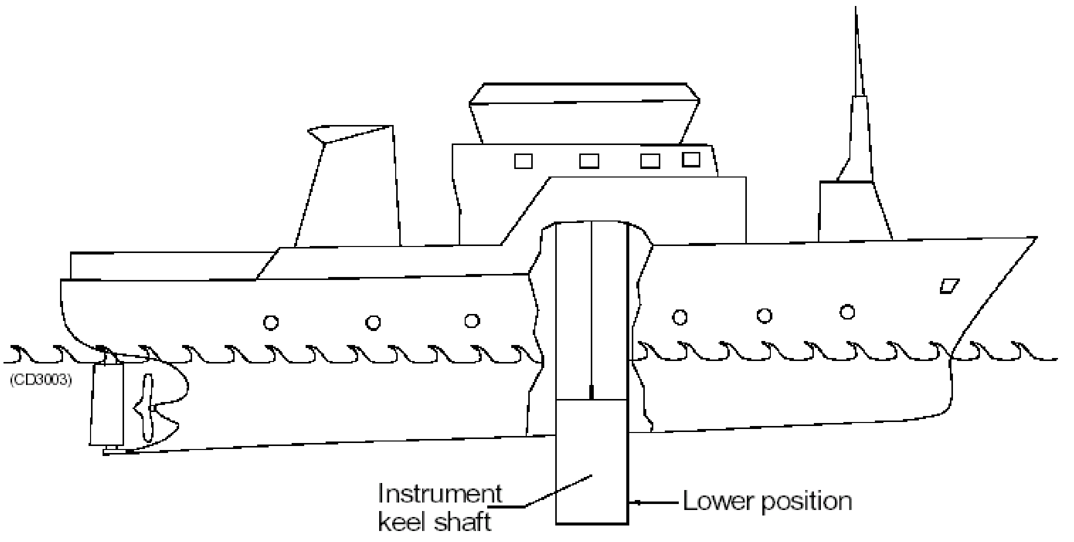


Figure 6. Protrudable centre-board (from SIMRAD, 1998).

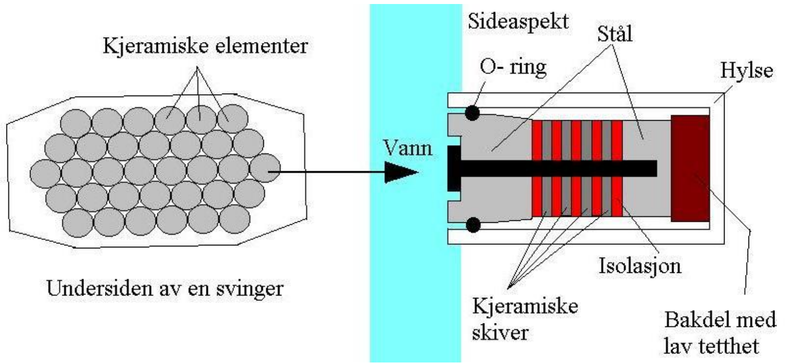


Figure 7. To the left is a picture of a ceramic transducer (SIMRAD ES 38-12). The middle picture show a typical array of elements in a transducer and to the right is the details of a single element. From McLennan and Simmonds (1992).

In the area close to the transducer (near field) the sound field is complicated and not suitable for acoustic measurements. The critical distance defining the near field for a transducer, R_c, is according to Ona (1999) determined by the largest dimension (d) of the transducer and the wave length (λ):

$$R_c = d^2/\lambda$$

The sound level at different directions from the transducer will due to interference patterns vary in a complex manner with several maxima and minima. The physical principle determining the directivity of the beam is identical to what in optics are called “optical gitter” (Olsen, 1981). We may consider the transducer surface as a row of point sources at a fixed internal distance. The corresponding beam directivity is shown in figure 8. The sound level is highest perpendicular to the transducer surface (acoustic axis) and decrease until first minimum is reached. Inside the first minimum is the main lobe. Outside the first minimum a new maximum is reached. This is the first side lobe. In figure 8 four side lobes are shown outside the main lobe. The figure is a cross section, so the four side lobes on each side are sections of four rings encircling the main lobe.

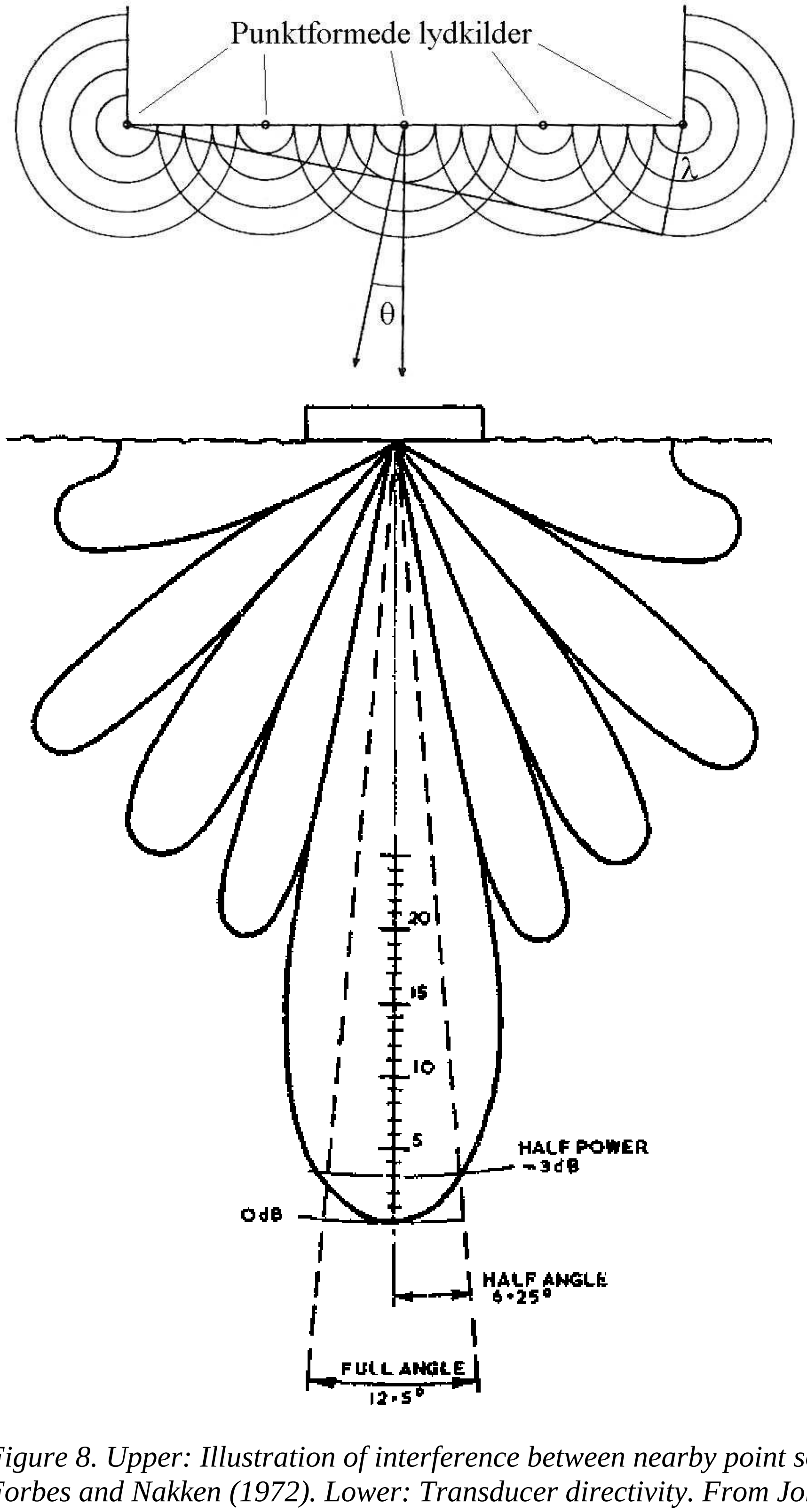


Figure 8. Upper: Illustration of interference between nearby point sources. From Forbes and Nakken (1972). Lower: Transducer directivity. From Johannesson and Mitson (1983).

The beam angle (θ) does usually not refer to the first minimum, but to the angle between the points in the beam cross section where the sound intensity is half the value at the axis; the half value angle (θ_{-3dB}). For a common rectangular transducer this is approximately:

$\theta_{-3dB} = 50 * \lambda / L$, degrees

where λ is the wave length and L is the length of the transducer. We see that a narrower beam would either require a larger transducer or shorter wave length (higher frequency).

One should notice that narrowing the beam means focussing the energy. This results in higher intensity at the axis (source level) and thereby better signal- noise ratio and larger range for detecting a certain target size. It is useful to have a measure of how well the transducer concentrates the transmitted (or received) acoustic intensity. This measure is called directivity index (DI). This is an important parameter in the calculations in acoustic echo integration.

Split beam echo sounder

Split beam echo sounders were developed for common use in the late 80-ies. The principles have earlier been used to calculate the direction of targets in radar and sonar technology. The principles are illustrated in figure 9 and 10. Echo sounders used for fish abundance estimation may include split beam systems where the receiver splits the transducer surface in 4 quadrants (see figure 9). During transmission all transducer elements act simultaneously (as in the single beam case), while the received signals are treated separately in the 4 quadrants. To calculate the angle to the target relative to the along-ship plane, the signals from the two fore ship quadrants are compared to the signals from the two aft ship quadrants. Similarly the signals from the two port quadrants are compared to the signals from the two starboard quadrants to calculate the angle relative to the athwart-ship plane.

Let d be the distance between two point receivers (for instance ceramic elements). For a wave front approaching these elements at an angle θ, the following will apply:
$\sin \theta = c * \Delta t / d$ (1)

Where Δt is the time difference between the front hitting the two elements and c is the sound speed (Reynisson, 1999). The distance $c * \Delta t$ can be expressed by the phase difference δ (given in radians, ranging from $-\pi$ to π) and the wave length λ

$c * \Delta t = \delta * \lambda / (2\pi) = \delta / k$ (2)

where k is the wave number. By inserting (2) in (1) we get:

$\theta = \sin^{-1} [\delta / (k/d)]$ (3)

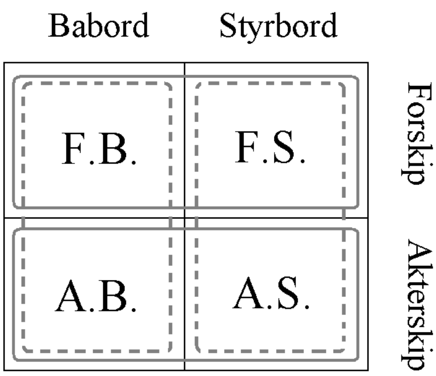


Figure 9: Scematic drawing of a split beam echo sounder. From Reynisson (1999).

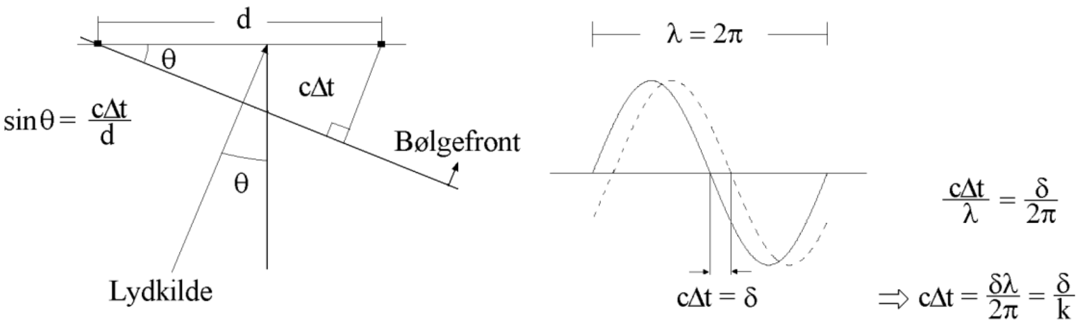


Figure 10: The split beam principle. From Reynisson (1999).

The constant terms $k*d = \delta / \sin\theta$ characterizes the geometry of the elements for a given wavelength. Adding another pair of elements, not parallel to the first two described (like using both along-ship and athwart-ship elements), give the opportunity to calculate the angle relative to another plane, thereby precisely estimating the direction of the wave front and thereby the direction to the target.

Sonars

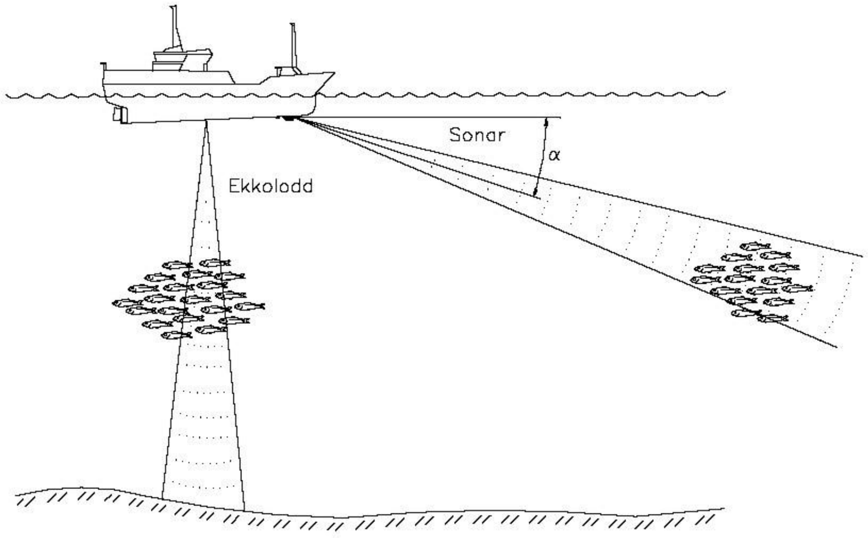


Figure 11. Sonar and echo sounder. From Kvamme (1999).

There are two types of sonars; active and passive. An active sonar detects echoes from objects from the directions where sound is transmitted. A passive sonar do not transmit signal, but only listen to sounds from other vessels (or biological sound)

Searchlight sonar
This is a single beam instrument used for fish finding. It is operated like a searchlight. You point it where you want to see. Otherwise it is constructed like an echo sounder, where the transducer can be mechanically pointed in various directions. The transducer is mounted on a protrudable steel pipe, to avoid to much shadowing and interference from the ships hull when pointing horizontally. The display was originally similar to an echo sounder display. Later it has been common to have it presented on a screen with the vessel in centre and the targets shown relative to the vessel (Simmonds and McLennan, 2005).

Side-scan sonar
This is a single beam sonar on a towed body, with the beam oriented perpendicular to the towing direction. The transducer is narrow in the fore-aft direction and wider in the vertical direction. Side-scan sonars are mainly used for mapping the sea floor. By using a towed body the transducer can be operated close to bottom with the beam pointing nearly parallel to the sea floor or at a slightly oblique angle towards bottom. Then weak echoes are obtained for a smooth and flat bottom while objects sticking up or small ridges or valleys will by clearly visible on the echogram. This way the echogram show a two dimensional picture of the part of the sea floor covered. Side-scan sonars have also been used for mapping and counting fish schools, for instance herring schools. Mapping the sea floor is also of interest for describing the demersal habitat (Simmonds and McLennan, 2005).

Sector scanning sonars
In searchlight and side scan sonars the transducer is moved or rotated to search new parts of the water volume. Sector scanners can do this quicker without moving the transducer. A wide pulse is transmitted so that targets in many directions can be

ensonified, and thereby return echoes. The receiver forms a number of neighbouring narrow beams sequentially, thereby observing with rather high resolution in a wide sector in the “horizontal” plane, but usually only one beam in the vertical plan. The function of sector scanners are more detailed described by Simmonds and McLennan (2005). Such instruments have been used both for fish finding, fish behaviour studies and bottom mapping.

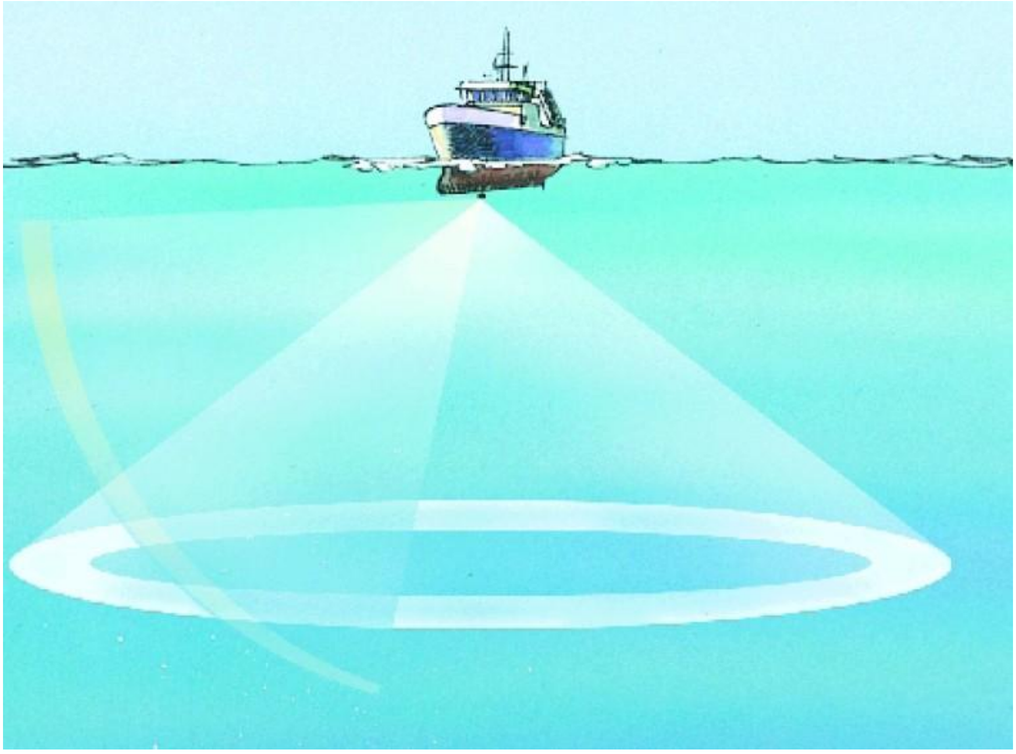


Figure 12: Omni sonar. From SIMRAD (2002).

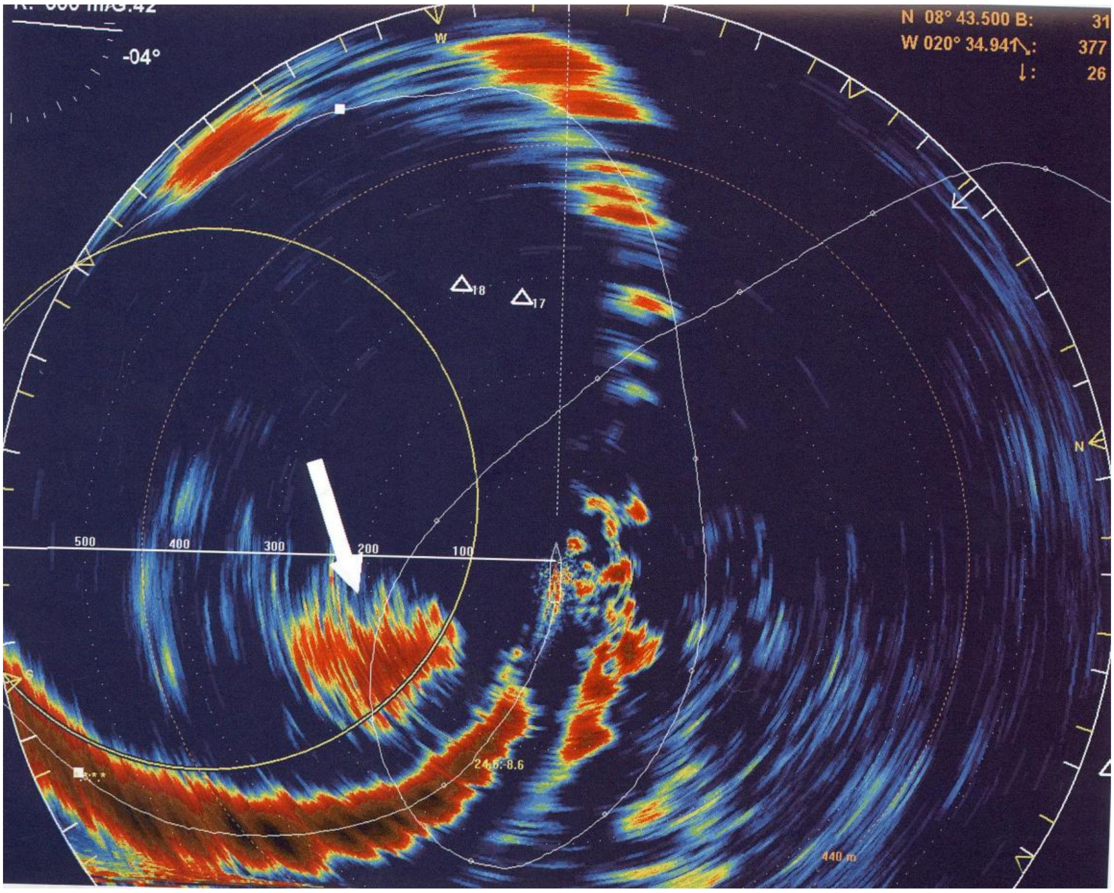


Figure 13: Omni sonar display (SIMRAD) from a purse seiner encircling a tuna school (arrow). The ship's track is shown by a thin white line. The propellar wake is seen as the dark red half circle in the lower left of the picture. From Simmonds and McLennan (2005).

Three dimensional sonar systems (omni sonars)

Omni sonars use electronic scanning to localise targets in two dimensions in different sectors in the half sphere below the vessel by using two sector scanning systems operating at the same time (see figure 12). Where these sectors are crossing each other the schools can be located three dimensionally. By connecting navigational instruments to the sonar it is possible to present the ship's track and the movements of the school and the vessel on the sonar screen. Another useful feature for the fisherman is the tracking function. This is a software which can keep track of a chosen target and orient the sectors so that both sectors cover the school and the full information is presented. Figure 13 shows a screen presentation of an omni sonar where the school and the vessel and the track lines are seen from above. Figure 14 shows a sardine school observed with another type of multy-beam sonar.

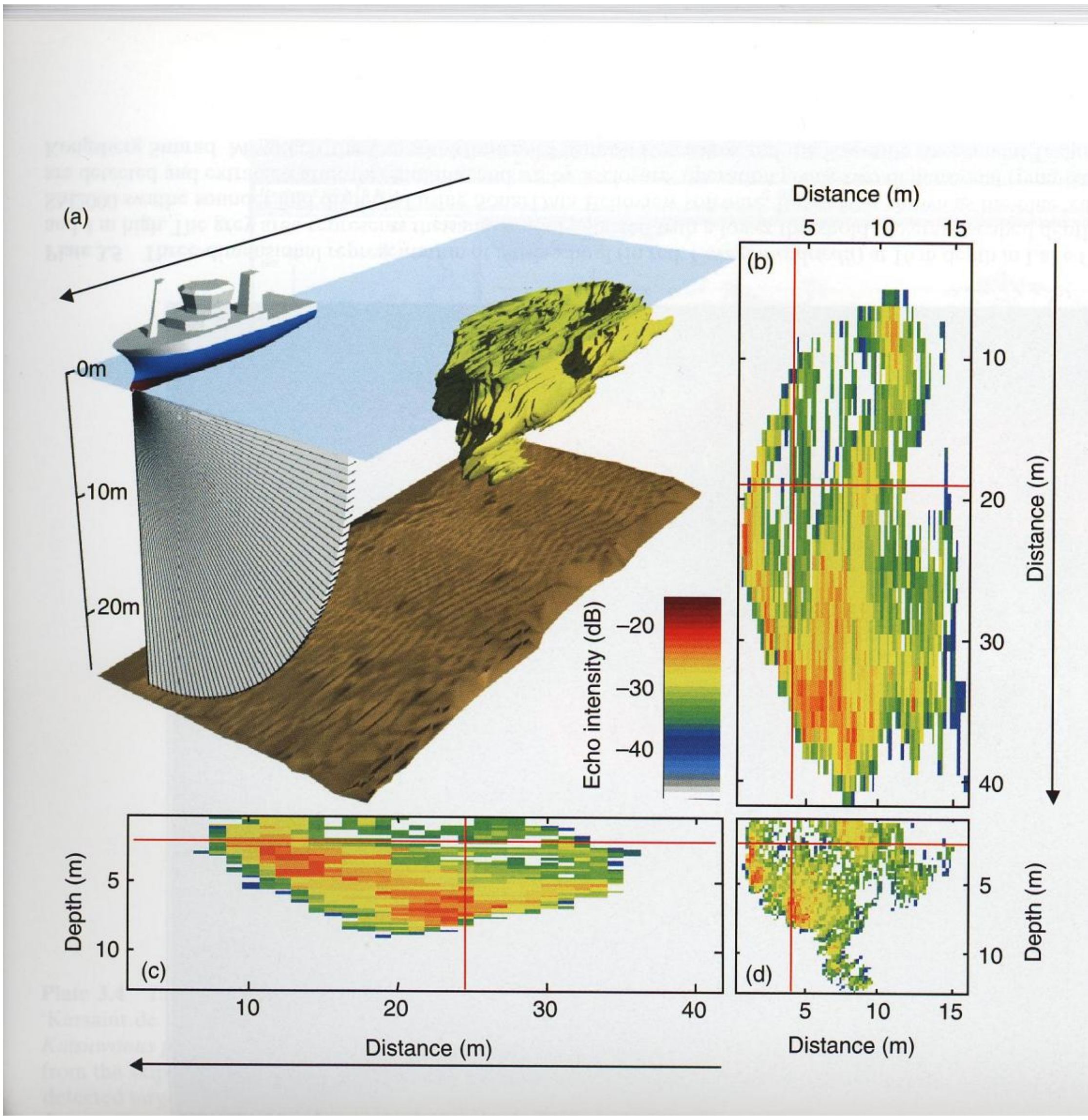


Figure 14. Presentation of a sardine school based on data collected from a 455 kHz Reson Seabat multy-beam sonar. A) 3D picture with possibilities for calculating volum, surface, length, width and height. The 60 beams for reception of signals are illustrated in the front of the picture. Panel b,c and d show sections of the school in three planes: b) horizontal, c) vertical along-ship, and d) vertical athwart-ship. From (Simmonds and McLennan, 2005).

Calibration

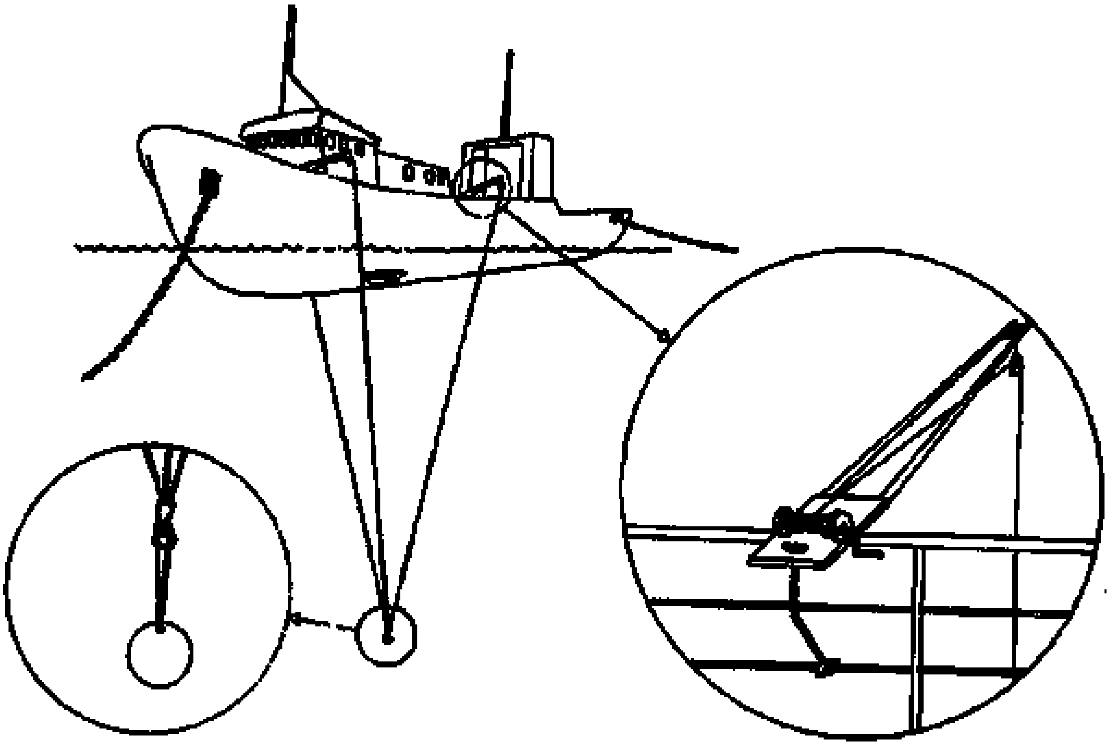


Figure 15: Suspension of calibrating reference sphere. From Foote et al. (1983).

The purpose of acoustic abundance estimation is to estimate density and biomass of fish or other organisms in a certain area. Precise and repeatable calibrations are a prerequisite to obtain precise fish abundance estimates. Another prerequisite for absolute abundance estimation is to know the target strength of the organisms measured.

The most common way of calibrating echo sounders is to use a standard reference sphere with precisely known target strength. Common reference targets are made of copper or wolfram carbide. Different echo sounder frequencies may require different size of the reference sphere (Foote *et al*., 1983; Foote and MacLennan, 1984). A 60 mm copper sphere is found useful for 38 kHz while a 42 mm copper sphere is found useful for 120 kHz.

With a hull mounted transducer three winches can be used to move the sphere within the echo sounder beam (figure 15). With a split beam presentation the movement of the sphere can be followed both across the beam and vertically.

Calibration of a split beam sounder is done in two steps (SIMRAD, 1999):

1) Measuring the sensitivity at acoustic axis
2) correction of the directivity diagram and the along-ship and athwart-ship beam angles

Measuring the sensitivity at acoustic axis

The sphere is lowered and manoeuvred to the acoustic axis. The TS gain is adjusted to obtain the correct target strength for the sphere. Then the echo intensity is measured. The *theoretical* s_A- value can be calculated as:

$$theoretical\ s_A = \frac{4\pi r_0^2 \cdot \sigma_{bs} \cdot (1852m/nm)^2}{\Psi \cdot r^2}$$

where $r_0 = 1$ is the reference distance, σ_{bs} is the back scattering cross section of the calibration sphere, r is the distance to the sphere, and Ψ is the equivalent two-way beam angle (The value is usually given as 10 log Ψ in the documentation from the transducer producer). If the measured s_A- value is different from the theoretical, this can be adjusted. In EK500 this is done by the equation:

New s_V *gain = Old* s_V *gain + 10log(measured* s_A*/theoretical* s_A*)/2*

Correction of the directivity diagram

For the Simrad sounders the producer supply the user with a software (Simrad, 1999) that logs all observations when the calibration sphere is moved around in the beam. If there is sufficient data coverage of the main beam area, the software calculates the beam characteristics (TS- gain, beam angles, directivity diagram, 10 log Ψ). Figure 15 shows an example of how the reference target can be suspended below the transducer, while figure 16 shows an example of calibration parameters calculated by the software LOBE (SIMRAD, 1999).

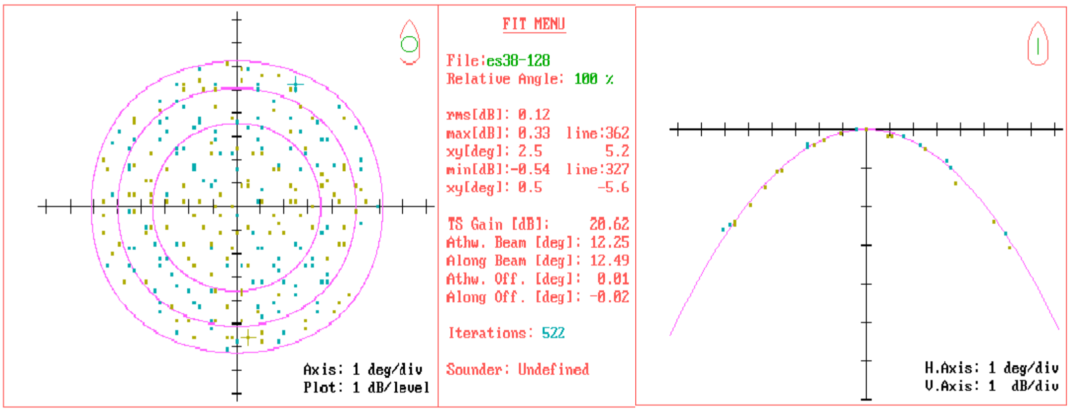


Figure 16: Software output of calibration parameters for a split beam echo sounder.

3 Sound propagation in water

Sound pulses, sound speed and diffraction

Echo sounders and sonars works by transmitting pulses and the sound reflected by targets are received as echoes. The reflected echo contains information regarding the distance to the targets and the characteristics of the reflecting targets. There is a relation between the sound speed (*c*), the wave length (λ), and the frequency (*f*):

$$c = \lambda \cdot f$$

At a given sound speed the wave length and frequency are inverse related. If one is increased, the other has to decrease (Johannesson og Mitson, 1983; Karlsen et al., 2001). We use the symbol c for the sound speed in water and we use the unit meters per second (m/s). The sound speed varies with temperature, salinity and depth. The depth dependence is rather insignificant for the use in fisheries acoustics. The influence by temperature and salinity is shown in figure 17.

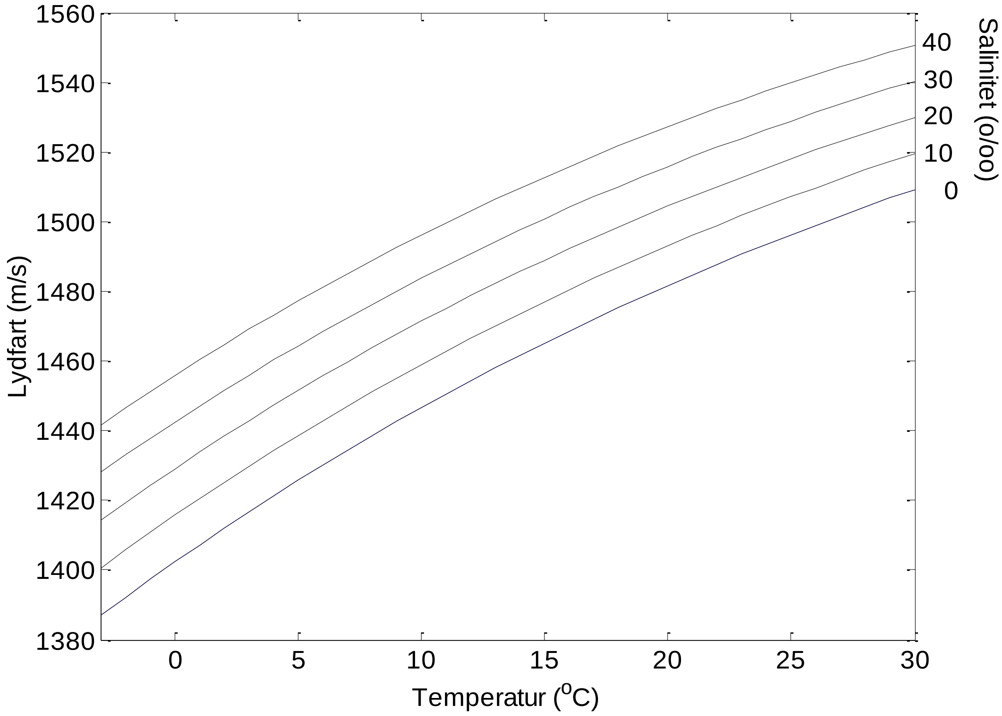


Figure 17: Sound speed as function of temperature and salinity. (calculated according to Clay og Medwin (1977): c =1449.2 + 4.6·T - 0.055·T^2 + 0.00029·T^3 + (1.34-0.010·T)·(S-35) + 1.58·1e-6, where T is temperature (℃) and S is salinity (PPM)).

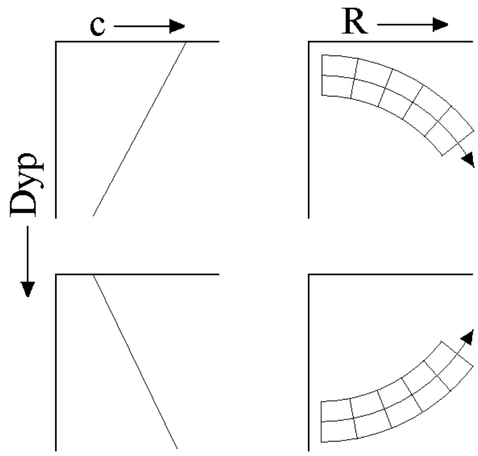


Figure 18: Diffraction of acoustic waves.

The depth can only be measured correct if the sound speed is known. As seen by figure 17 this is dependent on the hydrographic conditions that varies between locations and between seasons.

Most hydro acoustic instruments operate somewhere in the frequency range 10 kHz to 200 kHz (1 kHz = 1000 Hz). Within fisheries acoustics a limited number of single frequencies are in common use. For various historic reasons the use of 38 kHz has become most common. Even if we refer to single frequencies, the echo sounder transmits a wider band of frequencies. The sound intensity is thereby distributed over this band of frequencies. When talking about the frequency of the echo sounder one usually refer to the frequency in the centre of this band.

If the sound is transmitted horizontally or at oblique angles, as normally is the case with sonars, the hydrographical conditions may cause the sound to bend off (diffract) due to different sound speed in different layers, as illustrated in figure 18. When the upper part of the wave front travels at lower speed than the lower part, the wave will bend upward and end at the surface. In the opposite case it bends down to bottom. This often causes the transmitted pulse to end up either at the surface or the bottom, thereby reducing the effective searching range when searching for fish schools in midwater. If there is a sound speed minimum in the midwater, a “sound channel” is generated. Sound waves coming along these channels will be kept there and can travel over long distances.

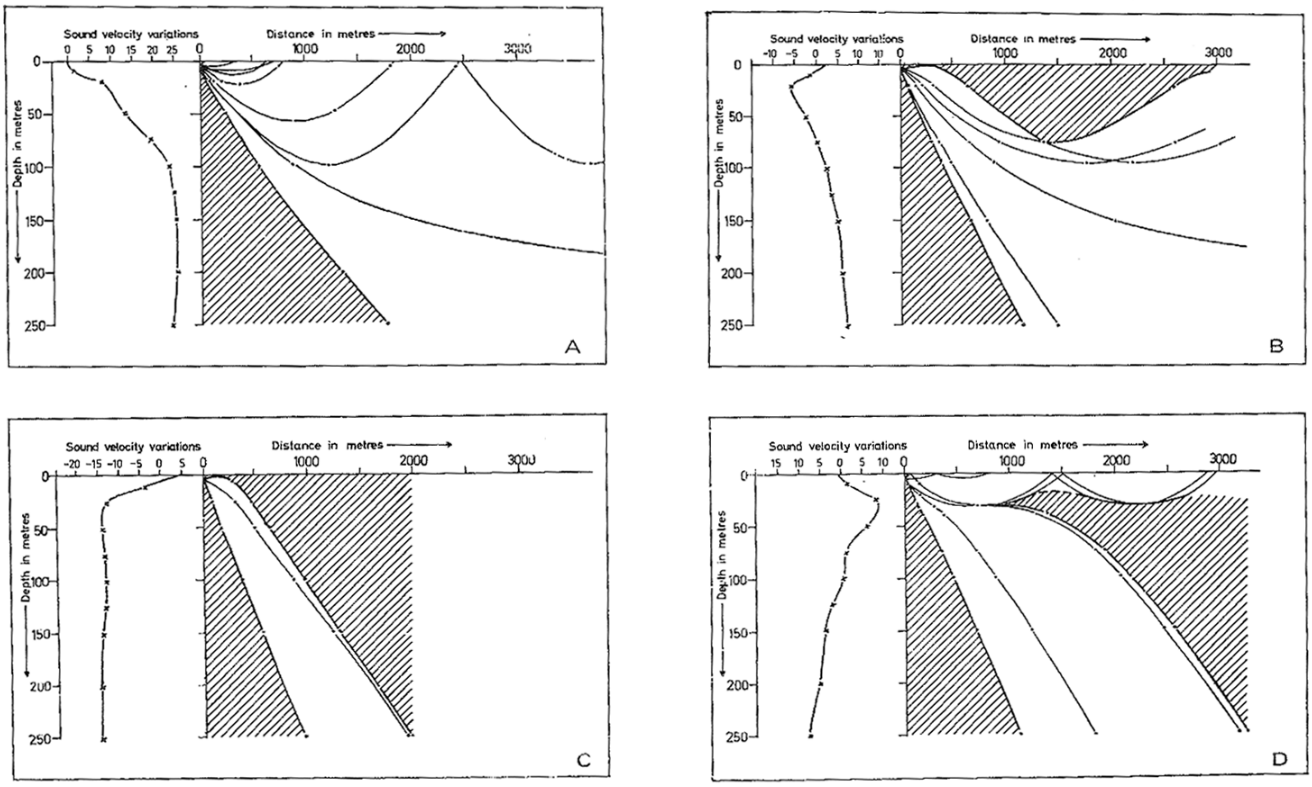


Figure 19: Four seasons in northern cold temperate waters. Vertical axis is depth(m). Left hand part of the horizontal axis is the sound speed, the right hand part is the horizontal distance from the vessel and the lines in the right hand part is the sound propagation paths at various transmitting angles. The hatched areas indicate difficult or blind zones. From Forbes and Nakken (1972).

In figure 19 typical sonar conditions for four seasons in our waters are shown. (A, B, C, D = winter-, spring-, summer-, autumn). Homogenous water masses give good sonar conditions, while strongly stratified water masses, is bad, causing shadow zones. The summer situation is particularly bad. Then the sound speed is sharply decreasing with depth and the horizontally transmitted sound rather soon “sink to bottom”. One should, however, take note of the distance scale of these graphs. Within the nearest 300-500m the sound propagation is fairly linear even in the summer conditions.

The frequency of the propagating sound does not change with the sound speed, but the wave length does:

$\lambda = c/f$ (11)

If sound velocity is 1500 m/s and the frequency is 38 000 Hz, the wave length is:

$\lambda = 1500/38000 = 0.0395 \text{ m} \approx 4 \text{ cm}$

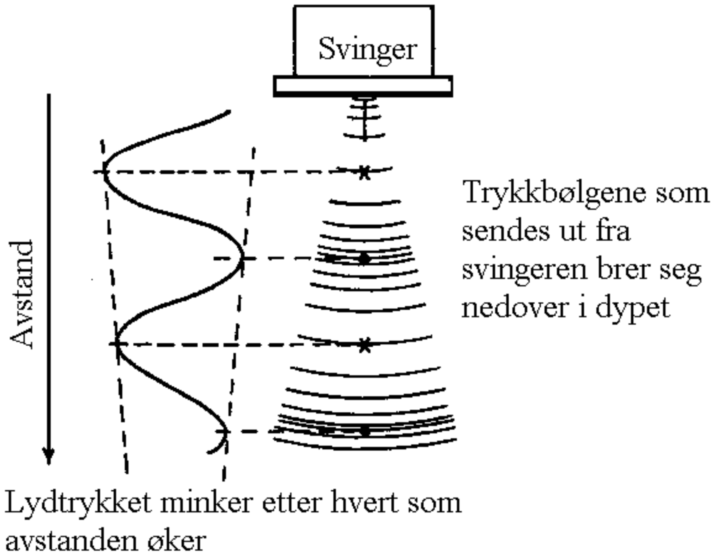


Figure 20: Propagation of a pressure wave from the transducer (Svinger = transducer, Avstand= range, Trykkbølgne som.....= Pressure waves transmitted from transducer propagates downward, Lydtrykket.....=Sound pressure decreases as the range increases).

The sound is pressure waves are generated at the transducer surface set in vibrations (oscillations) by aid of electrical power. Pressure can be imagined as a mecanical force causing alternating compression and decompression of the water. The transducer sets up a mechanic pressure wave with sinusoidal oscillations with alternating compressions and decompressions of the water (over-pressure and under-pressure relative to the average pressure). Any measurement of sound pressure in acoustic waves is done by observing the electrical signal generated by a pressure sensitive instrument (in our case a ceramic transducer). In other words the sinusoidal pressure wave is transformed to an electrical sine wave that can be used to determine the acoustic properties.

Acoustic waves are a form of energy propagating through a medium, like water. At any point where the waves are found in the water there will be energy present as a change compared to the normal condition of pressure and particle movements. The energy propagates through the medium as oscillations of the particles of the medium. The propagation speed depends of the specific density and temperature of the medium. In water it is also influenced by the salinity (see figure 17).

Sound pressure and sound intensity

For a sound wave there is a certain relation between the sound pressure (*p*) and the velocity of particles (*u*):

$$p = Z \cdot u$$

Z, " the acoustic impedance", is here a constant depending of sound speed (*c*) and specific density (ρ):

$$Z = \rho \cdot c$$

Acoustic impedance, ρc, is defined as the density of the medium (ρ, kg/m^3) multiplied by the sound speed (*c*, m/s). The unit for acoustic impedance is (kg/m^2) often referred to as Rayl and is about 1.54×10^6 Rayl. The relation between pressure, particle velocity and impedance (ρc) is analogous to the relation between voltage, current and impedance in electricity.

The unit for sound pressure is micro Pascal (μ Pa). One μ Pa equals 10^{-6} Newton/m^2. Sound pressure is often a measure of the strength of sound in water even if sound intensity in many cases is more relevant. Pressure is measured by observing the voltage in pressure sensors. The voltage is proportional to pressure. The average value is zero since it oscillates between a positive maximum and negative minimum. Therefore the rms voltage is used. This is the square root of the averaged squared voltages. (to find the rms value (p_{rms}) of a sinusoidal signal one may use the difference between maximum and minimum (peak to peak) and divide by $2\sqrt{2}$)

Acoustic intensity (*I*) is defined as the fraction of energy per second that passes through a unit area perpendicular to the acoustic propagation direction. Acoustic intensity (*I*) is proportional the squared pressure amplitude (*p*), and may be expressed as:

$I = p^2/(\rho c)$, which means that: $I \propto p^2/(\rho c)$

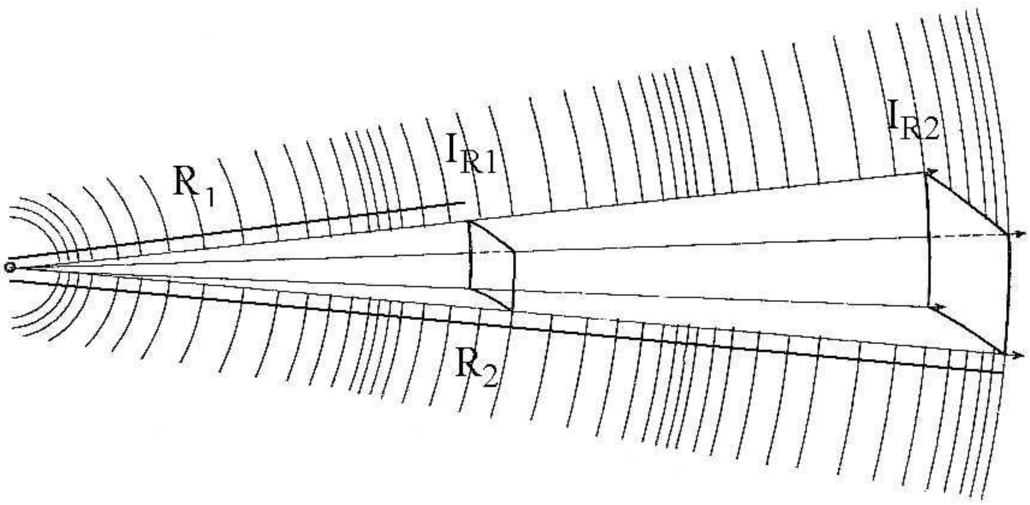


Figure 21: Spherical sound spreading from a point source, illustrating the spreading loss at increasing distance from the sound source and increasing area. From Forbes and Nakken (1972).

The intensity of an acoustic wave is expressed with reference to a plane wave with (rms) pressure equal to 1μ Pa at 1 m distance from the source. (A plane wave can be described as a wave that is not significantly curved over dimension of the target, like a fish). When the sound pressure and the acoustic impedance of water are known, the sound intensity can be calculated.

Geometric spreading and absorption

A propagating sound wave is attenuated by two processes; geometric spreading and absorption. When a point source in midwater transmits sound in all directions, the sound intensity (*I*) will be diluted as the sound spread out over a larger area. It will decrease by the square of the distance from the source (figure 21).

$$I_{R2} = I_{R1} *(R_1^2 /R_2^2)$$

I_{R1} and I_{R2} is the sound intensity at the range R_1 and R_2 from the source.

In addition to this geometric intensity reduction there is a general attenuation mainly caused by some energy being absorbed by chemical processes in the water. The loss in decibel is linearly dependent of the range, so that per unit distance travelled a fixed fraction gets lost. The symbol α[1] is commonly used for this absorption and it is often expressed as decibel per kilometer (dB/km). α increases rather strongly with frequency as shown in figure 22. Absorption has been shown to depend on temperature. At the common echo sounder frequencies 38 and 120 kHz the temperature effects are as shown in figure 23.

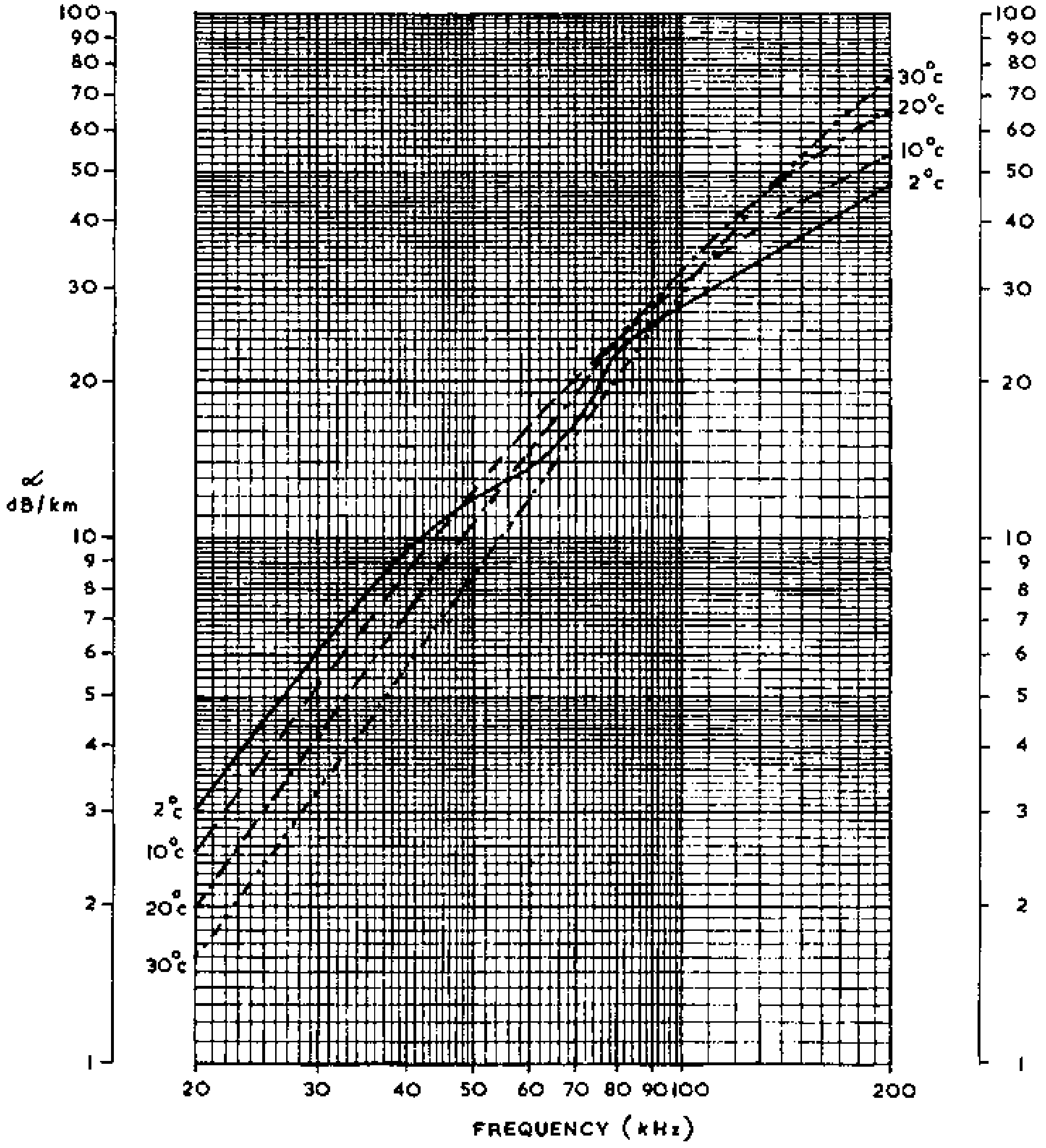


Figure 22: Absorption and frequency. From Johannesson og Mitson (1983).

[1] In the equation below absorption is described by another constant (β) where: $\alpha = 10\ (\log_{10}e) \cdot \beta = 4.3\ \beta$

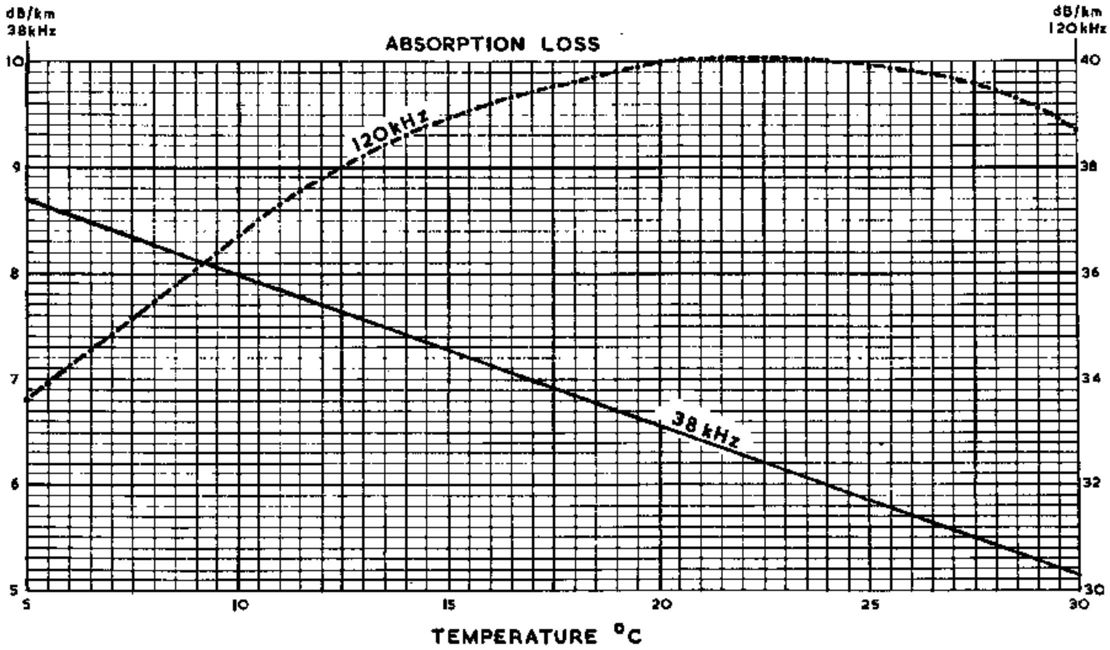


Figure 23: Absorption and temperature at 38 and 120 kHz. From Johannesson og Mitson (1983).

α depends on temperature, and at frequencies below ca. 70 kHz the gradient is mainly negative, while at higher frequencies the gradient is increasing.

When taking account of both geometric spreading and absorption the sound intensity (I_R) at range R from the transducer is:

$$I_R = I_0 \cdot \frac{1}{R^2} \cdot \frac{1}{e^{\beta R}},$$

I_0 is the sound intensity at 1 m from the transducer

Decibel

Within hydroacoustics the dynamic range is huge in terms of sound pressure and sound intensity; from high values for the transmitted sound close to the transducer to very low values of returned echoes from small targets at long range. Historically it has been considered useful to do calculations by logarithmic transformation. The logarithmic term decibel (dB,) has been introduced and is commonly used in acoustic literature. Logarithmic transformations have been found useful both for the calculation (before the computers) and for graphical presentations. Multiplications and divisions are replaced by addition and subtraction.

The term Decibel is 1/10 of one Bel. It is not a unit like meter, kilogram or second. It is the logarithm (base 10) of a ratio (a value realtive to a reference value, where the reference value may be a unit value). The logarithm of the ratio ½ is log (1/2)=–0.301, while log (2/1) is +0.301. To convert these ratios from Bel to desibel they are multiplied by 10.

10 log (1/2)=-3dB , and 10 log (2/1) = + 3 dB

+ 3 dB means that the value is twice as large as the reference, while –3 dB means that it is half the reference. Similarly:

10 log (10/1) = + 10 dB and 10 log (1/10) = -10 dB.

10 log (100/1) = + 20 dB and 10 log (1/100) = -20 dB.

Power and intensity in decibel

Electrical power, (*W*, watt) corresponds to acoustic intensity (*I*). Power expressed in decibel is then:

$N = 10 \log (W/W_0)$ (dB)

Where W_0 is the chosen reference value. Similarly for acoustic intensity (*I*):

$N = 10 \log (I/I_0)$ (dB)

Where I_0 is the chosen reference value.

Voltage and pressure in decibel

The received acoustic signals generates electric voltages in the receiver. Electric power (*W*) is proportional to the squared voltage (*V*). The same relation exists between acoustic intensity and pressure ($I \propto p^2/(\rho c)$).

When V og V_0 to meaured values of volage and Ω denotes the resistence (impedance) then the ratio between voltages in decibel are
$10 \log (V/V_0)$ while the ratio between corresponding powers are

$$10 \log [(V^2/\Omega)/(V_0^2/\Omega)] = 20 \log (V/V_0) \qquad (8)$$

and for corresponding sound intensities:

$$10 \log [(p^2/\rho c)/(p_0^2/\rho c)] = 20 \log (p/p_0) \qquad (9)$$

where V_0 and p_0 denote reference values and ρc is the acoustic impedance (resistance). Thus there is a proportionality between the pressure in a received sound wave and the resulting voltage in the receiver:

$$p \propto V$$

This is utilized for measuring sound pressure in water.

Back scattering of sound

The ability for a target to back scatter sound is dependant of two main factors. Firstly the difference between the acoustic impedance in the water and in the target. The degree of back scattering can be express through the back scatter index (u):

$$u = \frac{z_1 - z_2}{z_1 + z_2} = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}$$

where $\rho_1 c_1$ and $\rho_2 c_2$ is the density and sound speed in the water and in the target respectively. If the target contains an airfilled swim bladder, the echo from the swim bladder will dominate the reflected signal from the target. This because air has much lower density and sound speed than water. If the target is very small compared to the wave length, the whole target will experience the same pressure wave simultaneously. The target will oscillate in phase with the sound wave. If L characterises the size of the target and λ the wave length, the reflected energy will be proportional to $(L/\lambda)^4$ as long as d is much smaller than λ (the left hand part of figure 24).

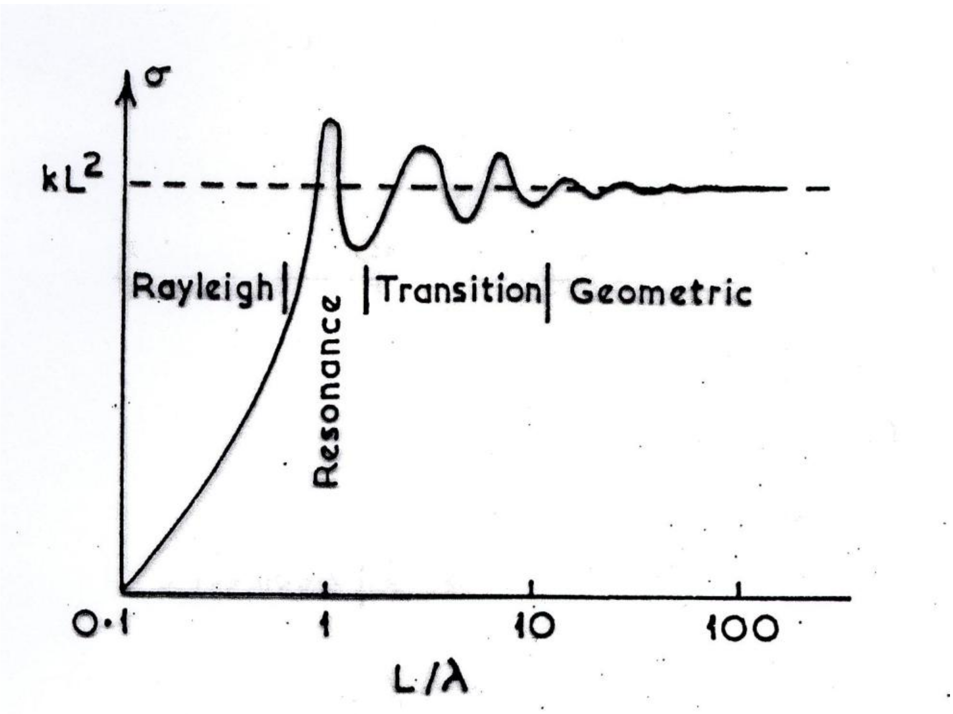


Figure 24: Frequency dependant back scattering for a gas bubble. L is the length of the target and λ is the wave length.

The strongest back scattering normally occurs in the resonant area where the size of the target and the wavelength are similar. In fisheries acoustics the wavelength is usually smaller than the target, and we operate in the geometric region (to the right in figure 23).

If a transmitted pulse with starting intensity I_0 is hitting a reflecting target at range *R*, a fraction (*k*) of the sound will be back scattered from the target. The intensity I_r of the reflected sound at 1m from the target is expressed as:

$I_r = k * I_0 * R^{-2} * e^{-\beta R}$

k is a constant depending of the acoustic properties of the target (Forbes og Nakken, 1972). The above can be expressed in decibel:

$10 \log I_r = 10 \log k + 10 \log I_0 - (20 \log R + \alpha R)$

There is a convention that the intensity (I_0) of the transmitted sound is referring to the acoustic axis and at 1m distance from the source. $10 \log I_0$ express the transmitted intensiy in decibel with reference to the measurement unit used for I_0 . $10 \log I_0$ is commenly called the source level (*SL*).

$20 \log R + \alpha R$ is often called the one way propagation loss. When the back scattered echo returns at the receiver the sound has travelled the same distance *R* again and thereby experienced the same propagation loss as the transmitted sound on its way to the target. The echo intensity returned to the receiver is then

$I_e = I_r * R^{-2} * e^{-\beta R} = k * I_0 * R^{-4} * e^{-2\beta R}$

The echo level (*EL*, the sound intensity of the received echo, expressed in decibel) is then:

$EL = SL + 10 \log k - (40 \log R + 2\alpha R)$

The expression in brackets is now the two way propagation loss.

If the target is not located at the acoustic axis, the sound intensity hitting the target will be reduced according to the directivity of the beam (se figure 8), and the back scattered echo will be reduced. This can behandled by introducing a directivity function:

$$b(\theta,\phi) = \frac{I_{(\theta,\phi)}}{I_{(0,0)}}$$

This function takes values according to the angular positins in the beam, described by the angles θ (reltive to acoustic axis) and ϕ (relative the along-ships vertical plane through the axis). The values in any point is related to the mawximum value (at the axis), and will then have values beteween 0 and 1. In echo sounders used for abundance estimation the same beam directivity applies for receiving signals as for transmitting. Therefore, the squared value of the directivity should be used for compensating the signal of the received echo. (Foote, 1990; Gundersson, 1993). This inserted in the equation for I_e then gives

$$I_e = \frac{I_0 k \cdot b^2(\theta,\phi) \cdot e^{-2\beta R}}{R^4}$$ *, or:*

$$EL = SL + 10 \log k + 20 \log b(\theta,\phi) - (40 \log R + 2\alpha R)$$

The expression *10 log k* has got a special name, Target Strength (*TS*). Then we can write the following equation, known as the sonar equation:

$$EL = SL + TS + 20 \log b(\theta,\phi) - 2\alpha R - 40 \log R$$

The TS is given in decibel with reference to 1 m^2 back scattering surface. The back scattering cross section of a target is usually denoted σ_{bs} so that.

$$TS = 10\log_{10}\left(\sigma_{bs}\right), \quad or \quad \sigma_{bs} = 10^{0.1TS}$$

Some litterature replaces σ_{bs} by $\sigma/(4\pi)$.

4. The target strength of fish

We have already stated that when a sound wave hits a fish a fraction of the energy is back scattered. When the wave front meets the boarder between two media (like water and the fish flesh, figure 25) with different acoustic impedance, the back scattering starts. The intensity of the total back scattered sound pulse will largely depend on whether the fish has a gas filled swim bladder. Further it depends on the relation between the fish length and the wavelength. The back scattering cross section *(σ_{bs})* has the unit m^2 . For an ideal reflecting target this can be described as the surface or cross section of the target ”seen” from the propagation direction of the incoming pulse. The σ_{bs} for fish with gas filled swim bladder can be described by the swim bladder surface ”seen” from the propagation direction of the incoming pulse.

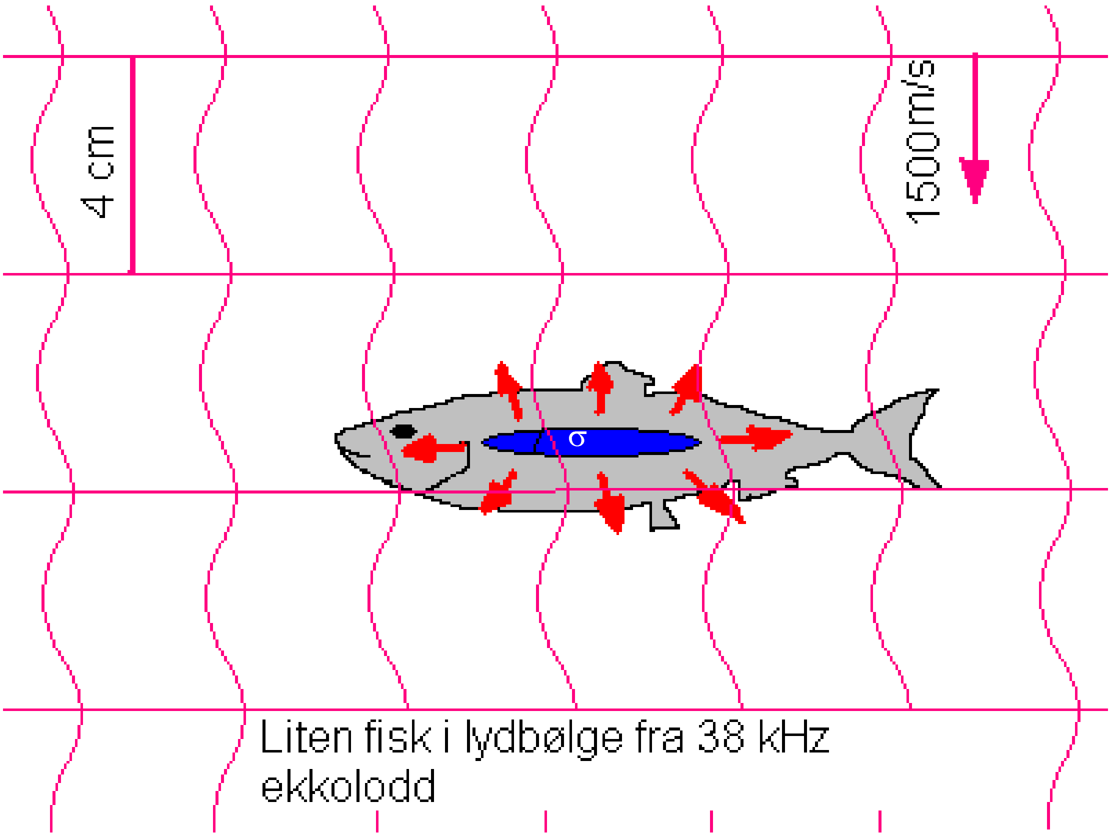


Figure 25: *Back scattering of sound from fish. The σ can be described as the swim bladder surface (blue) ”seen” from the propagation direction of the incoming pulse. “Liten fisk i lydbølge fra 38 kHz ekkolodd”= A small fish in the sound wave from a 38 kHz echo sounder.*

According to MacLennan et al. (2002) the backs cattering cross- section is defined as[2]:

$$\sigma_{bs} = R^2 \left(\frac{I_{scat(R,\theta,\phi)} \cdot 10^{0.1\alpha R}}{I_{inc}} \right)$$, with the unit m^2

Here R is the range from the target where the reflected intensity $I_{scat(R,\theta,\varphi)}$ is measured and I_{inc} is the intensity of sound pulse that hit the target. The terms $R^2\ 10^{0.1\alpha R}$ are correcting for propagation loss over the distance R. The combined nominator $I_{scat(R,\theta,\varphi)} \cdot R^2\ 10^{0.1\alpha R}$ then corresponds to the scatter intensity that would be measured at 1 m distance from the target in the same direction (θ,φ).

The scattering properties of a target are influenced by the size of the target relative to the wavelength. This also influences the directivity of the target. The directivity describes how the echo will vary according to the orientation of the fish (see figure 26). Wave components generated at different parts of the fish body will interfere (like the interference forms different parts of the transducer (figure 8), thereby generating a complicated directivity diagram. Some sound is scattered in nearly all direction, but the main energy is focused in a main lobe (as for a transducer), and in general the width of this main lobe increases (less directive) at decreasing size of the target relative to the wavelength (as for a transducer). In this context the fish size could be expressed as “number of wavelengths”. A 40 cm fish is 10 wavelengths at 38 kHz, while it is 32 wavelengths at 120 kHz. The capelin in figure 26 is rather small relative to the wavelength at 38 kHz, and it would probably be more directive at higher frequencies (like 120 kHz).

[2] The ”old” definition of back scattering cross section (Urick, 1983) is in MacLennan et al. (2002) now defined as ”spherical” back scattering cross section (σ_{sp}) so that: $\sigma_{sp} = 4\pi\ \sigma_{bs}$

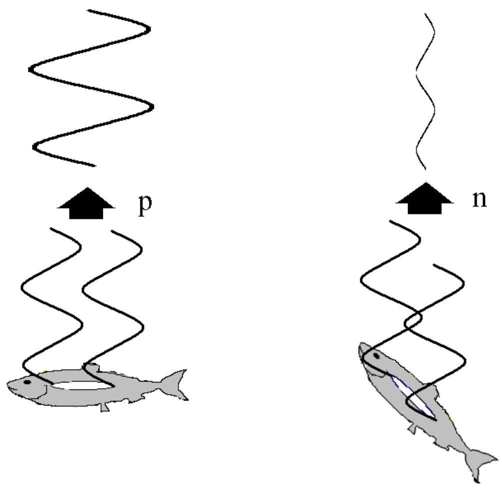


Figure 26: Interference amplifying (p) or reducing (n) the echo.

As mention a big fish will at a certain frequency be more directive than a small fish. This tendency is observed in figure 27 where the small capelin is less directive than the larger saithe. This means that for capelin the echo returned in the direction towards the transducer is less dependent on the tilt angle of the fish than what is the case for saithe. The same pattern is observed in figure 28 comparing a 40 cm saithe and a 17.5 cm saithe. Here the directivity is presented by the tilt angle along the x-axis.

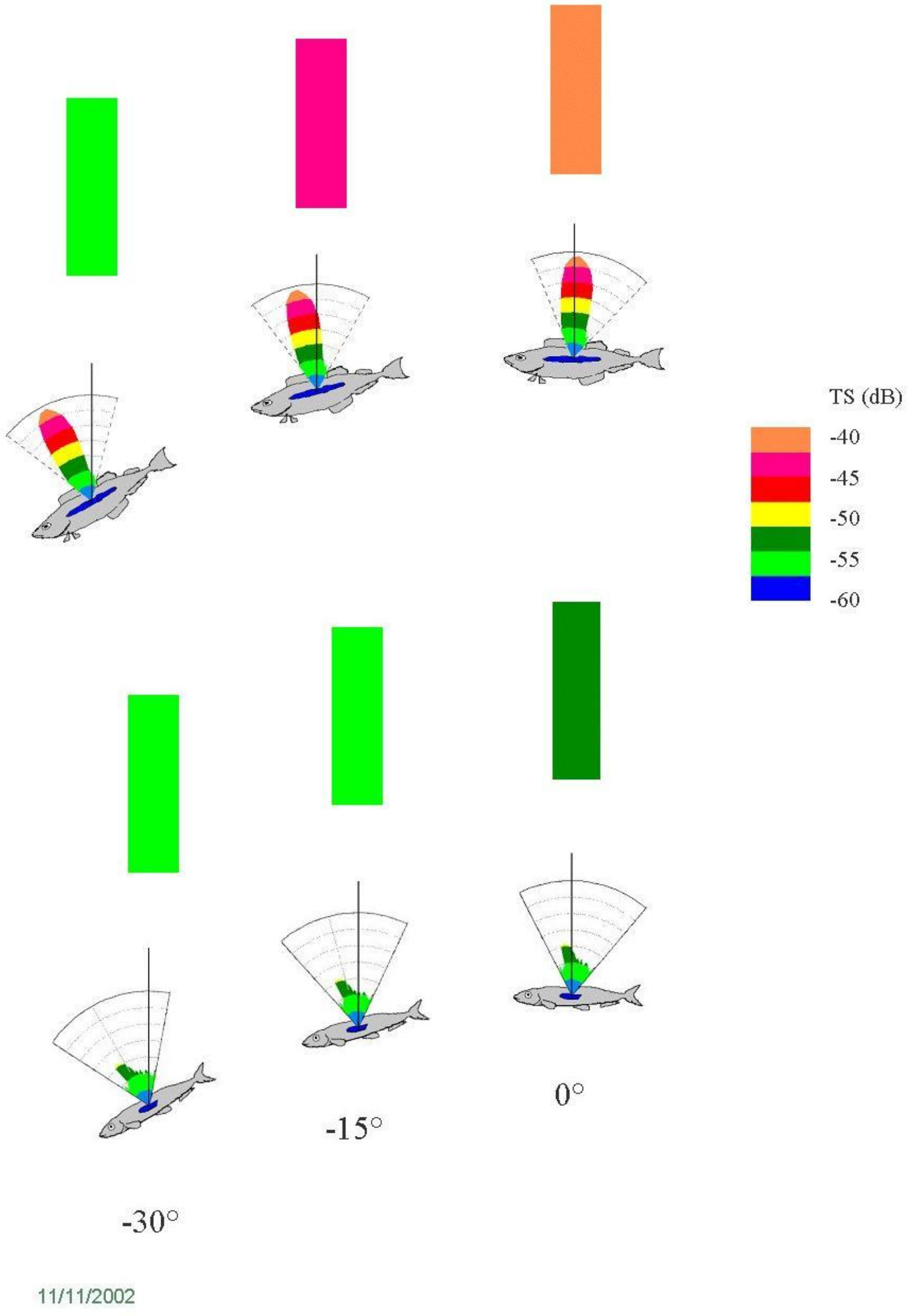


Figure 27: Tilt angle (0, -15 og -30°) and target strength at 38 kHz for a 30 cm saith (upper) and a 11 cm capelin (lower). Based on data from Jørgensen (1998), Jørgensen and Olsen (2002).

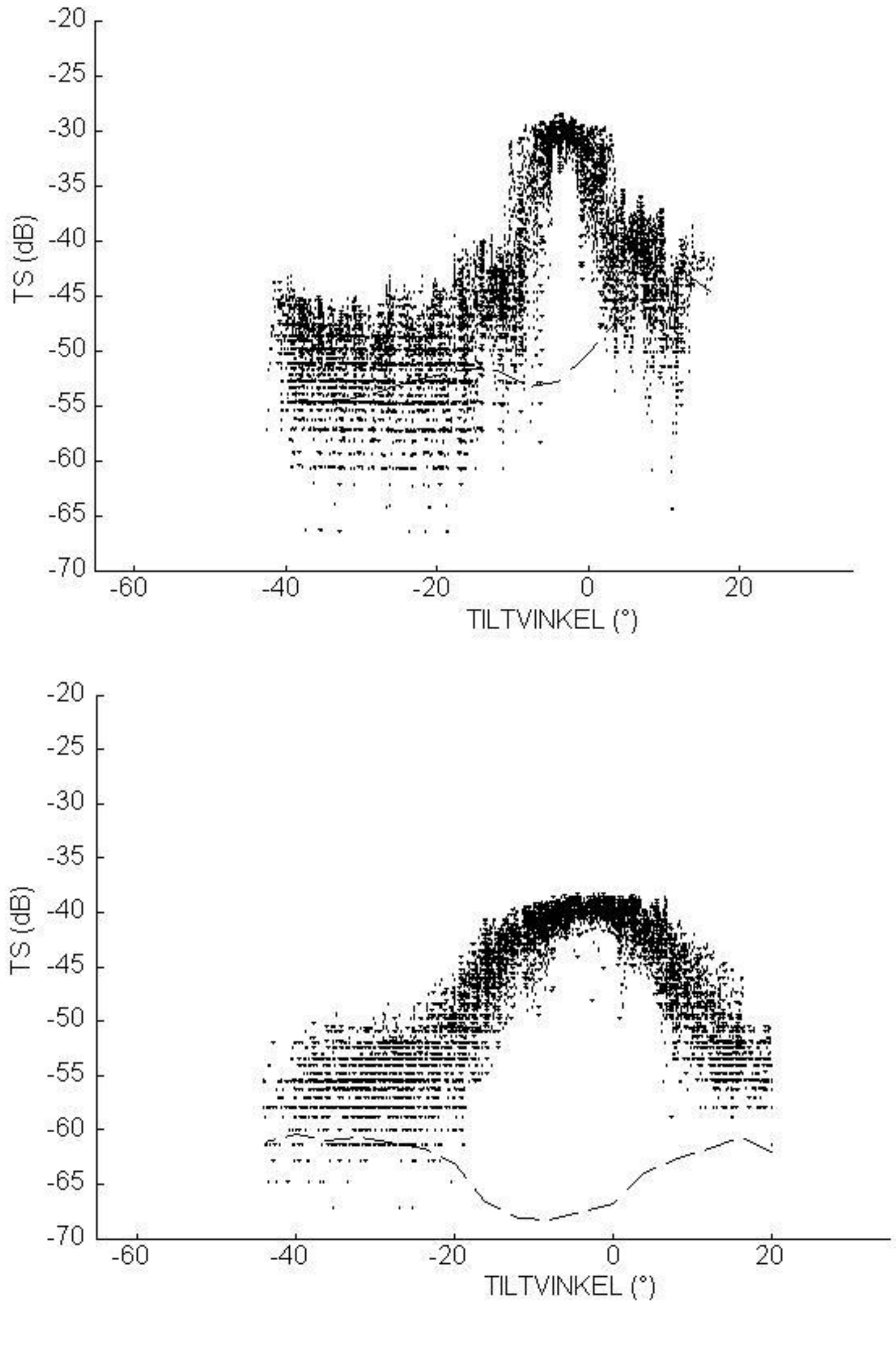


Figure 28: Target strength against tilt angle (tiltvinkel) for a 40.0 cm saithe (upper, 8345 ping) and a 17.5 cm saithe (lower, 9890 ping). The measurements were made at 5 m depth with a 38 kHz echo sounder. After Jørgensen (1998).

The description has so far been related to cases where the body shape of the fish remain fixed. In reality the body shape varies slightly due to swimming activity (muscular activity, bending body) and due to pressure changes during vertical movements. It is possible to model back scattering cross section based on morphometry of the various anatomic parts. This can be tested by comparison with direct measurements on individual fish or small groups of fish (Ona, 1999).

Metods to measure (σ_{bs})

In situ

Indirect

During acoustic surveys, Comparing acoustic density with

-fish density obtained from fishing (purse seine)

-fish density obtained by echo counting

Single beam measurements of single fish echo levels (EL)

”Craig and Forbes algorithm”

Numerical method calculating the frequency distribution of TS based on the observed frequency distribution of (range compensated) single fish EL. A set of linear equations corresponding to the relative areas between isolines in the beam directivity is used for ”deconvoluting” the observed EL distribution to a TS -distribution.

Direct

Split beam echo sounder (an example in Ona (2002))

”Dual –beam” echo sounder

Ex situ

TS- measurements of stunned or dead fish (ex. Nakken og Olsen, 1977)

Cage experiments (an example in Jørgensen and Olsen, 2002)

Mathematical modelling of TS based on the shape of the fish or the swim bladder.

Estimating TS distribution by use of single beam echo sounder

(”Craig and Forbes algorithm”)

The rationale for the method is based on classifying a large number of echoes into dB classes and combining this with the relative area between corresponding dB iso-lines in the two way directivity pattern of the beam. When considering a large number of single fish echoes it is reasonable to assume that their positions in the beam cross section is quite evenly distributed. Then the echoes observed in the highest dB class would originate from the highest TS class in the inner dB area of the beam, the second biggest echoes from the second highest TS class in the inner dB area plus the highest TS class in the second inner dB area, and so on.

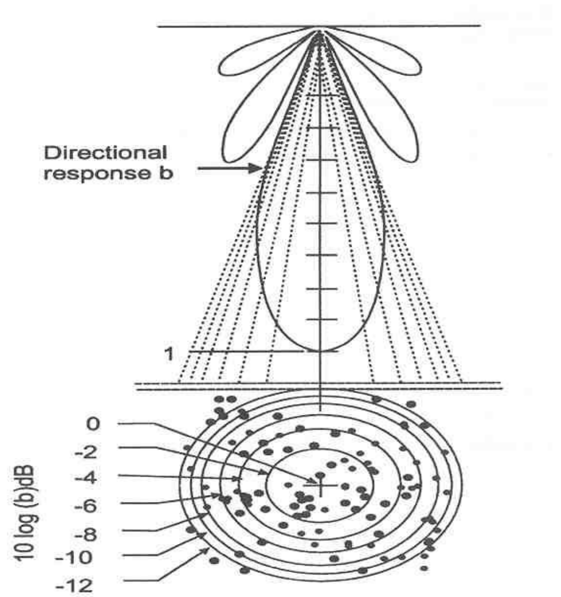


Figure 29: ”Craig and Forbes algorithm”. Upper: Polar diagram of beam directivity. Lower: Illustrating the corresponding dB areas (between 2dB iso-lines) in the beam cross section.

Based on the known beam directivity for the actual transducer, the corresponding relative area of the dB areas can be drawn and calculated (see figure 29). The rational given above gives the following set of equations:

$N_1 = \rho_1 V_1$

$N_2 = \rho_2 V_1 + \rho_1 V_2$

$N_3 = \rho_3 V_1 + \rho_2 V_2 + \rho_1 V_3$

…….

$N_i = \rho_n V_1 + \rho_{n-1} V_2 + ... + \rho_1 V_n$

Where N_i is the observed number of echoes in dB class *i*, ρ_i is the area density of fish in *TS* class *i*, and V_i is the size of the dB area number i (see figure 29). (*i* is starting at 1 for the highest echo class (*N1*), highest *TS* class (ρ_1) and the inner dB area (V_1)).

Calculating average TS from fish directivity and tilt angle distribution

By combining an experimentally measured fish directivity diagram (figure 27) and an (photo/video) observed tilt angle distribution of the same species and size group, the average back scattering cross section corresponding to the tilt angle distribution can be calculated. Later we denote such an average σ_{bs} as $<\sigma_{bs}>$ and the corresponding *TS* as <*TS*>. The following equations are relevant:

$$\langle TS \rangle = 10 \cdot \log(<\sigma_{bs}>) \ ,$$

$$<\sigma_{bs}> = \int_{v_{\min}}^{v_{\max}} \sigma_{bs}(\theta) \cdot f(\theta) \cdot \partial\theta \ ,$$

where $\sigma_{bs}(\theta)$ is the σ_{bs} at the tilt angle θ, and $f(\theta)\cdot\partial\theta$ is the probability for observing a fish in the tilt angle interval $\partial\theta$ (Foote, 1980a). v_{min} and v_{max} is the minimum (head down) and maximum (head up) angle relevant for the calculations.

The length dependence of TS

There are three different approaches to presenting the TS fish length relation. One is to normalize the back scattering cross section to the squared fish length and plot it against the fish length (L) to wavelength (λ) ratio (Foote, 1979) as in figure 30.

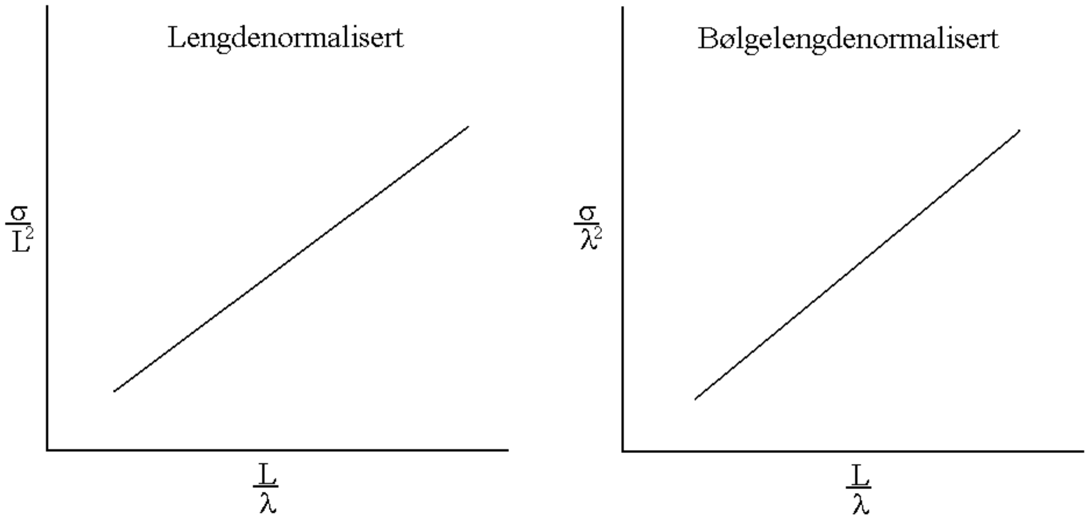


Figure 30: Length normalized (left) and wavelength normalized (right) presentations of back scattering cross section. The plots have logarithmic axis.

Another presentation is back scattering cross section normalized by squared wavelength plotted against the fish length to wavelength ratio. In both of these cases measurements at different frequencies (wavelengths) can be shown in the same plot. (Love, 1971; Foote, 1979). Love (1971) suggested the following relation:

$$TS = m \cdot \log_{10}(L) + a \cdot \log_{10}(f) + b$$

where *L* is the fish length, *f* is the frequency and *m, a* and *b* are constants for a given fish orientation. Later studies have shown that the conditions determining the *TS* are too complex to be described by this simple formula, originally meant to cover all fish species. (MacLennan og Simmonds, 1992).

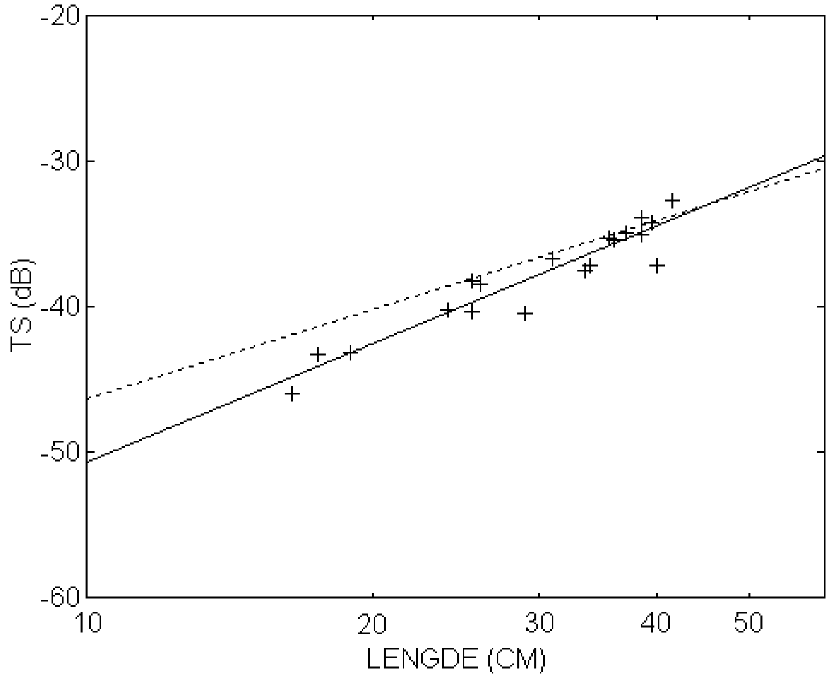


Figure 31: Regression of average dorsal aspect TS of saithe against fish length on logarithmic x-axis. The points are calculated from measured directivity diagram of saithe at 38 kHz for various fish lengths, assuming a Gaussian tilt angle distribution with mean= -4.4° and SD=16° (n=19). Full line: TS = 27 log L – 77.7 (Jørgensen, 1998). Broken line: is the regression line TS = 20.4 log L – 66.7 for saithe as given by Foote (1979).

The third way of presenting target strength data is without normalizing (see figure 31). The data are simply presented as *TS* against length, usually the length is on log scale, (Foote, 1979). Examples of such presentations are in Nakken and Olsen (1977), Foote (1979) and Foote (1987a). With this method it is not convenient to present measurements made with different sound frequencies on the same plot. The theory behind the normalizing procedures earlier suggested is not properly verified (Foote, 1979) and the non-normalized presentations is therefore more direct and transparent. Target strength-length relationship is usually expressed by the function:

$TS = m \cdot log_{10}(L) + b,$

Where m and b are constants for a given frequency and species, and L is the fish length (Foote, 1979). This equation is now accepted as a reasonable but not necessarily precise representation of the *TS* length relationship (MacLennan and Simmonds, 1992).

The equation has been further simplified to:

$TS = 20 \cdot log_{10}(L) + b$

The reason for this is that the back scattering cross section, σ, has in many case been found to be close to the squared fish length for several species measured at 38 kHz. (Foote, 1987a, 1987b; MacLennan og Simmonds, 1992). It also seems intuitively logical, since the surface of an object increases with the squared length of the object, and σ refers to a surface or a cross section area. In the litterature zited above large amounts of TS measurements have been analysed by linear regreesion (*TS* against $log_{10}(L)$. Some of those results are presented in Table II.

Tabell II: TS *functions that has been used for abundance estimations in routine acoustic surveys for gadoids, polar cod, herring, capelin and mackerel.* L *is in cm.*

TS-function	Species	Reference
TS = 20 log L – 67.4	Gadoids	(Foote, 1987b)
TS = 20 log L – 68	Gadoids	
TS = 21.8 log L – 72.7	Polar cod	(Gjøsæter, pers. com.)
TS = 20 log L – 71.9	Herring	(Foote, 1987b)
TS = 19.1 log L -74	Capelin	(Anon, 2000)
TS = 20 log L – 84.9	Mackerel	(Anon, 2002)

Acoustic effects of vertical migrations

Several physiological and behavioural conditions may affect the *TS*. The most important are the fish orientation (tilt angle) and the size and shape of the swim bladder. Since the hydrostatic pressure is proportional to depth, vertical migrations may change the size and shape of the swim bladder. This may change its acoustic properties, and may change the fish behaviour and tilt angle (Olsen, 1976, 1987, 1990; Ona, 1982, 1990). Based on experimental measurements of single fish directivity diagrams and observed tilt angle distributions the corresponding average *TS* by length functions have been calculated (Foote, 1987b). In recent years there has been several attempts to include depth dependence in these calculations (Halldorsson, 1983; Mukai og Foote, 1997; Ona, 2002). Depth dependent *TS* is particularly relevant for species with ”open” swim bladder (*physostomous fish*), like herring and capelin. Mukai og Foote (1997) describes a depth depenent TS for anesthesised individuals of the *physostomous* (”closed” swim bladder) species pacific salmon, *Oncorhynchus nerka*. This depth dependence was found to correspond to what would be expected by assuming that the swim bladder is compressed according to Boyle’s law. Then the swim bladder volume is inversely proportional to pressure (p) and swim bladder surface (or cross section, σ) is proportional to $p^{-2/3}$ (since area goes by L^2 and volume by L^3). $10 \cdot \log p^{2/3} = 10 \cdot (-2/3) \log p$, and at the depth z (m) the pressure is $1+z/10$. Then TS can be expressed as:

$$TS = TS_0 - \frac{20}{3} \cdot \log\left(1 + \frac{z}{10}\right),$$

where TS_0 is the theoretical TS at surface (z = 0). Ona (2002) describes the *TS* of herring as:

$$TS = TS_0 + 10 \cdot \log\left(\left(1 + \frac{z}{10}\right)^{\gamma}\right)$$

For herring γ has been estimated to be around -0.23. According to the considerations above Boyle’s law would give γ equal to -0.67. We should notice the observed depth related TS changes are caused both by changes of the shape and volume of the swim bladder, and by behavioural changes (tilt angle). Since the buoyancy changes, the swimming beahviour will changes. A typical compensation for negative buoyancy is to swim with a positive tilt, ”head up” (Olsen, 1990). At moderate negative buoyancy horizontal swimming may be sufficient to obtain a sufficient hydrodynamic lift caused by the pectoral and pelvic fins (Magnusson, 1978). It is clearly demonstrated in figures 26-28 that moderate changes in tilt may cause dramatic changes in TS.

Edwards and Armstrong (1984) report a cage experiment on schools of haddock (*Melanogrammus aeglefinus*). The fish where originally adapted to 2-3 m depth and then lowered to 17.5 m depth. At this lower depth TS was mesured to slowly increase over the first 24 hours, then stabilising. Furhter lowering to 70 m caused an about 3 dB drop in TS, then increasing slowly during the next 36 hours. Here it stabilised at a slightly lower value than at 17.5 m. When reducing the pressure no change in TS was observed. Similar experiments with other gadoids showed similar patterns. (Rose and

Porter (1996) used a linear model to study *in situ* TS measurements of cod from 49 combined acoustic/trawl experiments at depths between 200 and 375 m. They found a 1.5 dB higher TS at night compared to during the day. The cod was 140 m higher above bottom at night compared to day.

Table III: Estimated parameters of depth dependent TS. L is fish length (cm), P is pressure (atm), P = 1 + depth/10.

	Species	Reference
TS = 20 log L – 2.3 log P – 65.4	Herring	(Ona, 2002)
TS = 23.3 log L -4.9 log P - 74.3	Capelin	(Jørgensen, 2004)

Modelling TS

According to Foote (1980b) the swim bladder is responsible for at least 90% of the acoustic back scattering from swim bladdered fish. Knowledge about the properties of the swimbladder, the remaining parts of the fish and the sea water form the basis for theoretical estimation of back scattering properties of fish.

Ona (1982) has described 3D models of the swim bladder of pollack (*Pollachius pollacius*) and saithe (*Pollachius virens*). These models included the use of Hertzholtz-Kirchhoff integrals for calculating acoustic back scattering properties. The theoretical estimates fitted well with experimental measurements on the same species (Foote, 1985).

Mathematical modelling may also be based on x-ray images. Furusawa (1988) used approximations based on a prolonged sphere, while Clay and Horne (1994) used a row of cylindrical elements of various size to approximate the swim bladder shape.

5 Fish abundance estimation

Early studies: counting fish traces and counting schools

The acoustic based methods applicable to various conditions are to a large extent determined by the behaviour of the target species and by how it is distributed in the water column. In the early years of developing these methods the use of sonars was limited to cases when fish was distributed in schools not too close to bottom and the application using echo sounder was limited to cases when fish could be resolved in single fish traces. Then density could be estimated by counting single fish traces. It was rather soon recognized a need for compensating the signals for the propagation loss. Such electronic range compensations were later developed under the name Time Varied Gain. Then the same signal could be obtained for the same fish size independent of range. The number of fish recorded was then a function of fish density and the water volume covered by the beam.

The limitation of this method is often the variable fish distribution. For many species pure single fish distribution are observed only for a few hours during night. For smaller scale studies that can be performed during the course of a few hours it is, however, a quite practical method. There is developed some soft ware systems handling this procedure (Lindem, 1978). This has widespread use, mainly in small scale studies in freshwater.

Some early studies were also made on counting schools on sonars. The sampling area was estimated and the number of schools per unit area could be calculated. Later studies on quantitative use of sonars are reported by (Misund, 1997; Kvamme, 1999).

Echo integration

Following the development of the echo integrator a new method for acoustic abundance estimation was introduced by Dragesund og Olsen (1965) and was further developed at the Institute of Marine Research in Bergen in cooperation with other institutions (Dalen og Nakken, 1983; Foote *et al*., 1991). The method is most suitable when the fish is not distributed too close to the bottom or the sea surface (see figure 32). The advantage compared to the early methods is that it can be used both for scattered and schooled distributions of fish.

The echo integration is based on a theoretical principle that the electric energy measured from one or more fishes is (in average) proportional to the fish density. In the previous sections we have learned that the electric energy, or V^2, generated by a received sound pulse is proportional to the sound intensity. During the early development of the echo integrator it was discovered that just summing up the recorded electric voltages (V) from received echoes did not give values proportional to the density of fish in the beam, but that the summed V^2 did. If several fish are so close to each other that they give overlapping (multiple) echoes, the sound waves from the individuals will interfere with each other. It has been shown that in average this interference works in such a way that the total echo energy adds up to the sum of the individual echoes (as if they were received separately and then added), so that total echo energy is proportional to the number of fish (N). Then also the total electrical energy (or summed V^2) is proportional to the number of fish.

Combined with what we have learned earlier we then have the following chain of proportional parameters

$I \propto p^2 \propto V^2 \propto N$

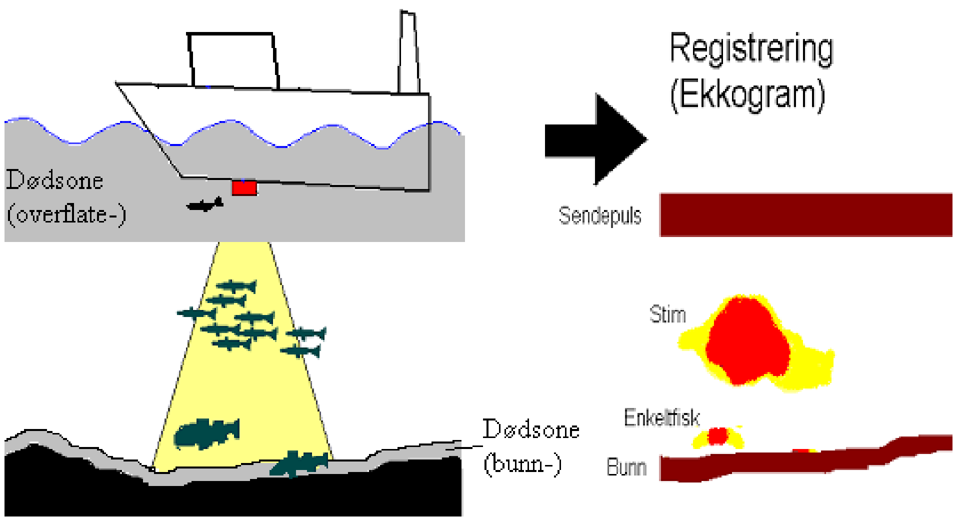


Figure 32: Acoustic dead zones.

This also implies that the instantaneous sound intensity received from a multiple echo, and its corresponding recorded squared voltage is a measure of the fish density.

If the multiple echo is generated by n identical scatterers, the expected combined sound intensity ($I_{e,n}$) from n fishes is:

$I_{e,n} = n \cdot I$

If the various contributing fishes have different back scattering properties, giving different echo intensity, then the expected combined sound intensity ($I_{e,n}$) from n fishes is:

$$I_{e,n} = I_1 + I_2 + \ldots\ldots +I_n = \sum_{i=1}^{n} I_i = n \cdot \text{average } I$$

We remember that the requirement for having overlapping (multiple) echo is that the targets are closer than half a pulse length ($c\tau/2$), and defined this as the resolution distance. We may now consider the corresponding resolution volume ($Vr/2$). This will be the volume within which all targets will contribute to the same echo. This half pulse volume is a bit difficult to quantify, since the outer border of the beam is not well defined. It is common to use the term Ω representing the solid angle covering the cross section of the main lobe, so that the surface area of the pulse front is $\Omega \cdot R^2$. The thickness is $c\tau/2$, so that:

$$\frac{Vr}{2} = \Omega \cdot R^2 \cdot \frac{c\tau}{2},$$

If average fish density is N (#/m^3) the number of fish contributing simultaneously from this volume is

$$N \cdot \frac{Vr}{2} = N \cdot \Omega \cdot R^2 (\frac{c\tau}{2})$$

The expected echo intensity received from these fishes located at random positions across the beam can be expressed by integrating the (two way) beam directivity across the beam area ($\Omega \cdot R^2$):

$$I_e = I_0 \sigma_{bs} \cdot \frac{e^{-2\beta R}}{R^4} \int^{\Omega} b(\theta,\varphi)^2 \cdot (NR^2) \frac{c\tau}{2} d\Omega$$

$$I_e = I_0 N \sigma_{bs} \frac{e^{-2\beta R}}{R^2} \cdot \frac{c\tau}{2} \int^{\Omega} b(\theta,\varphi)^2 d\Omega$$

Here, for simplifying, it is assumed that the fishes all have the same σ_{bs} so that σ_{bs} could be kept outside the integration (as a constant).

The integral $\int^{\Omega} b(\theta,\varphi)^2 d\Omega$ is a constant for a given transducer and can be denoted ψ,

which can be described as the solid angle for an equivalent ideal beam. This means a hypothetical beam with directivity equal to 1 across the whole beam, and containing the same pulse energy as the actual beam. (se figure 33).

We then may write a simpler expression for the multiple echo intensity (I_e) received from the fish density N at range R:

$$I_e = I_0 \cdot N \cdot \sigma_{bs} \cdot \frac{c\tau}{2} \cdot \frac{e^{-2\beta R}}{R^2} \cdot \psi$$

The echo level (*EL*) in decibel from the fish density N is then:

$$EL = SL + 10 \log N + TS + 10 \log(\frac{c\tau}{2}) + 10 \log(\psi) - (20 \log R + 2 \alpha R)$$

We should notice that now, when considering fish density (s_V or s_A measurements), the range dependence is equal to $20 \log R + 2 \alpha R$, compared to $40 \log R + 2 \alpha R$ when considering the single fish echoes (for TS-measurements). The difference is that the sampling volume (increasing by the square of the range) has been taken into account when considering density measurements.

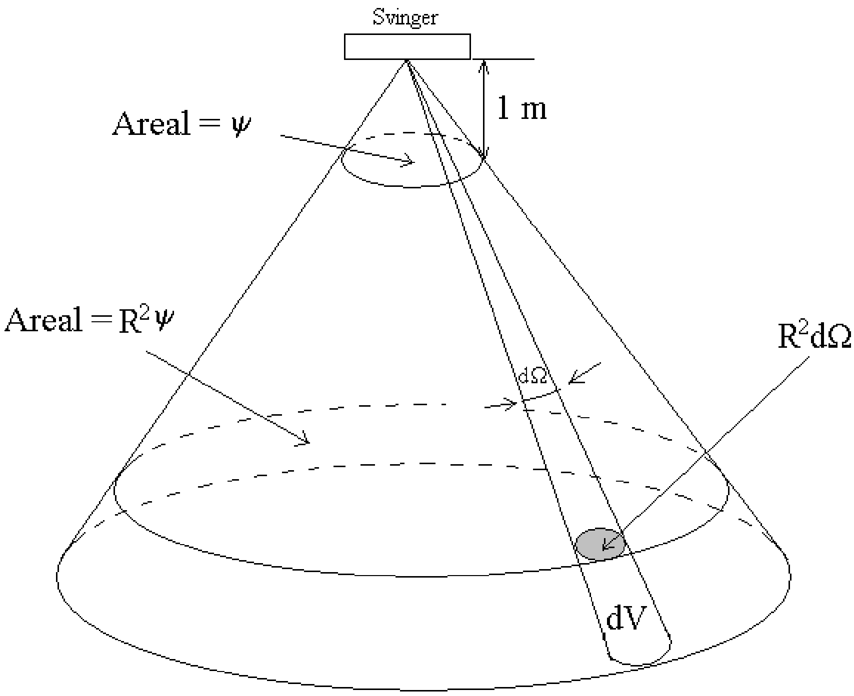


Figure 33: At any range the pulse volume is described by the area $R^2\psi$ (defined by integration over dΩ*), and the resolution distance ($c\tau/2$). From Gunderson (1993). Areal=area, Svinger = Transducer*

Another way of describing this is that the volume covered by the beam increases with R^2 and thereby cancel the effect of geometric spreading in the downward propagation, but the absorption still applies both ways. This is why in old echo sounders a ”20 log R + 2αR” time varied gain (TVG) was used for echo integration and ”40 log R+ 2αR” time varied gain was used for target strength measurements. In new sounder this is covered by the term s_V transducer gain for echo integration and TS transducer gain for TS measurements. Figure 34 shows few fish within the beam at short range compared to more fish in the beam at longer range when the density of targets is the same. Without any compensation the fishes at long range give weaker received echo, due to the one way propagation loss. Compensating for this by the 20 log R TVG, the recorded signals are equal (se figure 34). A two-way compensation (40 log R TVG) would over compensate.

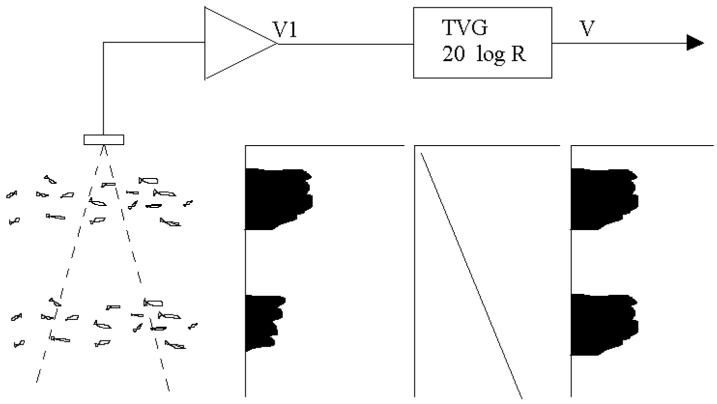


Figure 34: Non-compensated echo signal (V1) and " 20 log R" TVG compensated (V). (From MacLennan og Simmonds, 1992).

We again return to the expression for the received echo intensity for a volume density N (fish/m^3):

$$I_e = I_0 \cdot N \cdot \sigma_{bs} \cdot \frac{c\tau}{2} \cdot \frac{e^{-2\beta R}}{R^2} \cdot \psi$$

Through the instrument calibration procedure all the parameters except N and σ_{bs} is incorporated in the s_V transducer gain, so that the output from the integrator system is

$$s_V = N \cdot \sigma_{bs} \cdot 4\pi$$

which is the back scattering surface per unit volume. (The reason for including 4π is connected to the use of σ_{bs} instead of $\sigma/(4\pi)$)

For density estimation during normal surveys it is convenient to have a measure of the density of scatterers per unit area rather than per unit volume. This can be obtained by adding volume densities per m depth over the vertical range of scatterers. This then becomes the back scattering surface per unit area and is usually represented by the symbol s_A. Let ρ_A be the corresponding area density, so that

$$s_A = \rho_A \cdot \sigma_{bs} \cdot 4\pi$$

This is then the added back scattering cross section for all scatterers present below a unit area of the sea surface. A common unit for s_A is m^2 backscattering area per square nautical mile.

In the field situation we never have identical σ_{bs} for all targets. To make this more generic we may replace it by $< \sigma_{bs} >$ which denotes the average σ_{bs} over all scatterers contributing to the s_A value. Then number of fish per unit area is then

$$\rho_A = \frac{s_A}{4\pi \cdot < \sigma_{bs} >}$$

Storing and post processing

The s_V values are calculated and stored for each transmission with high vertical resolution (about 500 values, evenly spread over the vertical range chosen). During post processing the operator may define vertical intervals over which the s_V values (per m depth) are summed vertically, as s_A values. Each transmission may be considered as a single density measurement. These single measurements may be averaged over chosen distance intervals. Then each single value is weighted according to the sailed distance between neighbouring transmissions. Typical averaging distance is 1 nautical mile.

Allocating s_A-values to species or acoustic categories

Echo recordings contributing significantly to the s_A values are frequently sampled by trawl. When those samples show a mixture of species and size groups, the s_A values observed may be allocated to different groups according to their representation in the catch. The average back scattering cross section for this mixture might be calculated according to the trawl catch composition if there exists reasonable TS-length functions for the actual species. Let us denote the ($<\sigma_{bs}>$), for the various groups in the catch by:

$<\sigma_{t1}>, <\sigma_{t2}>, \ldots. <\sigma_{ti}>, \ldots\ldots.<\sigma_{tn}>$

and denote the frequency of each group by:

$F_{t1}, F_{t2}, \ldots.F_{ti}, \ldots\ldots F_{tn}$

so that:

$$\sum_{1}^{n} F_{ti} = 1$$

The are fish density for the respective groups is:

$\rho_{At1}, \rho_{At2}, \ldots\ldots\rho_{Ati}, \ldots.\rho_{Atn}$

The total are fish density is then: $\rho_A = \sum_{1}^{n} \rho_{Ati}$

Thereby:

$\rho_{Ati} = F_{ti} \cdot \rho_A$

We may thus calculate the density for each group when we know the frequency in the catch and the total density. By similar logics:

$$s_A = \sum_{1}^{n} s_{Ati}$$

This leads to:

$s_{At1} = \rho_{A\,t1} \cdot <\sigma_{t1}> \cdot 4\pi = F_1 \cdot \rho_A . <\sigma_{t1}> \cdot 4\pi$

$s_{At2} = \rho_{A\,t2} \cdot <\sigma_{t2}> \cdot 4\pi = F_2 \cdot \rho_A . <\sigma_{t2}> \cdot 4\pi$

$s_{Ati} = \rho_{A\,ti} \cdot <\sigma_{ti}> \cdot 4\pi = F_i \cdot \rho_A . <\sigma_{ti}> \cdot 4\pi$

$$s_A = \rho_A \cdot \sum_{1}^{n} F_i \cdot \left\langle \sigma_{ti} \right\rangle \cdot 4\pi$$

Implying that:

$$\rho_A = \frac{s_A}{\sum_1^n F_i \cdot \langle \sigma_{ti} \rangle \cdot 4\pi}$$

Since $\rho_{ti} = F_i \cdot \rho_{A,}$ we can calculate the density for each group by:

$$\rho_{ti} = \frac{s_A \cdot F_i}{\sum_1^n F_i \cdot \langle \sigma_{ti} \rangle \cdot 4\pi}$$

Further the s_A value by group is calculated as:

$$sA_{ti} = \frac{s_A \cdot F_i \cdot \langle \sigma_{ti} \rangle \cdot 4\pi}{\sum_1^n F_i \cdot \langle \sigma_{ti} \rangle \cdot 4\pi} = \frac{s_A \cdot F_i \cdot \langle \sigma_{ti} \rangle}{\sum_1^n F_i \cdot \langle \sigma_{ti} \rangle}$$

The presumption for these calculations is that the trawl catch gives a representative sample of species and size composition.

When the average area density $\bar{\rho}_A$ is estimated, the total abundance (N_{TOT}) within an area (A) is calculated as:

$N_{TOT} = \bar{\rho}_A \cdot A$, fish per n.mil^2

And the total biomass is obtained by multiplying with the mean weight

Example: calculating $<\sigma_{bs}>$

$$<\sigma_{bs}>=\frac{\sum_i \sigma_{bsi}\cdot w_i}{\sum_i w_i}$$

where σ_i refers to length group *i*, calculated from the TS-length relation for the species.

Table EI: Calculating average σ_{bs} based on a length distribution.

Lengdegr	Lengde (cm)	Antall (n)	TS (dB)	σ_{bs} (m^2)	σ_{bs} n (m^2)
40	40.5	0	-35.3	0.00030	0
41	41.5	1	-35.0	0.00031	0.000313
42	42.5	4	-34.8	0.00033	0.001315
43	43.5	7	-34.6	0.00034	0.00241
44	44.5	5	-34.4	0.00036	0.001802
45	45.5	3	-34.2	0.00038	0.00113
46	46.5	2	-34.1	0.00039	0.000787
47	47.5	3	-33.9	0.00041	0.001232
48	48.5	8	-33.7	0.00043	0.003424
49	49.5	12	-33.5	0.00045	0.00535
50	50.5	20	-33.3	0.00046	0.009281
51	51.5	23	-33.2	0.00048	0.0111
52	52.5	30	-33.0	0.00050	0.015047
53	53.5	18	-32.8	0.00052	0.009375
54	54.5	20	-32.7	0.00054	0.01081
55	55.5	11	-32.5	0.00056	0.006166
56	56.5	6	-32.4	0.00058	0.003485
57	57.5	3	-32.2	0.00060	0.001805
58	58.5	0	-32.1	0.00062	0
59	59.5	1	-31.9	0.00064	0.000644
60	60.5	0	-31.8	0.00067	0
	Sum	177			0.085478

$<\sigma_{bs}>$ = (Sum σ_{bs} n)/(Sum n) = 0.000483

Example: allocating s_A values to species

When scruitinizing echo recordings some species can by experience be recognized through the shape of the schools (MacLennan og Simmonds, 1992). Sometimes two or more species occur in mixed aggregations, and cannot be separated according to the appearance on the recordings. It is possible to make a split based on the species and size composition in a trawl catch. (Nakken og Dommasnes, 1975). Let s_{Am} be the value observed from the mixed recordings composed of (*j*) species. The fraction of species *i* is w_i . The esimated s_{Ai} for species *i* is then:

$$s_{A,i} = s_{Am,i} \cdot \frac{w_i \cdot \overline{\sigma}_{bs,i}}{\sum_j w_j \cdot \overline{\sigma}_{bs,j}}$$

A pelagic haul gives the following mixture: 200 herring (25 cm), 7000 capelin (12 cm) og 177 cod (average σ_{bs} = 0.000483 m^2). From a total s_A of 50 (m^2/nm^2) the contribution from capelin (lodde) is then:

$$s_{A,lodde} = s_{Am} \cdot \frac{w_{lodde} \cdot \overline{\sigma}_{bs,lodde}}{w_{lodde} \cdot \overline{\sigma}_{bs,lodde} + w_{sild} \cdot \overline{\sigma}_{bs,sild} + w_{torsk} \cdot \overline{\sigma}_{bs,torsk}}$$

$$= 50 \cdot \frac{7000 \cdot 0.0000046}{7000 \cdot 0.0000046 + 200 \cdot 0.0000404 + 177 \cdot 0.000483} = 12{,}8\,(m^2/nm^2)$$

And for herring: $s_{A,herring}$ = 3,2 and for cod: $s_{A,cod}$ = 34.

This gives the following density:

$$\rho_{A,lodde} = \frac{s_{A,lodde}}{4\pi \cdot \sigma_{bs,lodde}} = \frac{12{,}8}{4\pi \cdot 0.0000046} = 222000 (\text{fish per nm}^2)$$

$\rho_{A,herring}$ = 6340 og vi $\rho_{A,cod}$= 5610 (fish per nm^2).

The investigated area is 20 nm^2, and the abundance within this area is:

$N_{capelin}$ = 222000 fish/nm^2 · 20 nm^2 = 4 440 000 fish.

$N_{herring}$ = 6340 · 20 = 127 000.

N_{cod} = 5610 · 20 = 112 000.

The mean weights are 10.0 gram for capelin, 100 gram for herring and 1.00 kg for cod, giving the following biomasses: 44 tonnes capelin, 13 tonnes herring and 112 tonnes cod.

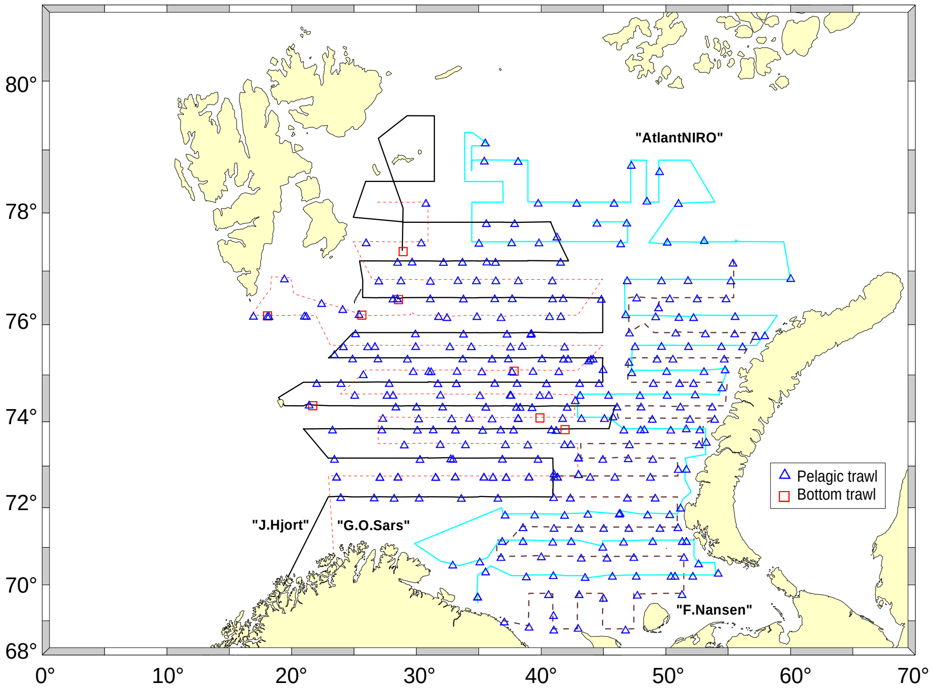


Figure 35: Survey grid and stations for "G.O. Sars", "Johan Hjort", "AtlantNIRO" and "F. Nansen" September - *October 2000 (Anon, 2000).*

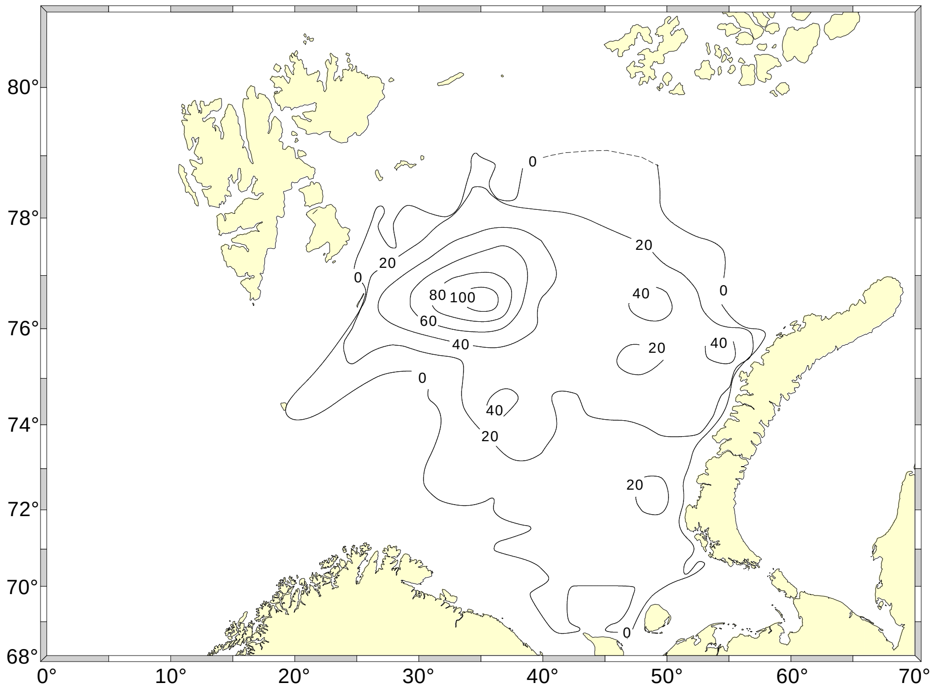


Figure 36: Estimated total density distribution of capelin (tonnes per square nautical mile) September -October 2000 (Anon, 2000).

Many vessel days are needed to cover large areas. Figures 35 and 36 are from the annual capelin surveys in the Barents Sea during September -October 2000 (Anon, 2000).