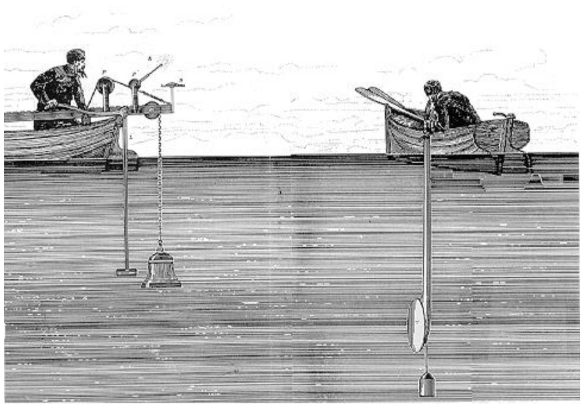
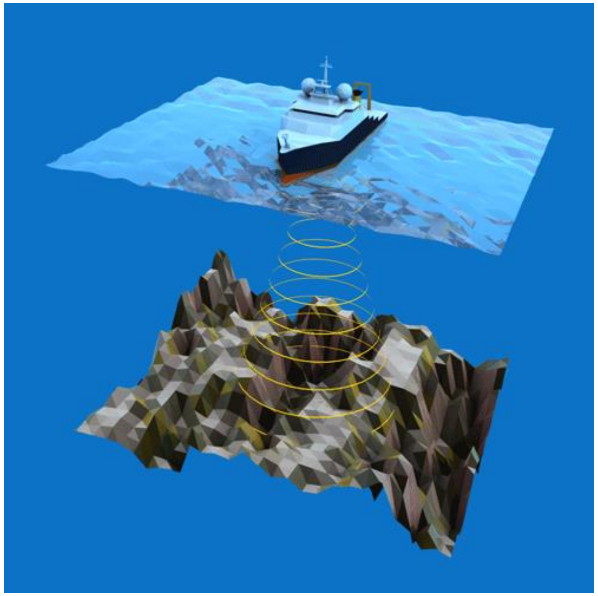
Depth measurement - construction and principle of operation of echosounders





Literatura:

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Norvald Kjerstad – Electronic and Acoustic Navigationsystems for Maritime Studies

Maciej Gucma, Jakub Montewka, Antoni Zieziula – Urządzenia nawigacji technicznej

Krajczyński Edward – Urządzenia elektronawigacyjne

Krajczyński Edward – Urządzenia nawigacji technicznej

Franciszek Wróbel – Vademecum nawigatora

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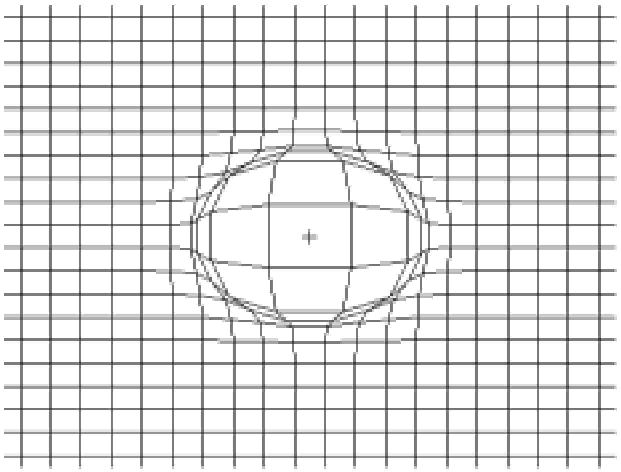
Fundamental concepts

The reason that acoustic and not electromagnetic waves or light are used for underwater purposes, is that elastic waves such as sound waves are exposed to far less attenuation upon movement through a medium with high density such as water.

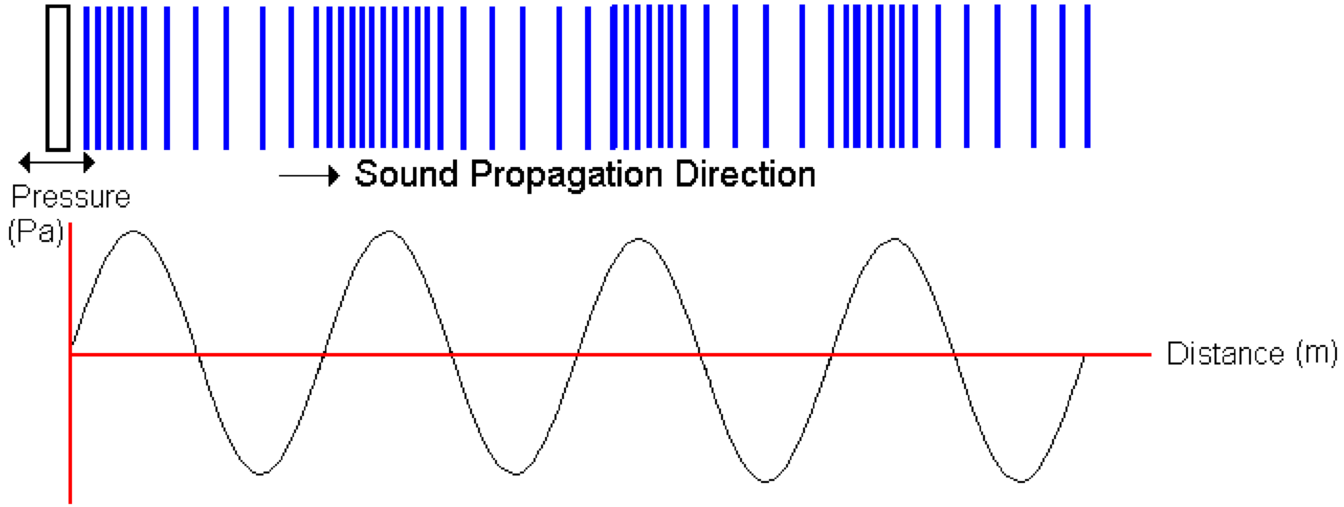


Fundamental concepts

Acoustic waves can be generated by setting a surface against the water in vibration. The pressure (p) in front of the surface will then pulsate according to a cosine function:

$$p = p_{max} \cos(2\pi f t + \varphi)$$

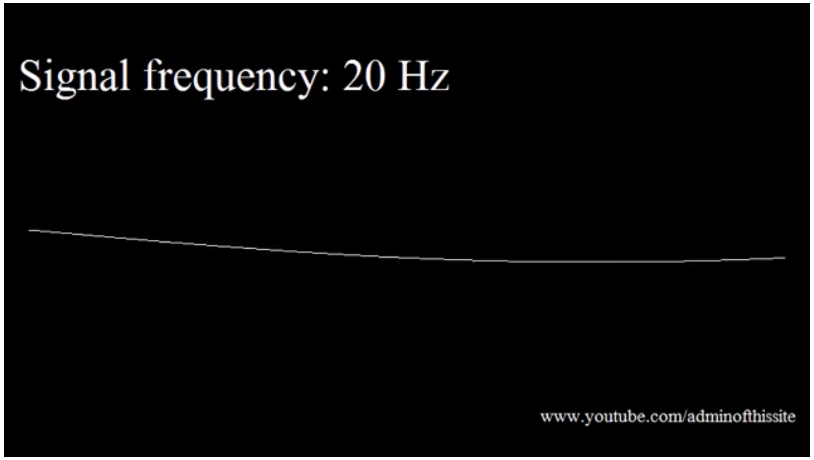
where: f – frequency, t – time, φ – phase angle

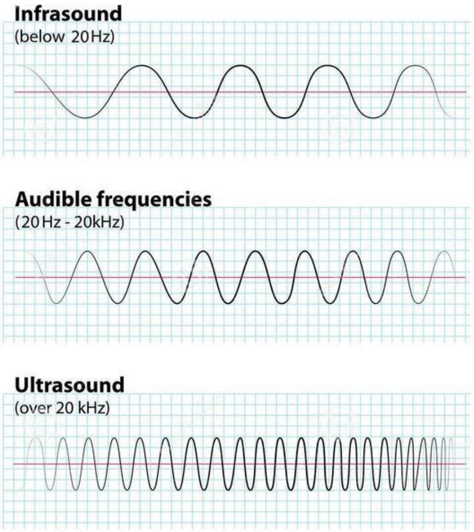


Fundamental concepts

Frequency (f) – number of pressure maximums (vibrations) per time unit. If the time unit is second the frequency unit is Hertz [Hz].

Typically the human ear is able to hear sounds between 20 Hz and 20 kHz. Frequencies under this range are called infrasounds, while frequencies over 20kHz are called ultrasounds. In hydro-acoustics ultrasounds will be used.





Fundamental concepts

Choice of the frequency is a quite complicated task, it should take into consideration a beam width (ability to distinguish objects) and the predicted depth of the area.

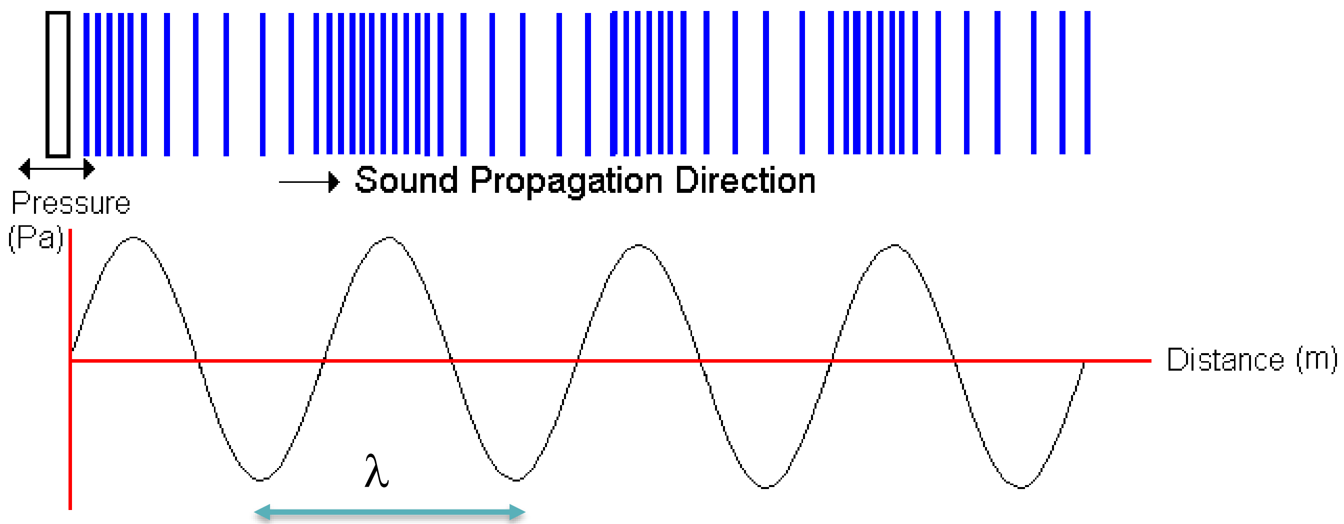
Experimentally, the following relationship was obtained:

$$f_{opt} = \frac{40}{\sqrt[3]{h_{max}^2}}$$

Fundamental concepts

Wavelength (λ) – the distance between two pressure maximums or amplitudes on the acoustic wave.

Time (t) – time between pressure-maximums. Typically given in seconds.



Fundamental concepts

Sound velocity (c) – the distance a pressure-maximum moves per time unit. On a general basis this is called velocity of propagation. Typically given in metres per second [m/s]

The sound velocity will vary according to the density, temperature, etc., of the medium. Increasing temperature will normally increase the sound velocity. For some substances the sound velocity will be approximately:

- air: 330 m/s
- water: 1500 m/s
- concrete: 3100 m/s
- copper: 3600 m/s
- iron: 5000 m/s
- limestone: 6000 m/s

Fundamental concepts

The real sound velocity in water is affected by temperature (t), pressure/depth(D) and salinity (S) of the water. Theoretically c^2 is inverse proportional with the product of the medium's compressibility and density.

Empirical approach:

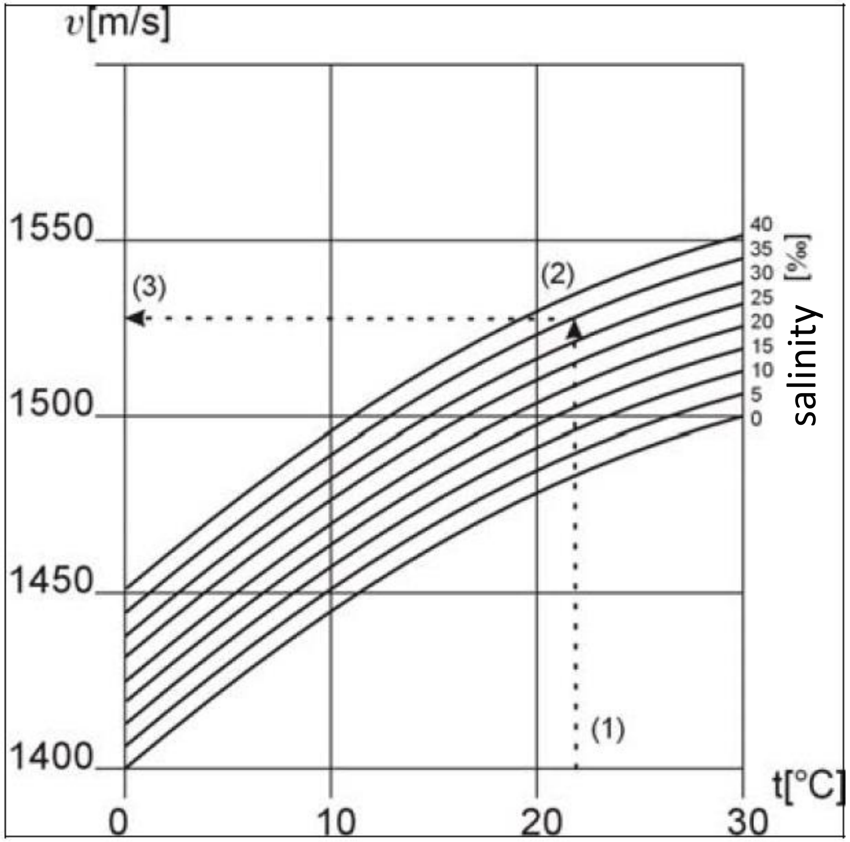
$$c = 1448.6 + 4.618t - 0.0523t^2 + 1.25(S - 35) + 0.017D$$

or

$$c = 1445.5 + 4.62t - 0.0452t^2 + (1.32 - 0.007t)(S - 35)$$

Fundamental concepts

Empirical approach:



Fundamental concepts

The connection between these parameters is given by the following formula:

$$\lambda = \frac{c}{f} \qquad \mathrm{c} = \lambda f \qquad t = \frac{1}{f}$$

The relation between frequency and wavelength:

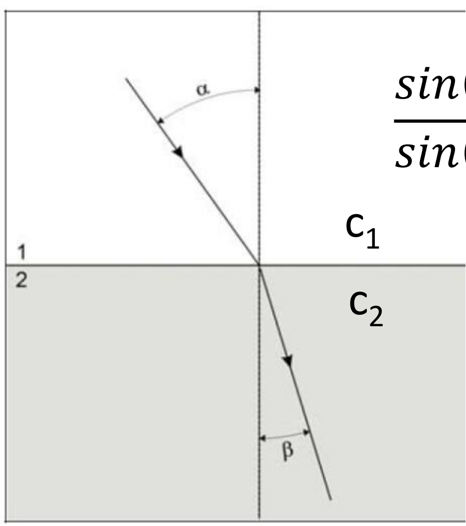
f = 30 kHz, λ = 50 mm
f = 50 kHz, λ = 30 mm
f = 200 kHz, λ = 7.5 mm

Propagation - Refraction

Refraction is the change in direction of wave propagation due to a change in its transmission medium.

The refraction of the hydro acoustic wave is influenced by:

- Differences in sound speed in different layers of water
- Temperature, salinity and pressure changes in the wave transition

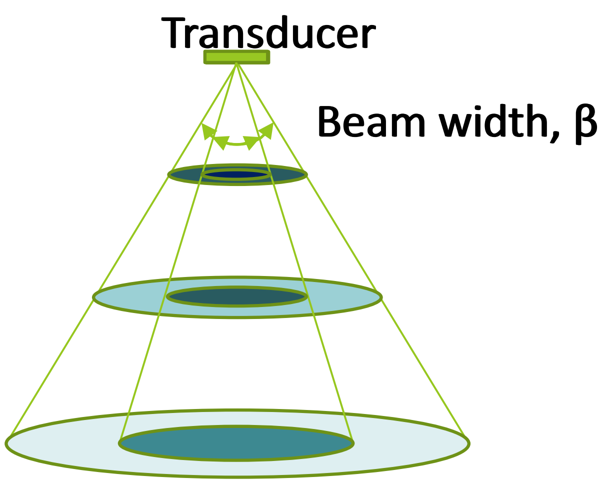


$$\frac{sin(\alpha)}{sin(\beta)} = \frac{c_1}{c_2}$$

Propagation – intensity loss – beam width

Pulse intensity is defined as energy that passes an area unit per time unit. Normally given in [m^2] and [s].

The intensity or sound pressure transmitted by the transducer will be reduced by spherical propagation as a function of the range (R). In the transducer's far field the intensity (I) will decrease according to the following quadratic course:



$$I = \frac{I_0}{R^2}$$

The propagation loss (PL) can be calculated with use of following formula:

$$PL = 20 \log\left(\frac{R}{R_1}\right)$$

Propagation – intensity loss - absorption

When the sound travels through the water, part of the acoustic energy will be absorbed and transformed into heat. Transmission loss which is due to absorption (AL) can be calculated as follows:

$$AL = 10\log\frac{I_1}{I} = \alpha(R - R_1)$$

for:

$$\alpha = 10A\log e$$

where:

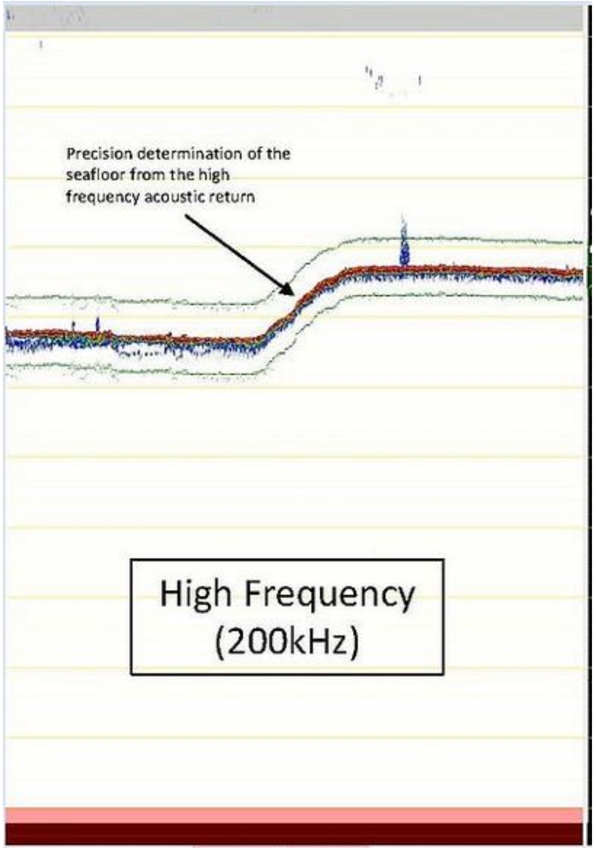
A – frequency dependant absorption factor

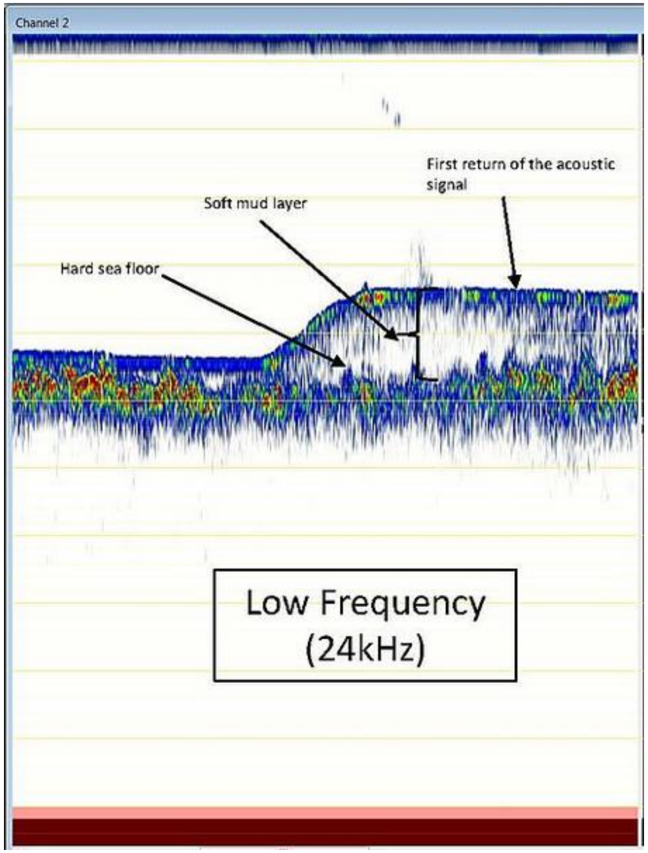
Value of co-efficient α is very dependant on the frequency, temperature, salinity, pH and pressure also have a certain significance.

Propagation – intensity loss - absorption

Frequency [kHz]	α [dB/km] (sea water, 35 ‰)	α [dB/km] (fresh water)
10	0.95	0.021
30	6.76	0.19
38	10	0.31
50	15.1	0.53
100	32.6	2.14
200	50.5	8.55

Propagation – intensity loss - absorption





Propagation – intensity loss – total transmission loss

Total transmission loss (TL) is a sum of the propagation loss and absorption loss. In decibels, the total loss will be as follows:

$$TL = 20\log\left(\frac{R}{R_1}\right) + \alpha(R - R_1)$$

The logarithmic element represents the propagation loss, while the second element represents a linear absorption loss

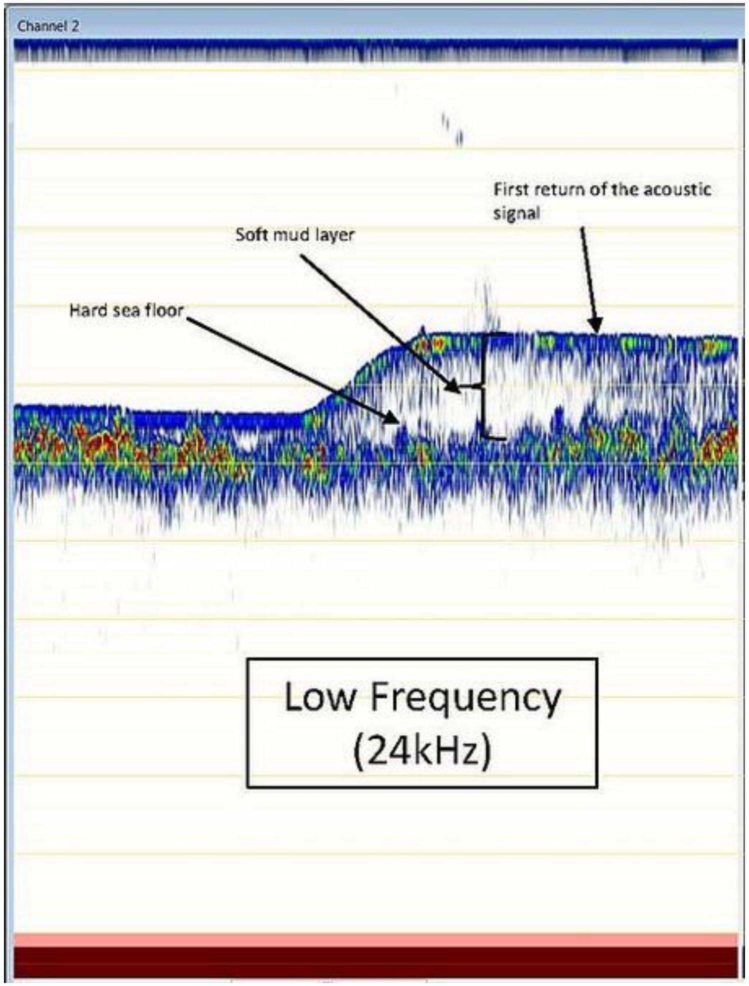
Propagation – reflective properties

The reflective properties of the surface are determined by the reflection coefficient which is different for different types of reflecting medium.

Percentage of energy reflected from different obstacles in the water

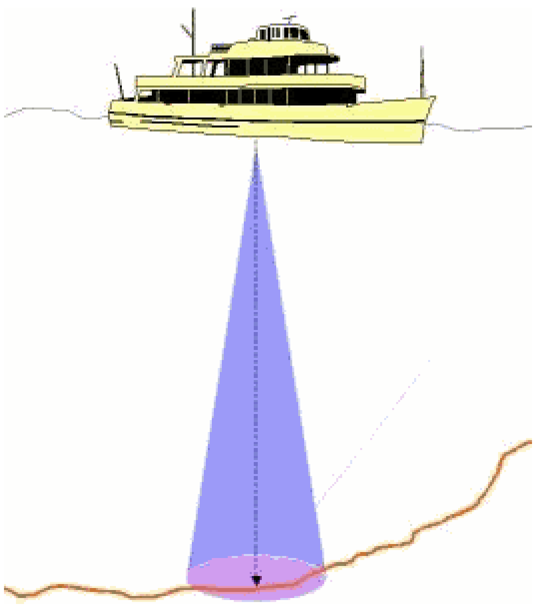
Obstacle	Reflected energy
air	99,9%
steel	85,0%
granite	65,0%
wood	21,0%
sand and ice	13,0%
loam	10,0%

Propagation – reflective properties



Pulse-based transmission

Most of the sonar systems use pulse-based transmission, i.e. that the transmitted frequency is transmitted in pulses („ping”) at given intervals. The number of pulses of a repeating signal in a specific time unit is called **pulse repetition frequency** (PRF). The length of each pulse is called pulse length (τ).



Pulse-based transmission

The pulse length will be of significance for the system's resolution of echoes in the depth direction. The ability to distinguish will be given by 0.5 pulse length. This factor arises because the pulse must travel forwards and back. The ability to distinguish is important if one is to separate targets that are relatively close to one another, e.g. a fish.

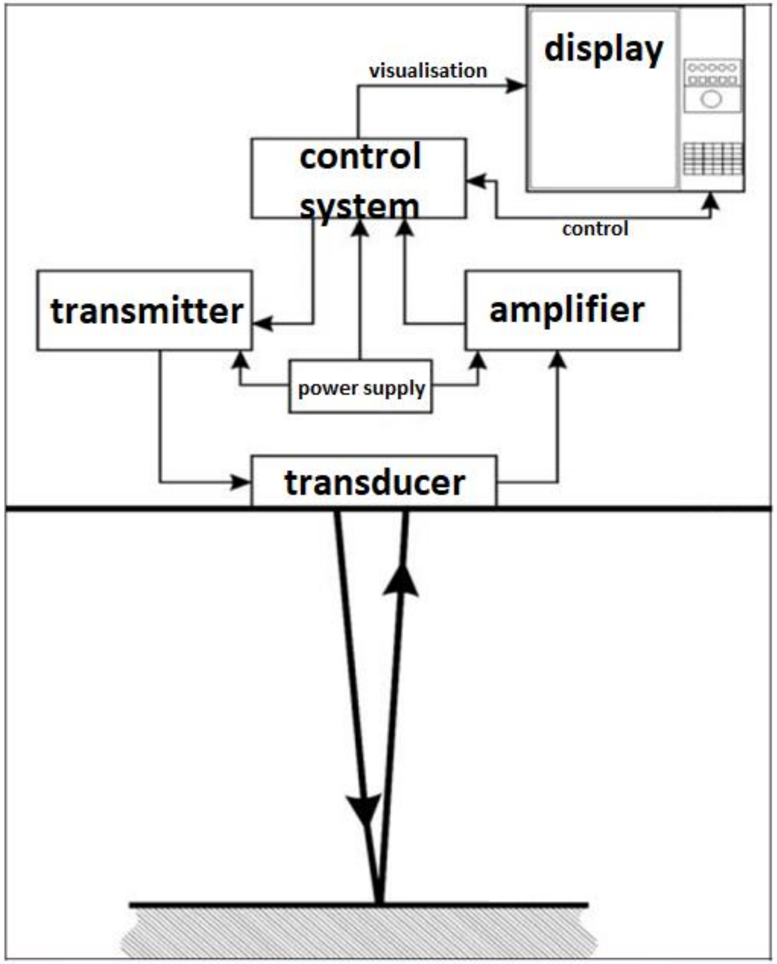
Echosounder resolution for the pulse length τ = 1ms is:

$$Res = 0.5 \cdot 1500 m/s \cdot 1 \cdot 10^{-3}\, s = 0.75\ m$$

If we wish to improve the ability to distinguish we must therefore reduce the pulse length.

Echosounder - block diagram

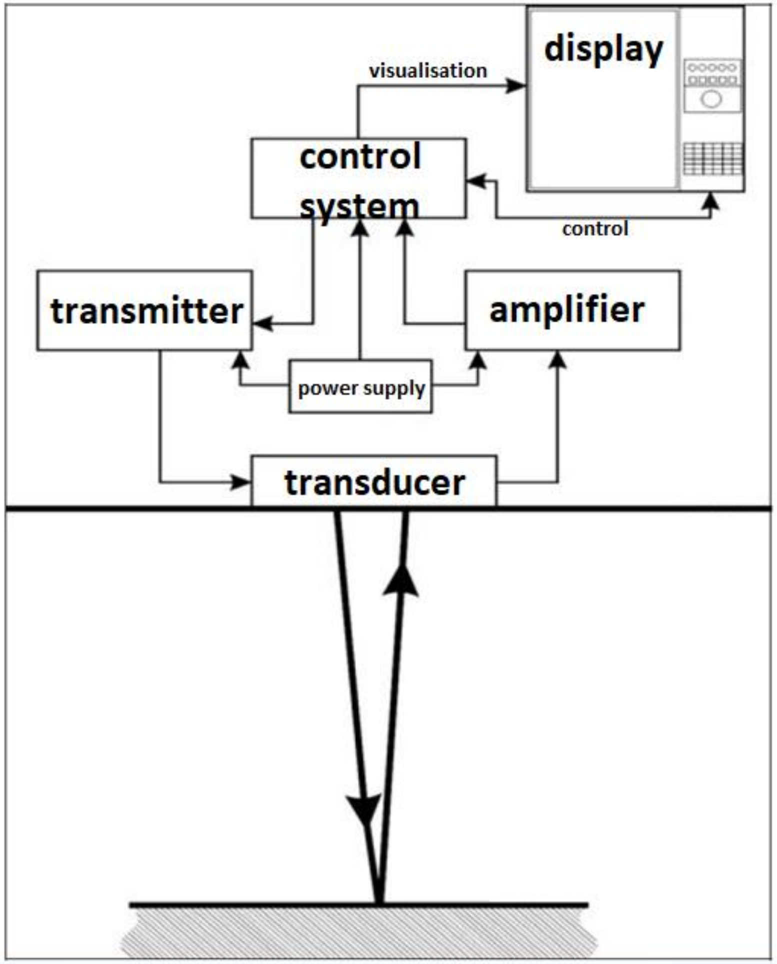
- Control system transmits the pulse initialising new work cycle
- Transmitter generates high voltage electrical pulse
- Transducer converts electrical pulse into sound wave and transmit it
- Sound pulse propagates, reflects and returns to the transducer



Echosounder - block diagram

- Transducer converts the sound energy of the echo to an electrical pulse
- Amplifier amplifies the returned pulse
- Control system measures time between the beginning of a pulse of sound and the return of the echo (τ) and calculates the under-keel clearance (UKC)

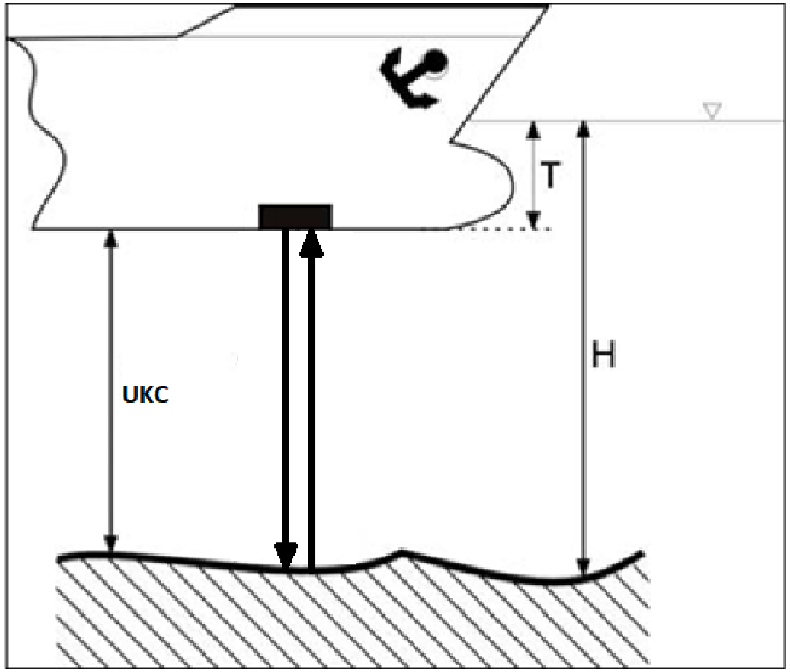
$$UKC = \frac{c\tau}{2}$$



Echosounder

$$UKC = \frac{c\tau}{2}$$

$$H = UKC + T$$



Echosounder – usual controls

Range Selector – governs the total depth are that is covered by the display. Presentation can be in metres, fathoms or feet. By varying the area the ping rate (PRF) will be changed automatically. On some sounders the output power and/or pulse length will also be changed according to range change.

On most sounders it will be possible to choose automatic range area selection.

Basic rule states that range should be the smallest one with visible sea bottom.

Echosounder – usual controls

Gain – can be adjusted on all echosounders. This is important since we need different gain for different purposes. Registering a powerful bottom echo needs considerably less gain than if one shall register a fish that is located near the bottom.

On many sounders it will be possible to choose automatic gain selection.

Echosounder – usual controls

TVG (Time Variable Gain) – as the name indicates, this is a control that varies amplification of the echo as a function of depth. As a rule, TVG works to a given depth and shall follow the function 20log R. By combining TVG and Gain one can reduce the disturbance from surface noise and shallow plankton layers, at the same time as the sensitivity for weak echoes near the bottom is maintained.

Echosounder – usual controls

Threshold – can be found on most colour sounders. This is a reference threshold that is set so that given colours shall indicate corresponding echo levels. Each colour have its own level threshold which is moved by operating the threshold control.

In this way echoes from fish can easily be distinguished from the bottom echo.

Echosounder – usual controls

Pulse length – can be adjusted automatically, but there are sounders where this can be varied manually. By increasing the pulse length, the average transmitted output will increase and give a higher source level. Increased source level will also increase the echo level and reverberation level. Whether the range is increased is therefore dependent on whether the range is reverberation limited. We shall also be aware that the resolution is given by half of the pulse length.

Echosounder – usual controls

Output power – can be adjusted on some sounders. The detection range can be increased with the output power, but we must also remember that the reverberation level also increases. A problem we face sometimes is that in shallow water such a powerful echo is reflected that the receiver exceeds its dynamic area and become saturated. The consequence of this is that we are not able to distinguish strong from weak echoes.

Echosounder – usual controls

Frequency – this is conditional upon having transducers that are adapter to the various frequencies. The most multi-frequency echosounders have two frequencies 50 and 200 kHz.

Noise Reduction – can be built – in on some sounders. The degree f noise reduction can often be done with a separate control. The filter shall suppress sporadic echoes that in all probability are false. The system can work in the way that the echo that does not repeat itself in the following pulse is not shown on the display. The risk by using a strong degree of noise-filtering is that one can lose weak, real echoes.

Echosounder – usual controls

Sound speed – changes the value of sound speed used to calculations. It can be adjusted manually, evaluated on the basis of input or measured salinity and temperature or measured. Precision of considered sound speed has a direct influence on precision of soundings.

Frame rate / paper speed – if the picture does not move between each ping we will not have an echogram drawn. On all echosounders therefore, there is a possibility of adjusting the frame movement. By using a high frame rate the bottom topography will be expanded so that steep edges can look like gentle slopes. Low frame rate leads to the opposite.

Echosounder – measurement errors

Main sources of measurement errors are:

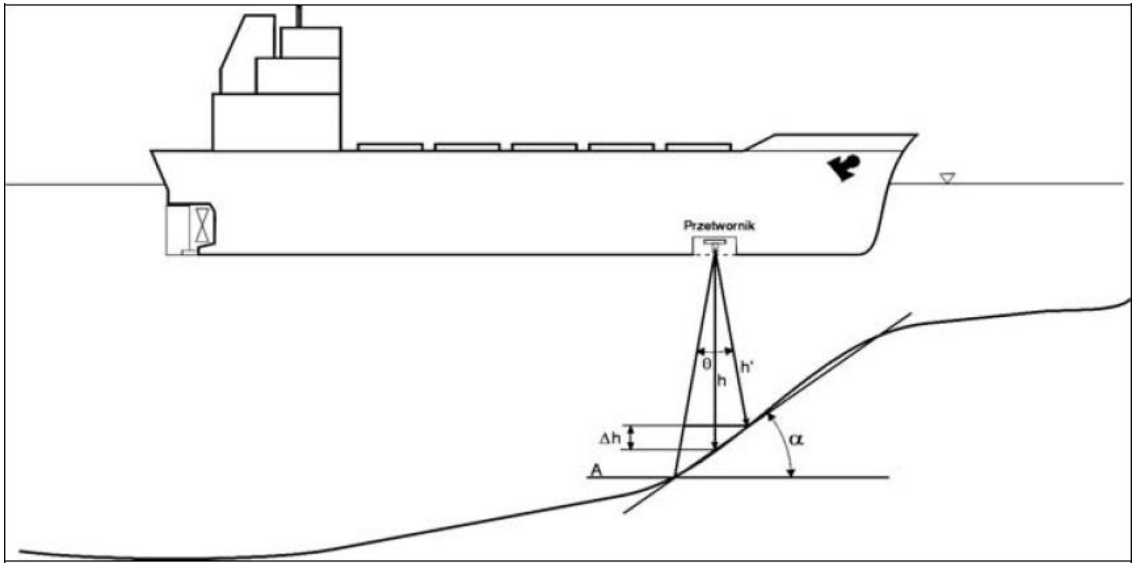
- Difference between actual sound speed and speed used to calculations
- Slope of the sea bottom
- Rolling of the ship
- Shape of the pulse

$$UKC = \frac{c\tau}{2}$$

Echosounder – measurement errors

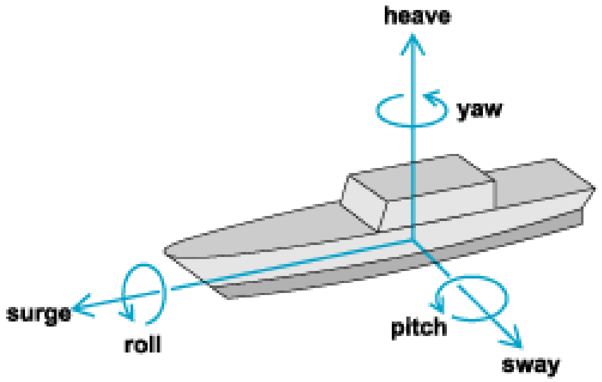
Slope of the sea bottom – if the bottom is inclined at an angle α with respect to horizontal plane A, the value h, is recorded instead of the actual value h.

It can be stated that for α ≤ 8 ° and θ ≤ 30 ° the slope error does not significantly affect the depth measurement



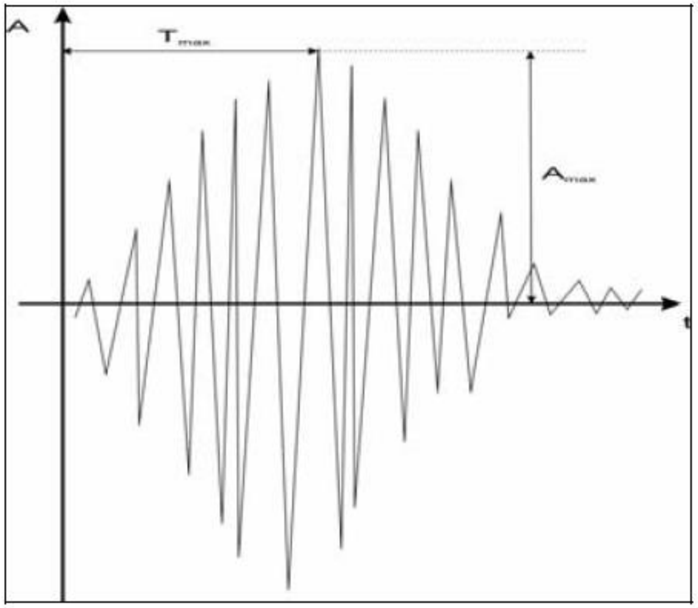
Echosounder – measurement errors

Rolling of the ship - in case of rolling, the transducer sends signals not perpendicular to the bottom, which causes variations in depth readings. The reduction of these errors is carried out at the construction stage by placing the transducer in the symmetry axis of the ship and during operation by selecting the lower transducer frequencies.



Echosounder – measurement errors

Shape of the pulse - pulse received by the transducer achieves the maximum amplitude after the T_{max} time. The average value of this time is approximately 5ms, which results with measurement error of 40 cm. This error can be minimized in modern echoes by the microprocessor and by the operator (selection of higher gain settings).

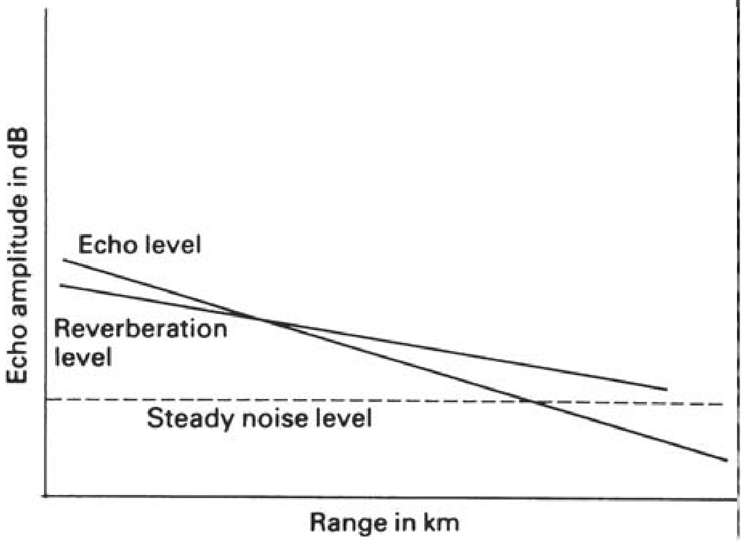


Echosounder – noise

Noise present in the ocean adversely affects the performance of sounder equipment. Water noise has two main causes:

- The steady ambient noise caused by natural phenomena.
- Variable noise caused by the movement of shipping and the scattering of one's own transmitted signal (reverberation).

The amplitude of the ambient noise remains constant as range increases, whereas both the echo amplitude and the level of reverberation noise decrease linearly with range. Because of beam spreading, scattering of the signal increases and reverberation noise amplitude falls more slowly than the echo signal amplitude.



Echosounder – ambient noise

Ambient noise possesses different characteristics at different frequencies and varies with natural conditions such as rainstorms. Rain hitting the surface of the sea can cause a 10-fold increase in the noise level at the low frequency (approx. 10 kHz) end of the spectrum. Low frequency noise is also increased, particularly in shallow water, by storms or heavy surf. Biological sounds produced by some forms of aquatic life are also detectable, but only by the more sensitive types of equipment.

Echosounder – ambient noise

The steady amplitude of ambient noise produced by these and other factors affects the signal-to-noise ratio (SNR) of the received signal and can in some cases lead to a loss of the returned echo. Signal-to-noise ratio can be improved by transmitting more power. This may be done by increasing the pulse repetition rate or increasing the amplitude or duration of the pulse. Unfortunately such an increase, which improves signal-to-noise ratio, leads to an increase in the amplitude of reverberation noise. Ambient noise is produced in the lower end of the frequency spectrum. By using a slightly higher transmitter frequency and a limited bandwidth receiver it is possible to reduce significantly the effects of ambient noise.

Echosounder – reverberation noise

Reverberation noise is the term used to describe noise created and affected by one's own transmission. The noise is caused by a 'back scattering' of the transmitted signal. It differs from ambient noise in the following ways:

- Its amplitude is directly proportional to the transmitted signal.
- Its amplitude is inversely proportional to the distance from the target.
- Its frequency is the same as that of the transmitted signal.

The signal-to-noise ratio cannot be improved by increasing transmitter power because reverberation noise is directly proportional to the power in the transmitted wave. Also it cannot be attenuated by improving receiver selectivity because the noise is at the same frequency as the transmitted wave.

Echosounder – reverberation noise

Furthermore reverberation noise increases with range because of increasing beam width. The area covered by the wave front progressively increases, causing a larger area from which back scattering will occur. This means that reverberation noise does not decrease in amplitude as rapidly as the transmitted signal. Ultimately, therefore, reverberation noise amplitude will exceed the signal noise amplitude and the echo will be lost. The amplitude of both the echo and reverberation noise decreases linearly with range. However, because of beam spreading, back scattering increases and reverberation noise amplitude falls more slowly than the echo signal amplitude.

Echosounder – reverberation noise

Three different 'scattering' sources produce reverberation noise.

- Surface reverberation. As the name suggests, this is caused by the surface of the ocean and is particularly troublesome during rough weather conditions when the surface is turbulent.
- Volume reverberation. This is the interference caused by beam scattering due to suspended matter in the ocean. Marine life, prevalent at depths between 200 and 750 m, is the main cause of this type of interference.
- Bottom reverberation. This depends upon the nature of the seabed. Solid seabed, such as hard rock, will produce greater scattering of the beam than silt or sandy seabed. Beam scattering caused by a solid seabed is particularly troublesome in fish finding systems because targets close to the seabed can be lost in the scatter.

THANK YOU