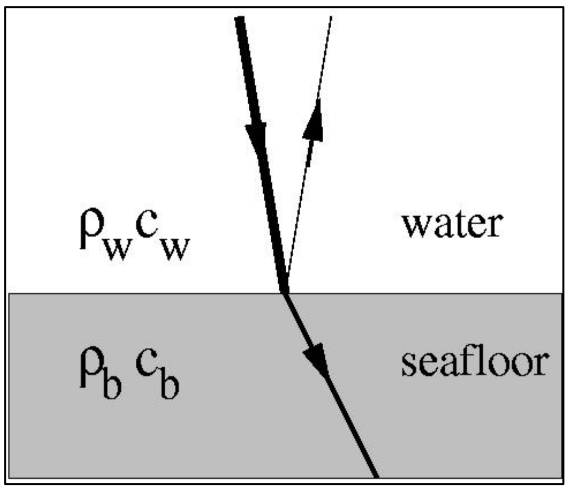
# Lecture notes
# “Seafloor mapping”

## part 2

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# 6 Acoustic seafloor mapping systems

## 6.1 Introduction

The oldest need for seafloor mapping is coastal navigation, for which good-quality bathymetric maps are vital to safety. Such maps have greatly benefited from acoustic techniques with regard to accuracy and completeness. National hydrographic offices aim at very accurate surveys of their territorial waters. Consequently, they extensively use specialized sonar systems. In shallow water, i.e., on the continental shelf, the required accuracy is better than 1 % of the water depth. The underwater maps produced are expected to provide accurate bathymetry, the presence of obstacles on the seafloor and, if possible, the nature of the seafloor. This requires the merging of various types of information, a large part of which can be collected acoustically.

Today, acoustic seafloor mapping is dominated by the multibeam echo sounder, which can, after transmission of a single signal, perform a large number (typically 200) of point measurements along a wide strip of seafloor terrain perpendicular to the ship's track. This system can measure simultaneously water depth and seafloor reflectivity. They appeared in the late 1970s and underwent significant development in technology and performance from then on. Improvements are still implemented today. Two other acoustic systems, based on older concepts, are in use:

The single beam echo sounder, in use since the 1920s, measures depth vertically below the ship. For each transmitted signal one obtains one point measurement of the water depth.

The sidescan sonar provides acoustic images of the seafloor from echos at grazing angles of incidence. They are in use since the 1960s.

This chapter is organised as follows. We start with a description and working principles of the single beam echo sounder. Subsequently, its performance and limitations are presented. Next, the sidescan sonar is treated. This allows us to introduce some fundamental notions, which will be used when we discuss the more sophisticated multi-beam echo sounder.

## 6.2 Single beam echo sounders

### 6.2.1 Signal transmission

A single beam echo sounder transmits, vertically below the ship, a short signal (duration $T$ typically 0.1 ms to 1 ms) in a beam with an angular aperture $\beta$ of typically 10°. For a circular transducer the 3 dB beam width, in degrees, reads (see chapter 5)

$$\beta = 65\frac{\lambda}{d}$$

with $\lambda$ the acoustic wavelength and *d* the diameter of the transducer, see Figure 1. For a rectangular transducer with dimensions $L_1$ and $L_2$, see again Figure 1, the 3 dB beam widths are given as

$$\beta_{1,2} = 50\frac{\lambda}{L_{1,2}}$$

This latter formula is relevant for the sidescan sonar, see section 6.3.

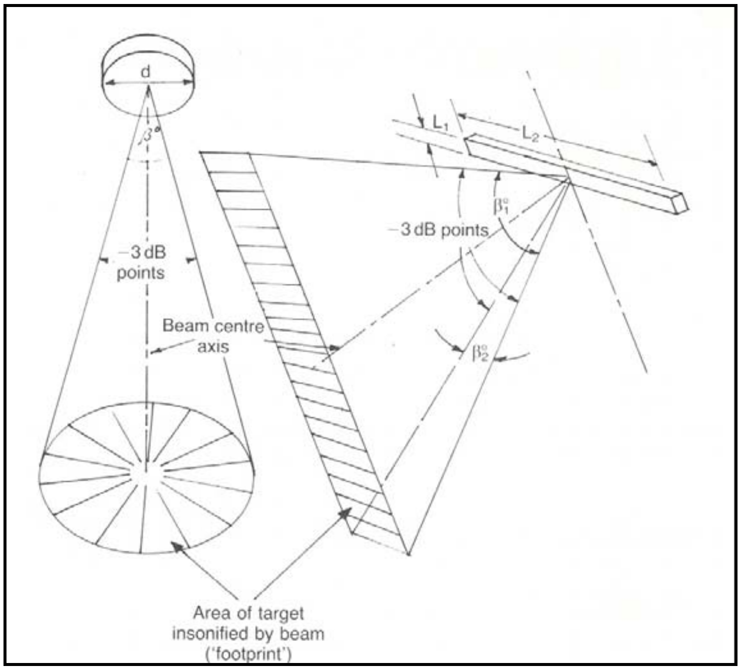


**Figure 1**

The instrument measures the two-way travel time of the signal, which, if the sound speed is known, gives the local water depth. A further analysis of the echo signal can provide information on the type of seafloor. The system can also detect echoes from targets in the water column and can hence be used for fishing.
The frequencies of (single-beam) echo sounders depend on the application, and range between 10 kHz for deep water applications to 500 kHz for shallow water applications. Dual frequency systems are also on the market. In general, the transmitted signals are not modulated as their duration (< 1 ms) is sufficiently short that the vertical resolution is acceptable. The source level of the echo sounder is typically in between 200 and 230 dB re 1 μPa at 1 m (see section 6.2.7 for a source level calculation of a deep-water echo sounder).

Examples of real data obtained with a dual frequency echo sounder operating at 200 kHz and 38 kHz, respectively, are presented in Figure 2. One notices the echoes from targets in the water column (possible schools of fish and isolated fish) as observed at both frequencies. The echo from a sediment interface at about 1.5 m in the bottom is better observed at the lowest frequency. This is due to the decreasing sediment sound absorption with decreasing frequency.

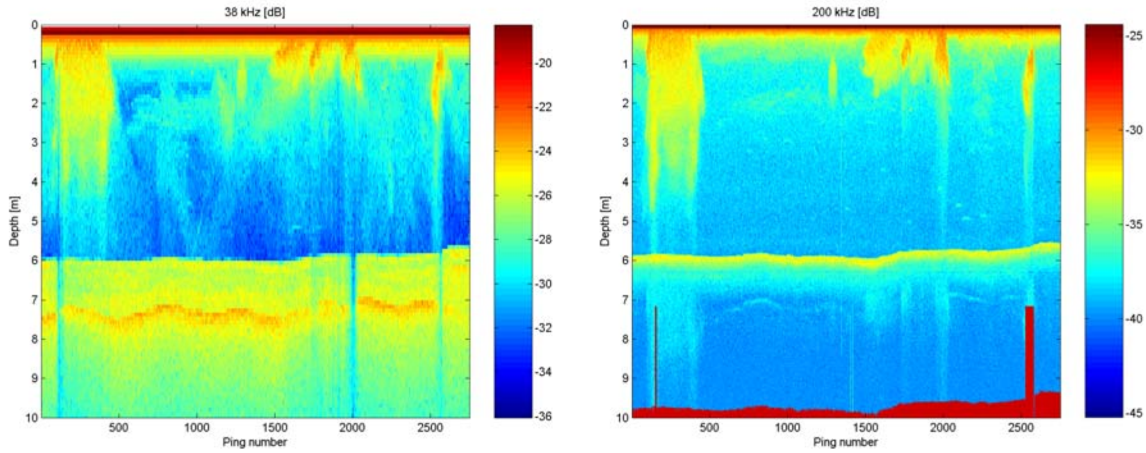


**Figure 2**

## 6.2.2 Transmission sequence

Normally, a new signal is transmitted after receiving the echo from the previous signal, thereby avoiding ambiguities. The repetition period is therefore given as

$$T_R > \frac{2H}{c} + T + \delta T$$

with $H$ the water depth, $c$ the (mean) sound speed in the water column, $T$ the signal duration and $\delta T$ its lengthening due to the seafloor reflection. Echoes of higher order, having travelled several times over the water column and having undergone multiple reflections at the ship's hull and seafloor, can still have considerable amplitude. To avoid these effects $T_R$ must be increased by the order $n$ of the multiples, i.e., $T_R$ becomes

$$T_R > \frac{2nH}{c} + T + \delta T$$

In certain situations it is necessary to take $n = 4$.

## 6.2.3 Transducers

In most echo sounders, the same transducer is used for both transmission and reception. It is installed below the ship's hull at a position where propeller noise and bubble clouds from the bow are avoided. The directivity patterns of circular and rectangular transducers are shown in Figure 1. The beam aperture (3 dB points) ranges from a few degrees to several tens of degrees. Beamforming (see chapter 5) is not needed.

6.2.4 Receivers

Generally, the receiver electronics consist of incoherent detection of the echo energy (i.e., band pass filtering around the signal's spectrum and envelope amplitude detection) and a Time Varying Gain (TVG) device to reduce echo level dynamics as much as possible. Reception is synchronised with transmission.
The echo from the seafloor is detected at the output of the receiver when the echo signal level crosses a threshold. The arrival or two-way travel time $t$ is then measured using an algorithm based on the detection of the leading edge of the time signal envelope crossing the threshold. The two-way travel time is converted into water depth $H$ using the simple linear relation

$$H = \frac{ct}{2}$$

One can easily verify that neglecting the actual sound speed profile, and using a constant (mean) $c$, results in a negligible depth error.
Now two ways of displaying are applied. First, the value of $H$ thus measured can simply be displayed digitally. Secondly and more elaborately, the entire backscattered signal versus time can be displayed, and the signal of each ping added to the previous ones. Such a presentation, see Figure 2, can be distorted horizontally by the irregular speed of the ship and the echo sounder's depth-dependent horizontal resolution (see section 6.2.6), and vertically by its movements (heave, roll, pitch). However, the acquired data is time-stamped and referenced with the location at which they were collected. This requires the echo sounder to be connected to the positioning system aboard the vessel. Further, the use of an attitude control unit can correct movements of the ship. The referenced acoustic data collected are then recorded digitally for later post-processing (e.g. for seafloor classification) and use in Geographic Information Systems (GIS).

6.2.5 Echo formation

The acoustic signal incident on the seafloor intercepts an active area that changes with time. This active area is also referred to as the *signal footprint*. We discuss the evolution of this area and the resulting echo under the following assumptions:

- the seafloor is flat and horizontal;
- the beam of the echo sounder has a conical directivity pattern;
- only the water-seafloor interface generates an echo.

The following echo formation steps are illustrated in
Figure 3.

(a) At the initial instant $t_0 = 2H/c$, the active area is just the impact point.

(b) From $t = t_0$ to $t = t_0 + T$ the active area $A$ is given as

$$A = \pi r_e^2 = \pi(R^2 - H^2) \approx \pi Hc(t - t_0)$$

Thus the signal footprint is a disc with (external) radius $r_e$ , the area of which increases approximately linearly with time $t$. The relation between two-way travel time $t$ and oblique range $R$ is $t = 2R/c$ .
When $R - cT/2 = H$ , then the two-travel time is exactly $t_0 + T$ . (The inner radius of the crown, see (c), is then $r_i = 0$ ).

(c) Beyond $t = t_0 + T$ the signal footprint becomes a crown with internal radius $r_i$ and external radius $r_e$. The area of the crown is given as

$$A = \pi(r_e^2 - r_i^2) = \pi\left( R^2 - \left( R - \frac{cT}{2} \right)^2 \right) \approx \pi HcT$$

i.e. approximately constant with time.

The active area or signal footprint disappears when the crown grows out of the *beam footprint* limits. We suppose that the echo sounder possesses the ideal conical beam pattern

$$D(\theta) = 1 \quad \text{for} \quad |\theta| \le \beta/2$$
$$D(\theta) = 0 \quad \text{for} \quad |\theta| > \beta/2$$

with $\beta$ the total beam aperture and $\theta$ the angle with the vertical.
Then the maximum possible outer radius is $r_{e,\max} = H\tan(\beta/2) \approx H\beta/2$ . The corresponding two-way travel time is denoted $t_{\max}$ and is given as

$$t_{\max} = t_0\sqrt{1 + \tan^2(\beta/2)} \approx t_0\left(1 + \frac{\beta^2}{8}\right)$$

We have assumed so far that the beam aperture is sufficiently wide for the signal footprint $A$ to reach its full extent. This is the so-called s*hort-pulse* or *pulse-limited regime.* The corresponding condition is

$$t_{\max} > t_0 + T$$

which can be approximated by

$$H > \frac{cT}{(\beta/2)^2}$$

For $t > t_{\max}$ the active area is

$$A = \pi(r_{e,\max}^2 - r_i^2)$$

with

$$r_{e,\max}^2 = H^2 \tan^2(\beta/2) \approx H^2(\beta/2)^2 \quad \text{and} \quad r_i^2 = (R - cT/2)^2 - H^2 \approx Hc(t - t_0 - T)\,.$$

The active area has become zero when $r_i = r_{e,\max}$ which corresponds to the two-way travel time $t_{\text{end}} = t_{\max} + T$ .

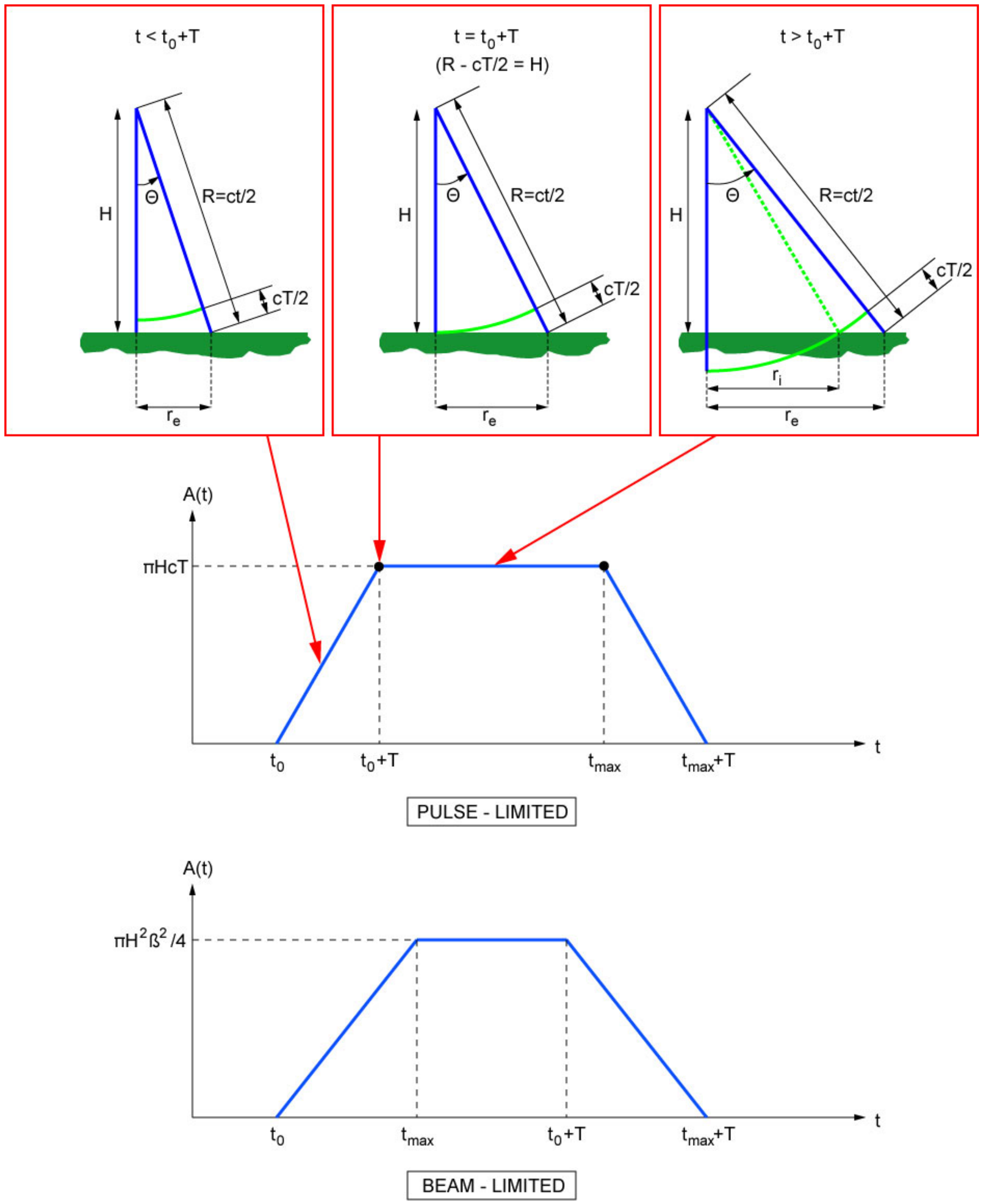


**Figure 3**

If the pulse is long enough, the interception by the beam footprint happens before $t = t_0 + T$ . This is the so-called *long-pulse* or *beam-limited regime.* The corresponding condition is

$t_{\max} < t_0 + T$ with $t_{\max}$ still equal to $t_0 \sqrt{1+\tan^2(\beta/2)} \approx t_0 \left(1+\dfrac{\beta^2}{8}\right)$.

In this regime we have:

(a) From $t = t_0$ to $t = t_{\max}$ the active area $A$ is grows as

$$A = \pi\, r_e^2 = \pi(R^2 - H^2) \approx \pi Hc(t - t_0)\,.$$

(b) From $t = t_{\max}$ and beyond up to $t = t_0 + T$ the active area is constant and given as

$$A = \pi r_{e,\max}^2 = \pi H^2 \tan^2(\beta/2) \approx \frac{\pi H^2 \beta^2}{4}\,.$$

Now the whole beam footprint is simultaneously insonified.

(c) Beyond $t = t_0 + T$ the active area decreases again as

$$A = \pi(r_{e,\max}^2 - r_i^2)$$

with

$$r_{e,\max}^2 = H^2 \tan^2(\beta/2) \approx H^2(\beta/2)^2 \quad \text{and} \quad r_i^2 = (R - cT/2)^2 - H^2 \approx Hc(t - t_0 - T)$$

and becomes zero at $t = t_{end} = t_{\max} + T$.

The received echo level not only depends on the signal footprint $A(t)$, as given in Figure 3 for the pulse- and beam limited situations. It also depends on the precise beam directivity pattern and the backscatter strength (as a function of $\theta$) of the seafloor. Qualitatively, the following happens due to these effects:

- The angular dependence of the backscatter strength will damp the theoretically linear increase of $A(t)$ and the constant signal footprint plateau will actually decrease;
- The cut-off in directivity pattern is not as sharp as was supposed with the ideal conical beam pattern: a lengthening of the signal is observed due to the beam side lobes.

Still, the formulas given above will provide a good first estimate of the behaviour of the received echo of a single-beam echo sounder.

6.2.6 Measurement resolution

The measurement resolution of an echo sounder is its ability to distinguish two close but distinct targets. In the vertical direction it is directly determined by the pulse duration *T*. The vertical resolution is given as

$$\delta z = \frac{cT}{2}$$

and typically ranges between 0.075 m for $T = 0.1$ ms and 0.75 m for $T = 1$ ms. When modulated signals are used, the vertical resolution is given as

$$\delta z = \frac{c}{2B}$$

with $B$ the bandwidth of the signal.
The angular aperture $\beta$ of the beam determines the horizontal resolution. For two targets to be distinguishable, they need to be spaced apart by at least the beam width (at – 3dB) at the depth $H$ considered. The horizontal resolution reads

$$\delta x = 2\tan\left(\frac{\beta}{2}\right)H \approx \beta H$$

A beam of 10 degrees aperture yields a horizontal resolution of 1.7 m at 10 m depth, 17 m at 100 m depth and 175 m at 1000 m, see also Figure 4.

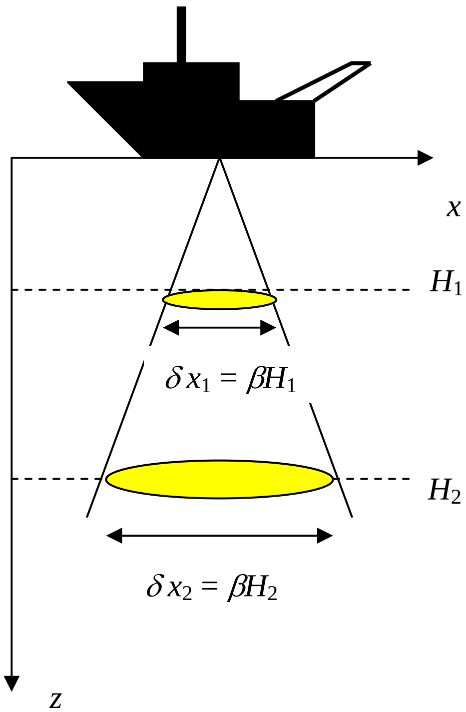


**Figure 4**

A target is observed by the echo sounder for as longs as its stays within the beam, i.e., for a time determined by the beam width $\beta$ and not by its own size. For example, a fish at 100 m depth will be observed by an echo sounder with $\beta = 10°$ for 17 m. It should not be concluded that the size of the fish is 17 m!

The oblique distance $d$ of a target to the echo sounder changes as the ship moves, see Figure 5 left part. The echo recorded with time for a target at ($x_0$, $z_0$) will have an orthogonal hyperbolic shape given as

$$\frac{z^2}{z_0^2} - \frac{(x - x_0)^2}{z_0^2} = 1$$

with $x$ the ship's horizontal position and $z$ the depth variable (see left part Figure 5). The oblique distance is $d = \sqrt{(x - x_0)^2 + z_0^2}$ .

The right part of Figure 5 gives the hyperbolically-shaped echoes for various target positions. For illustration purposes an unrealistically large beam aperture was chosen for these calculations ($\beta = 60°$).

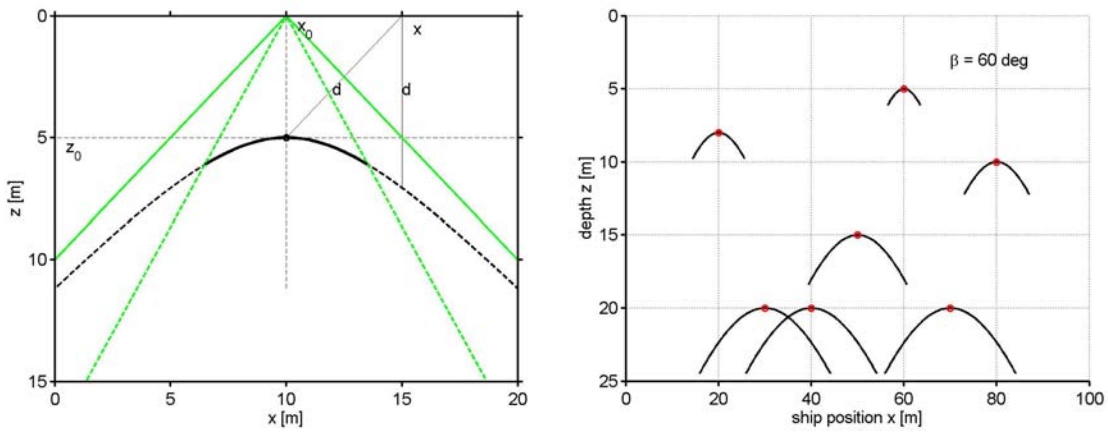


**Figure 5**

Because of the limited horizontal resolution, the mapping of seafloor bathymetric features with a single beam echo sounder causes many artefacts. A local trough in the seafloor will not be detected if its width along the track of the vessel is smaller than the beam footprint, since the edges of the trough will reflect a masking echo (see Figure 6 and right plot of Figure 7).

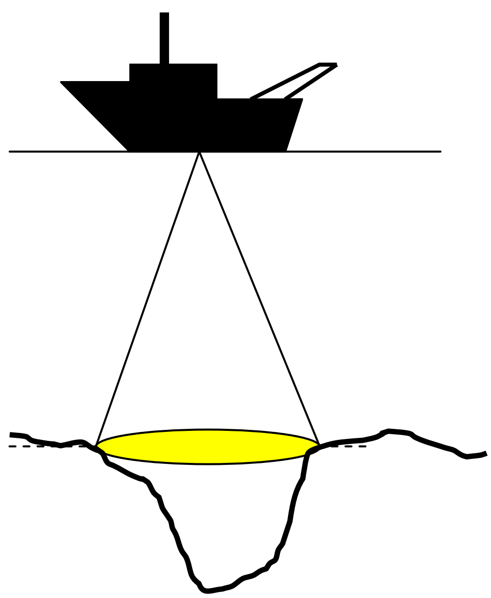

**Figure 6**

A local relief on the seafloor is easier to detect, but the hyperbolic process mentioned above will extend its original width (see left plot of Figure 7).

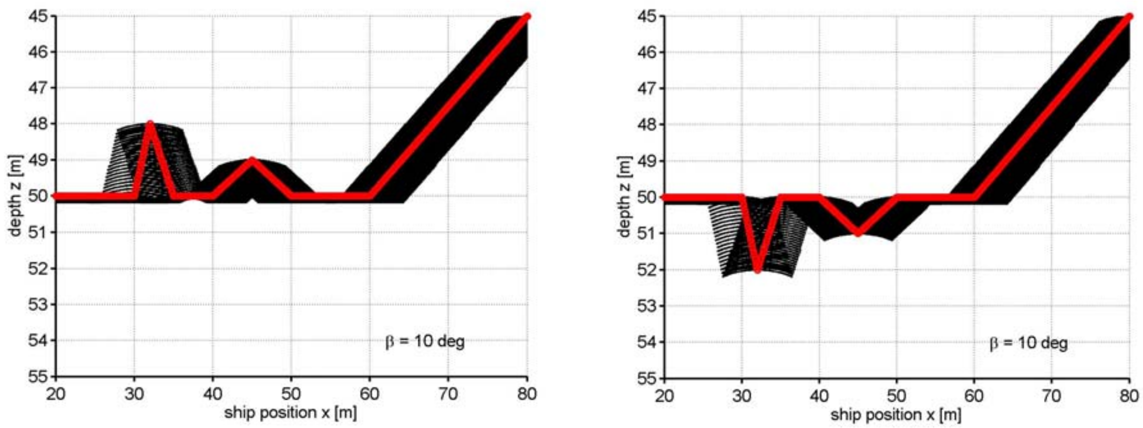


**Figure 7**

6.2.7 Maximum operating range

In this paragraph we discuss the parameters determining the maximum operating range of a single-beam echo sounder by considering the task of mapping the bathymetry of a deep water area (average water depth $H$ = 5000 m). The question then is: what are the required specifications for the echo sounder to be used, its frequency $f$ in particular?
Suppose the conditions are such that the observed noise level is resulting from sonar self noise (see paragraph 3.3.2), i.e. the sonar self noise level is much higher than the ambient noise level. The receiving bandwidth $W$ of the echo sounder is 500 Hz and the survey is carried at a ship speed $v$ of 15 knots.
We require the signal-to-noise ratio $SNR$ to be at least about 10 dB in order to be able to measure water depth accurately enough. For the $SNR$ the following expression holds

$$SNR = EL - BGL$$

with $EL$ the echo level (in dB) and $BGL$ the background level (in dB) due to the echo sounder's self noise. The echo level is given as

$$EL = SL - PL$$

with $SL$ the source level of the echo sounder. $PL$ is the propagation loss the signal encounters when travelling to and reflecting off the seafloor and travelling back to the echo sounder. The background level is given as

$$BGL = NL_W - DI$$

where $NL_W$ is the noise level in the band $W$ and $DI$ is the directivity index of the echo sounder.
The directivity of the echo sounder having a transducer with area $A$ is (see paragraph 5.6)

$$DI = 10^{10}\log\frac{4\pi A}{\lambda^2}$$

with $\lambda$ the acoustic wavelength of the echo sounder signal. For a (circular) transducer area of 400 $cm^2$, *DI* equals 19.5 dB at 20 kHz. Then the beam width $\beta$ equals 22°. The expression for the *SL* in dB is (see paragraph 5.8)

$$SL = 170.8 + 10^{10}\log P + DI$$

with *P* the radiated acoustic power (in Watt). If we take for *P* a typical value of 50 Watt, we find for *SL* = 207 dB re 1 μPa at 20 kHz.
A practical expression for the sonar spectral self-noise level in dB re 1 $\mu Pa^2$/Hz is (see paragraph 3.3.2)

$$NL = 33 + 1.8v - 20^{10}\log\left(\frac{f}{12}\right)$$

with *v* the ship speed in knots and *f* the frequency in kHz.
For obtaining the noise level in the 500 Hz band that we are considering here, the following holds

$$NL_W = NL + 10^{10}\log W$$

which equals 82.6 dB at 20 kHz.
The term left over is the propagation loss term *PL*. For this term we have (see equation (23) of paragraph 3.2.4)

$$PL = 60 + 20^{10}\log(2H) + 2\alpha H + BL$$

where $\alpha$ is the attenuation coefficient in the sea water. For a frequency of 20 kHz, $\alpha$ is 4.1 dB/km, see Figure 8 showing the attenuation coefficient (dB/km) as a function of frequency according to the Thorpe equation (see paragraph 3.1.9).

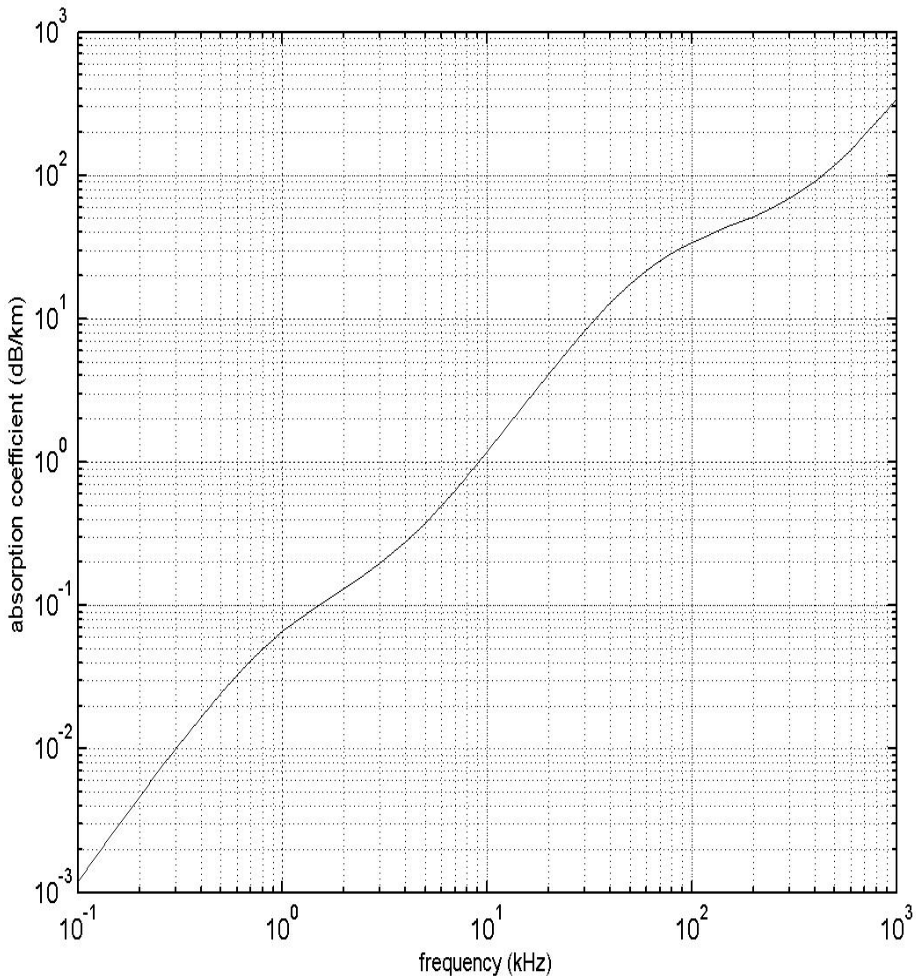


**Figure 8**

*BL* is the normal-incidence bottom loss in dB given as (see paragraph 3.1.10)

$$BL = -20^{10}\log\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}$$

For clay ($c_2$ = 1470 m/s, $\rho_2$ = 1.2g/cm$^3$) we find *BL* = 22 dB, whereas for coarse sand ($c_2$ = 1800 m/s, $\rho_2$ = 2g/cm$^3$) we find *BL* = 7.7 dB, see table 1 of chapter 4 for the geo-acoustic bottom parameters. Note that these values are independent of frequency.
Now all terms required for determining the *SNR* are known. Figure 9 shows the resulting *SNR* for four bottom types and for frequencies from 5 kHz to 35 kHz. One notices that a maximum in *SNR* is attained at a frequency of about 12 kHz, independent of bottom type. The increasing *SNR* at the low frequency end is due to the increasing directivity index of the transducer and the decreasing noise level. At the higher frequencies this effect is counteracted by the rapidly increasing absorption in sea water. Indeed, commercially

available deep-water echo sounders often operate at a frequency of 12 kHz. Further, it is clear that for deep-water surveying frequencies above ~ 20 kHz cannot be used.

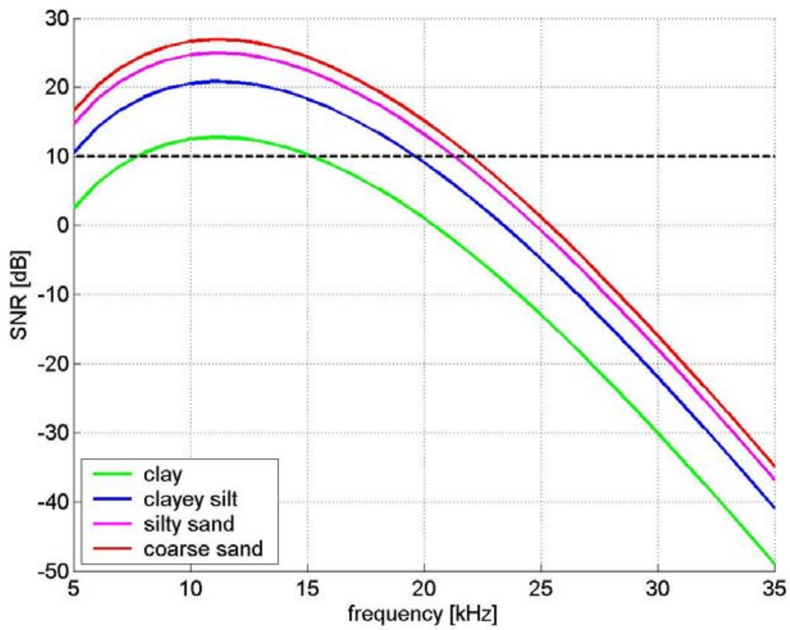


**Figure 9**

For surveying shallow water ($H$ < 100 m), the absorption term $2\alpha H$ in the formula for $PL$ is much less important, which allows higher frequencies to be used ($f$ > 100 kHz). Then the same directivity $DI$ and beam width $\beta$ is obtained with a smaller transducer.

### 6.3 Sidescan sonars

6.3.1 Signal transmission

A sidescan sonar is a visualisation tool providing acoustic images of the seafloor. They are usually installed on a fish towed near the bottom, which enables the system to work in good stability and noise conditions. A sidescan sonar insonifies the seafloor with two side antennas. The horizontal directivity of the antennas is very narrow, usually 1° or less. The narrow sound beam thus transmitted is intercepting the seafloor along a thin strip spreading out with distance, see Figure 10.

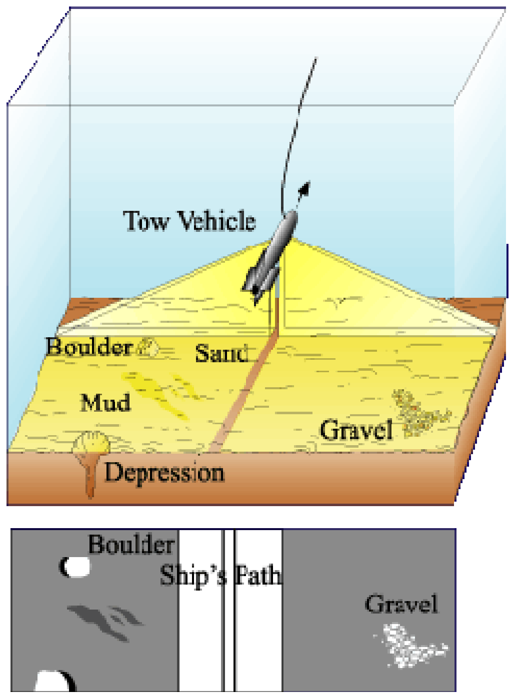


**Figure 10**

The instantaneously insonified area (the signal footprint, see Figure 11) inside this beam footprint or swathe is very small due to the very short transmitted signal (typically 0.1 ms or less). The signal recorded as a function of time represents the seafloor backscatter strength along the swathe, particularly the presence of irregularities and small obstacles. It is added to the signals recorded at previous positions of the tow fish. Line by line, it thus creates an image of the seafloor, see lower part of Figure 10.


**Figure 11**

According to Lambert's law, the rate of change of backscatter strength is largest at the smallest grazing angles. Hence, the contrast of a sidescan sonar image is highest for the smallest grazing angles of incidence. Therefore, the fish is towed as close as possible to the seafloor.

Sidecan sonars are usually lightweight systems (see Figure 12), easily movable and primarily destined for shallow water applications.

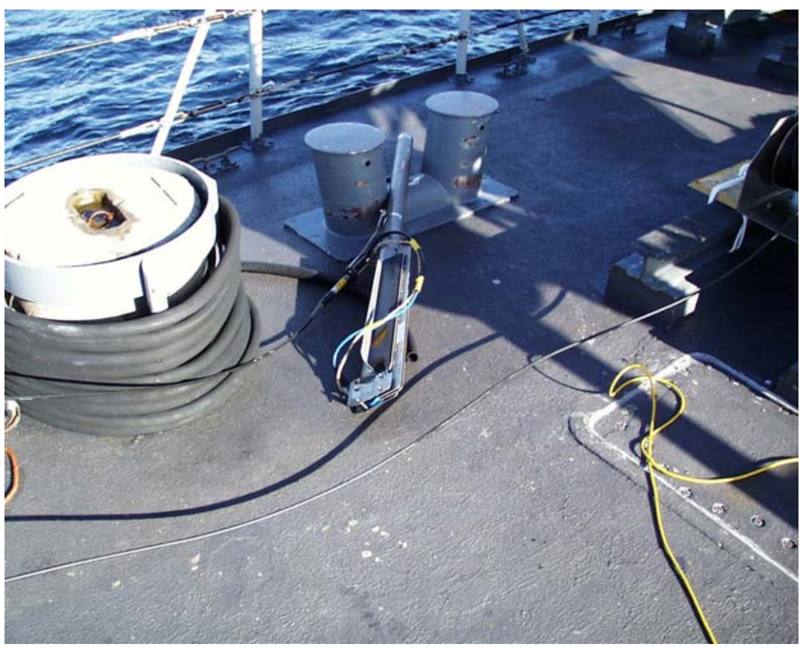

**Figure 12**

6.3.2 Transmission sequence

A new ping is transmitted after the signal from the previous one has been fully received, i.e., its level has sufficiently decreased. Hence, the repetition period is

$$T_R > \frac{2R_{\max}}{c}$$

with $R_{\max}$ the maximum reachable oblique range.

### 6.3.3 Transducers

A sidescan sonar basically consists of two long rectangular antennas (see Figure 1 in section 6.2), the directivity of which is largely open in the vertical plane (beam width several tens of degrees) and very narrow in the horizontal plane (about 1° or less). The vertical beam pattern is slightly inclined downwards, in order to insonify at far ranges (incidence angles $\theta$ up to 85° from the vertical), to avoid the sea surface and to limit downward vertical insonification. Ranges are typically hundreds of metres.
The antennas are installed on each side of a towfish. The frequencies are typically several hundred kHz, such that the required directivities are achieved with antennas of reasonable length (i.e. $L_2$ = 0.5 m at 150 kHz for $\beta_2$ = 1°). The range resolution for a pulse duration $T$ of typically 0.1 ms is 7.5 cm at the largest ranges.

### 6.3.4 Reception processing

The basic structure of the receiver is similar to that of the single-beam echo sounder and comprises the following operations:

- TVG (Time Varying Gain) equalisation of the received echo level;
- Demodulation and filtering;
- Analog-to-Digital Conversion (ADC);
- Bandpass filtering and envelope detection[1] (also called “non-coherent processing”);
- Processing gain compensation;
- Data storage.

About displaying the data:
The recorded echoes are displayed as a function of time, i.e., for every ping, the backscattered intensity is drawn as a line of pixels perpendicular to the towfish track. As a first approach, one simply displays a pile of successive echo lines, see Figure 13, thereby already obtaining a surprisingly good seafloor picture quality.

[1] A few systems use modulated signals and pulse compression.

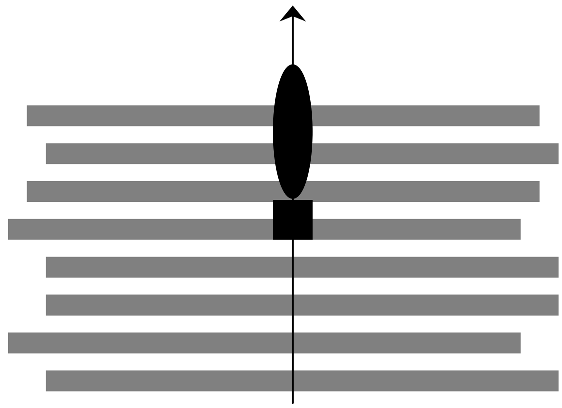

**Figure 13**

However, time *t* and transverse distance *y* on the seafloor are not proportional. Hence, equidistant time samples do not correspond to regular seafloor samples and a geometrical correction must be applied. If the seafloor is flat, this is simply (see
Figure 14)

$$y = \sqrt{R^2 - H^2} = \sqrt{\frac{c^2 t^2}{4} - H^2}$$

with $R(t) = ct/2$, the oblique distance, and *H* the sonar altitude (known from the first bottom echo).

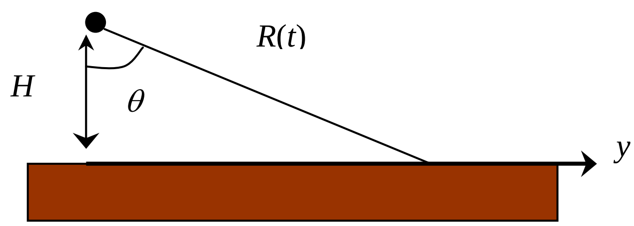


**Figure 14**

When the seafloor is not flat, geometrical correction requires simple a-priori assumptions about topography (e.g. regular slope) or additional recording of bathymetry. A standard sidescan sonar is not capable of measuring bathymetry.
Finally, if the towfish is equipped with a navigation and motion data unit, its movements can be compensated for and the pixels relocated in a precise geographic frame. Several tracks of the side-scan sonar may be added, the result of which is called a sonar image mosaic (see Figure 20 in the examples, section 6.3.8).

### 6.3.5 Echo formation

An example of the echo generated by a sidecan sonar is given in Figure 15.

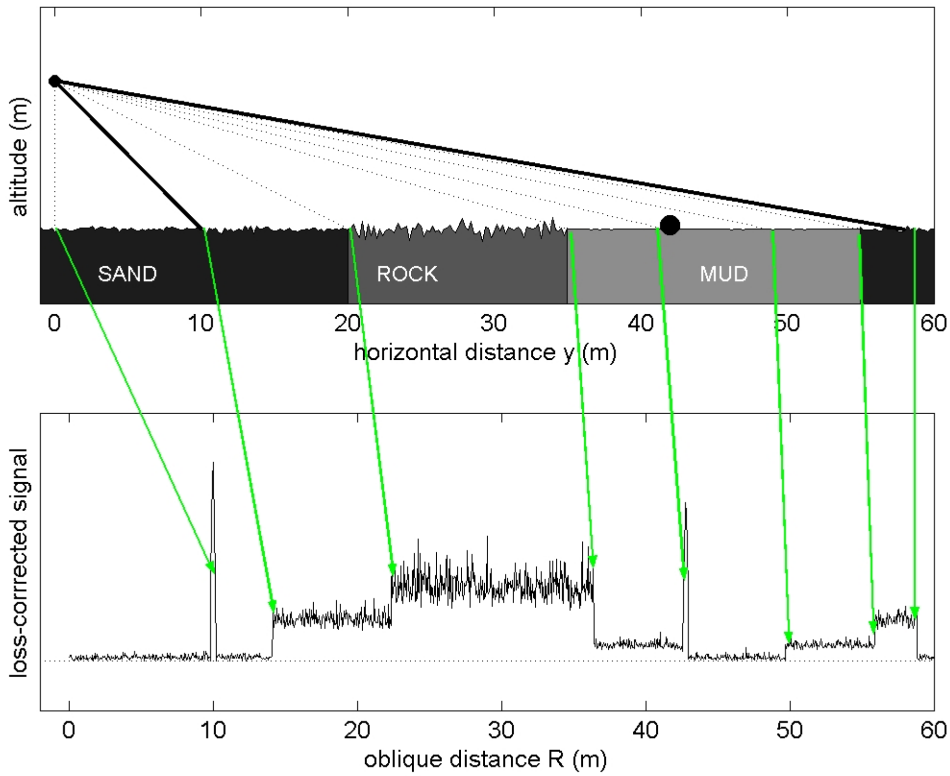


**Figure 15**

The sonar first only receives background noise. The actual echo from the seafloor starts when the transmitted pulse strikes the nadir of the sonar. This normal-incidence reflection creates a first intense echo, since the backscatter strength is maximal and the propagation loss is minimal. This signal is not used for imaging, but is useful to estimate the altitude $H$ of the sonar above the seafloor.

As the signal propagates with time, it will then explore the angular zone close to the vertical. This first part, with high backscatter strength and poor horizontal resolution (see next section), is generally of bad quality. When the signal reaches oblique and grazing incidence, it becomes really useful for imaging. Its average level then depends on the local type of seafloor (roughness), modulated with the transducer's vertical directivity pattern.

About shadow formation:

A large enough obstacle intercepts part of the angular sector transmitted and prevents backscattering from the seafloor at the times associated with these angles. The corresponding received signal will be as low as the noise level for a duration $\Delta t$ depending on the height $h$ of the masking obstacle. An analysis of the shadow provides information about the size and shape of the obstacle. This is particularly interesting for identifying objects on the seafloor like mines and shipwrecks. It can also be used to assess the scale of the seafloor relief. The obstacle height is given as

$$h = \frac{H\ \Delta t}{t_F}$$

with $t_F$ the end time of the shadow as measured from the transmission instant ($t$ = 0).

### 6.3.6 Resolution

The across-track resolution, in the $y$-direction, is given by projecting the equivalent length of the signal transmitted. Thus

$$\delta y = \frac{cT}{2\sin\theta}$$

As $\theta$ approaches 90°, then

$$\delta y = cT/2$$

which is exactly the resolution of the transmitted signal.
At normal incidence, $\theta$ = 0°, this approximate equation is not valid (as it would yield $\delta y \to \infty$) and the across-track resolution is then the same as that of a single-beam echo sounder in the short-pulse regime, i.e.,

$$\delta y = \sqrt{HcT}$$

The along-track resolution is the projected horizontal beam width:

$$\delta x = R\beta$$

with $R$ the oblique distance (slant range) from the sonar to the seafloor. The resolution of a sidescan sonar is thus inhomogeneous (as $\delta x$ and $\delta y$ differ). Moreover, it varies along the swathe (see Figure 16):

- at small distances $\delta y >> \delta x$;
- at large distances $\delta x >> \delta y$.

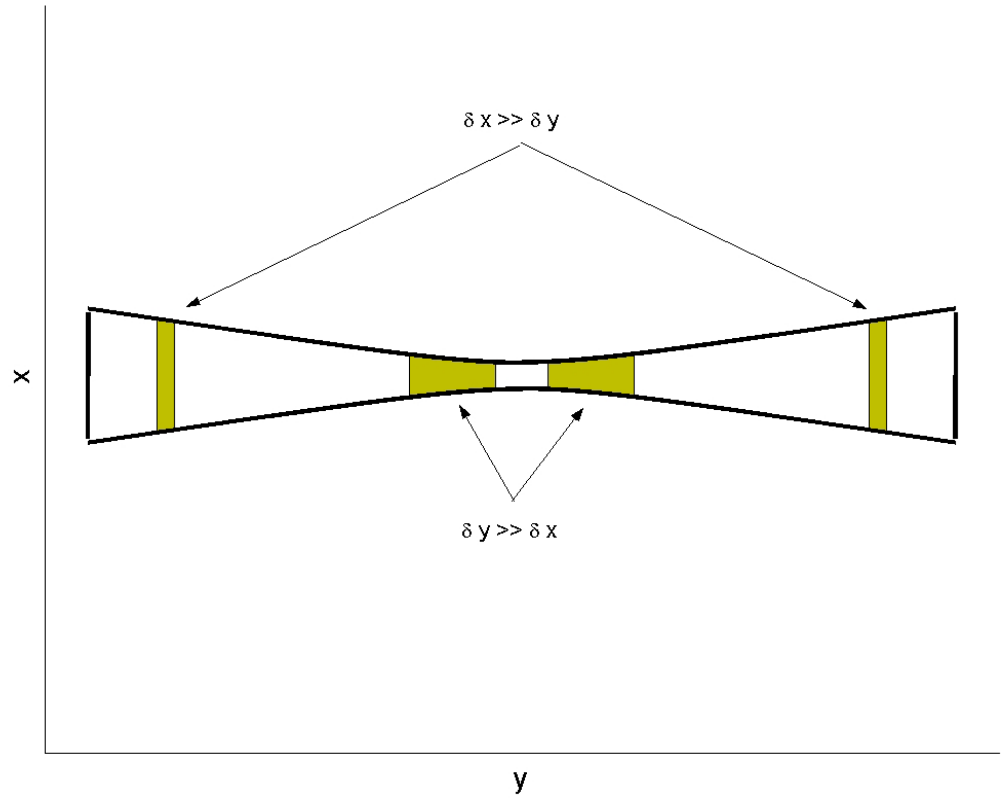


**Figure 16**

6.3.7 Coverage

A performance constraint of a sidescan sonar stems from the need to obtain 100 % coverage of the area to be surveyed. The condition to be fulfilled is then the removal of the gaps between the beam footprints or insonified strips of two successive pings. This condition is critical close to the vertical, since the insonified strip is narrowest there, see Figure 16. The along-track width of the insonified strip is equal to the along-track resolution for $y \to 0$, i.e., $\delta x = H\beta$. Here $\beta$ is the (3 dB) beam width (in radians) of the directivity pattern in the horizontal plane. Between two successive pings, the sonar advances a distance $vT_R$, with $v$ its speed and $T_R$ the inter-transmission delay or repetition period. Using $T_R = 2R_{\max}/c$ (see section 6.3.2), we obtain the ship's towing speed condition

$$v \le \frac{cH\beta}{2R_{\max}}$$

with $R_{max}$ the maximum reachable range.
The condition can be written as

$$v \le \frac{c\beta}{2}\cos\theta_{max}$$

where $\theta_{max}$ is the maximum insonification angle in the across-track plane. The 100 % coverage condition is now independent of water depth $H$.
A beam width of $\beta = 1°$ and a maximum angle of $\theta_{max} = 70°$ gives a limiting ship speed of $v = 4.5$ m/s = 8.7 knots.

### 6.3.8 Examples of sidescan sonar images

Figure 17 shows a 600 kHz image of the USS Utah, resting in Pearl Harbour near Ford Island.

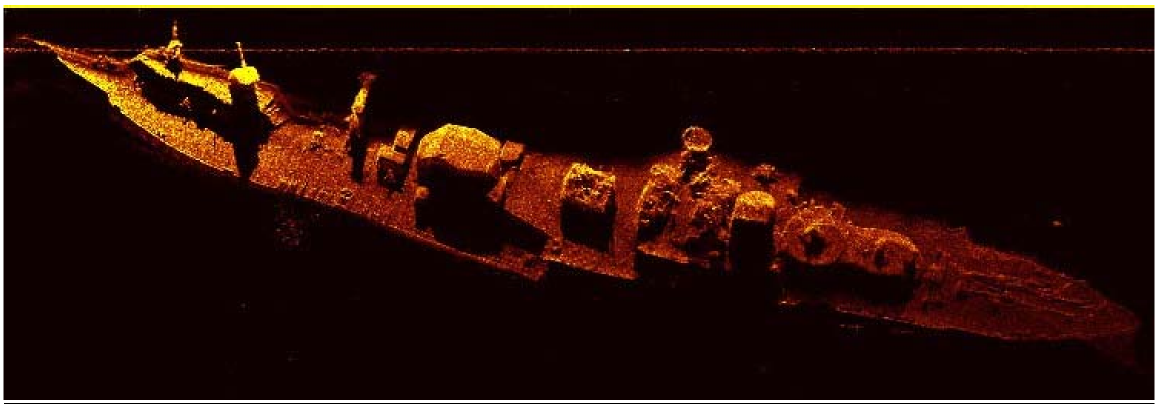

**Figure 17**

Figure 18 shows a Navy PB4Y-2 Privateer. One of 736 built from May 1943 to the end of the war. The aircraft sits in 164 ft. of water in Lake Washington, WA and was imaged with a 600 kHz sidescan sonar.

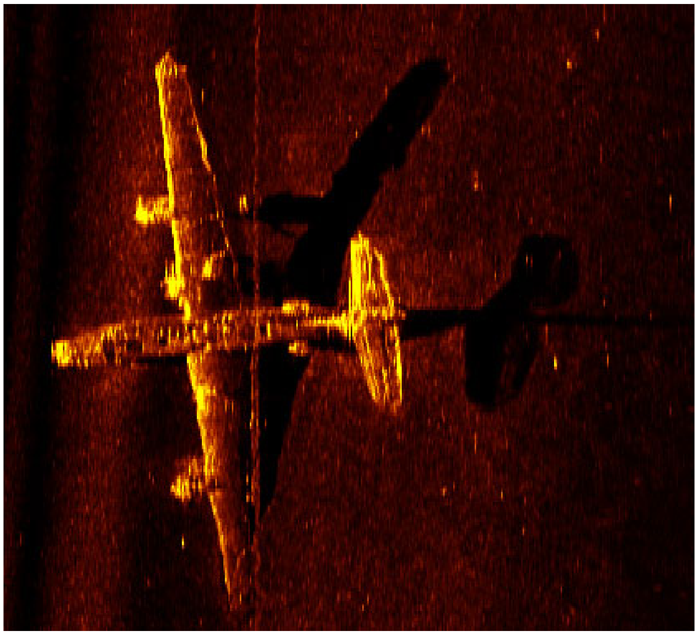

**Figure 18**

The 900 kHz image of Figure 19 is of a sea floor off the coast of New Zealand on a 20 meter scale. Interestingly it is composed of very different bottom textures. The most pronounced bottom consists of coarse sand and shell hash ripples, the other consists of fine sand with 0.15 meter bed forms.

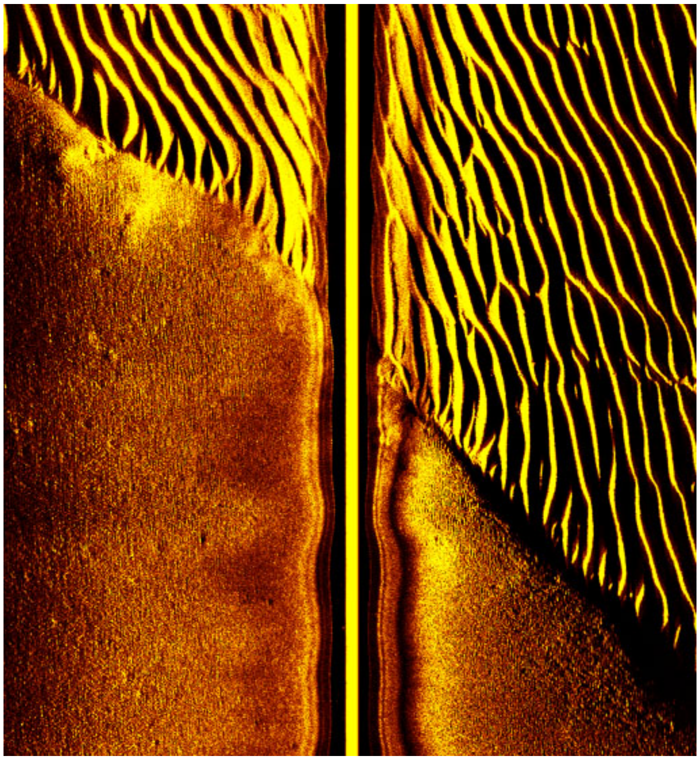

**Figure 19**

The images used in the mosaic shown in Figure 20 were collected using a 600 kHz sidescan sonar at 20 meters range and then mosaiced. The dredging operation shown here in this mosaic is in Red Brook Harbor in the Rhode Island Sound, North Falmouth, MA.

**Figure 20**

### 6.4 Multi-beam echo sounders

6.4.1 Overview

The multi-beam echo sounder is an extension of the single beam echo sounder. Instead of transmitting and receiving a single vertical beam, the multi-beam echo sounder transmits and receives a fan of beams, see Figure 21. The beam width of each of these beams is as small as 1-3° across the axis of the ship. This transversal beam width in the across-track direction is denoted $\theta_T$ .
The fan of beams (for each ping) enables the possibility of a large number of simultaneous depth measurements (typically as much as 200) along a swathe of width *L*, see Figure 21.

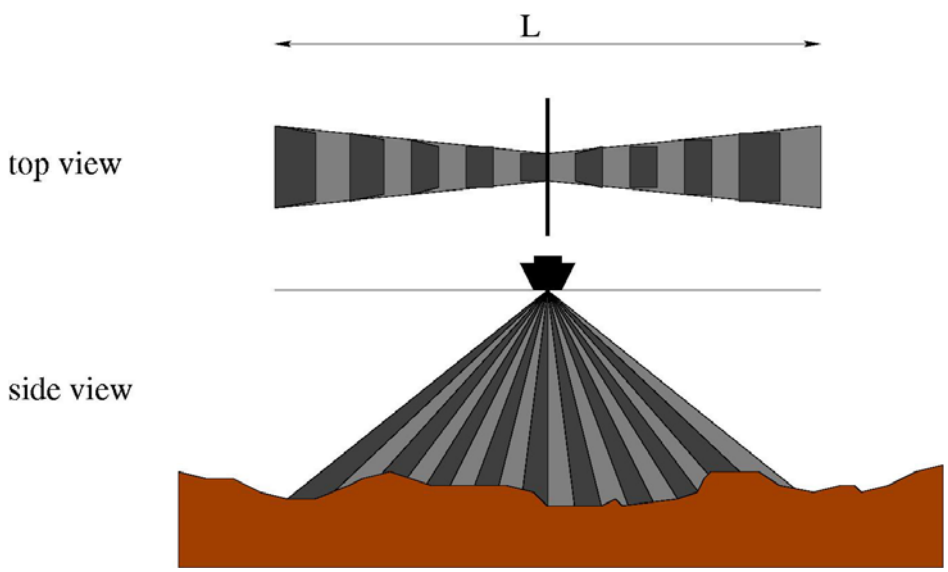


**Figure 21**

The multi-beam system thus sweeps a large corridor around the ship's path: a total angular width $2\theta_M$ of typically 150° covers up to $L = 7.5H$ , *H* being the water depth.
Most recent multi-beam systems also use this large angular width to acquire acoustic images of the seafloor using the same principle as that of the sidescan sonar. Hence, the multi-beam echo sounder provides, at the same time, bathymetry and backscatter measurements.
Since their appearance in the late 1970s, multi-beam echo sounders have greatly evolved, have become very varied, as a consequence of which they have become essential for seafloor mapping operations. Multi-beam systems can survey large areas rapidly and accurately and they are essential for the study of the geological morphology of the seafloor.
Several types of multi-beam systems are offered by manufacturers:

- Deep water systems operating at a frequency of typically 12 kHz. The corresponding large dimensions of the transducer array limits their installation to deep-sea vessels.
- Shallow water systems operating at frequencies of typically 100-200 kHz, designed for mapping the continental shelf.
- High-resolution systems operating at frequencies of typically 300-500 kHz, designed for local studies, such as shipwreck location and inspection of underwater structures. Their small size makes them suitable for installation on small ships, tow fishes or autonomous underwater vehicles (AUV).

### 6.4.2 Transmission and reception transducer arrays

Transmission:
The transducer arrays are designed such that the system has a narrow beam width $\theta_L$ in the horizontal plane. Similar to sidescan sonars, one wants to insonify a thin strip of seafloor terrain across-track of the support platform. This requires a long transmission array along the axis of the supporting platform. We further need a large transmission width $2\theta_M$ to cover as large a swathe as possible, corresponding to transmission arrays that are narrow across-track. The along-track discrimination is thus determined by the directivity of the transmission array. The left plot of Figure 22 shows a top and side view of a typical transmitted beam.

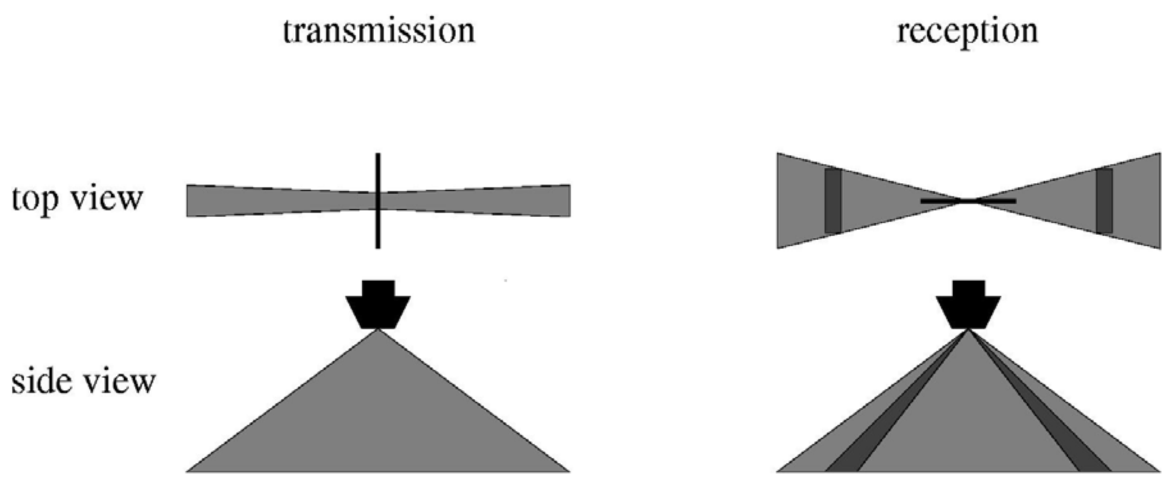


**Figure 22**

Reception:
Across-track discrimination is accomplished by the reception array, which must be wide in the across-track direction, see Figure 22 (right plot). The shapes used for the reception arrays are simple horizontal linear, V-shaped (larger swathe widths possible) or U-shaped, see Figure 23.

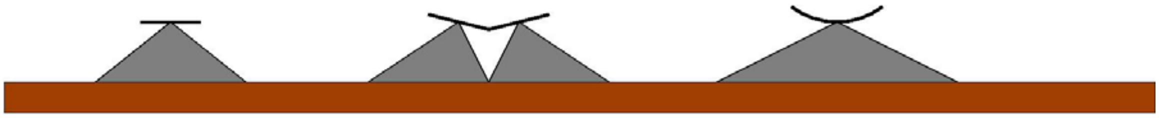

**Figure 23**

When the transmission and reception arrays are physically separated, the transmission array determines the along-track resolution and the reception array the across-track resolution. The final resolution is the product of the two (according to the so-called Mill's cross principle).

### 6.4.3 Reception processing

The reception processing unit performs the following operations:

- level correction as a function of time (TVG) to keep the received signal amplitudes as constant as possible;
- digitisation of the received signals;
- demodulation of the signals down to low frequency and subsequent low-pass filtering;
- beamforming to obtain the reception beams;
- determination of bathymetry (see section 6.4.5);
- correction for platform movements (see section 6.4.4);
- correction of the acoustic paths as a function of the prevailing sound speed profile (SSP), see section 6.4.7.

### 6.4.4 Ancillary systems

A multi-beam echo sounder has to receive and process data from several ancillary systems in order to locate the depth measurements accurately. These systems are:

- the positioning system giving the accurate geographical position of the ship (GPS, preferably in differential mode);
- the attitude sensor unit providing heading, roll, pitch and heave measurements to compensate for
  - orientation of the line of depth measurements relative to the ship's axis (heading);
  - orientation of the beams (roll and pitch);
  - vertical movements of the ship (heave);
- SSP to correct the acoustic paths from sonar to seafloor;
- Sound speed measurement close to the transducers to improve beamforming.

### 6.4.5 Determining bathymetry

The fundamental principle of bathymetry measurement by a multi-beam echo sounder is the joint estimation of time $t$ and angle $\theta$. Each pair ($t$, $\theta$) is used to determine the position of one depth measurement. When the sound speed profile is constant over the entire water column, the acoustic paths from each beam are linear. Then the coordinates ($y$,$z$) of the measurement point, taking the sonar position as the origin, are simply (see Figure 24)

$$y = R\sin\theta = \frac{ct}{2}\sin\theta$$

$$z = R\cos\theta = \frac{ct}{2}\cos\theta$$

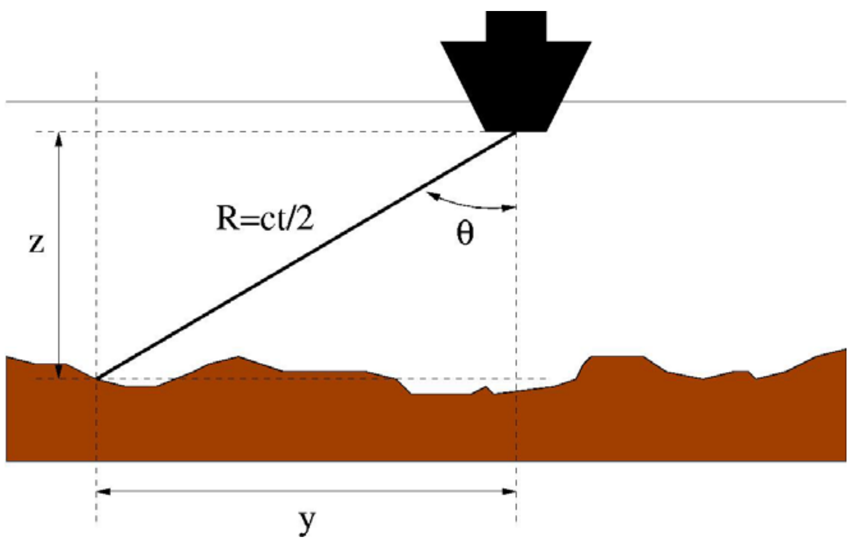


**Figure 24**

In the more realistic and thus more complicated situation where the sound speed profile is a function of depth $z$, the acoustic paths must be reconstructed using geometric ray-tracing software, see section 6.4.7.

The depth measurement is referenced to the position of the sonar. It is therefore mandatory to simultaneously know the position and attitude of the support platform, which enables the performance of angle corrections (roll in particular) and to associate geographical coordinates with the depth measurements, see also previous section 6.4.4.

Several techniques are being used to measure the couples ($t,\theta$). A treatment of these techniques would require a rather technical discussion, which is beyond the scope of these lecture notes. Here, we assume that the ($t,\theta$) - pairs are measured accurately by the sonar system and that they are available for further processing, including correction for platform attitude and sound speed profile.

### 6.4.6 Backscatter imaging

The principle of sonar (backscatter) imaging is the same for multi-beam echo sounders and sidescan sonars. The signal backscattered from the seafloor is recorded as a function of time and its instantaneous intensity represents irregularities of the seafloor strip swept by the signal. There are, however, also differences between backscatter imaging with a multi-beam echo sounder and that with sidescan sonar.
For the construction of a backscatter image from multi-beam data, time signals are indeed available after beamforming. Therefore, they must be recombined so as to provide a continuous image along the swath. Formation of the image is therefore ideally performed after the depth measurements have been processed (including the necessary corrections, see section 6.4.4). The central point of a beam can then be positioned on the swathe and the image pixels are distributed around it, until the boundary of the next beam is reached, see Figure 25.

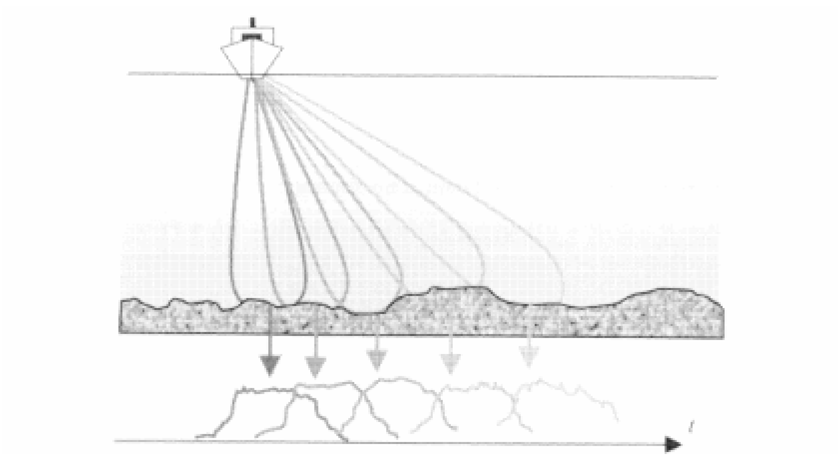

**Figure 25**

The topographic quality of the image thus obtained is much better than that obtained with a sidescan sonar without bathymetric capability. The image pixels are indeed associated with (*x*,*y*) coordinates in the horizontal plane with minimal geometric distortions. Unlike sidescan sonar, measurement of the oblique distance *R* alone is now replaced by a complete estimation of the position of the impact point on the seafloor, including corrections for movements of the support platform and for the sound speed profile.
Despite the improvement in geometrical accuracy of the backscatter image, there are also drawbacks:

- The along track resolution of a multi-beam echo sounder (1-3°) is usually worse than that of a sidescan sonar (less than 1°);
- The range of incidence angles of a multi-beam system, mounted on a surface vessel, is less grazing than for a sidescan sonar, towed close to the seafloor. The useful angular sector of a multi-beam system is often restricted to ±75°, beyond which bathymetric accuracy is very limiting (due to the depth-dependent sound

speed profile). The observed intensity contrasts, e.g. on micro-relief facets of the seafloor, is therefore less satisfactorily.

### 6.4.7 Bathymetric measurement errors

The estimation of the coordinates ($y,z$) of the depth measurement is affected by measurement inaccuracies in both range $R$ (or time $t$) and angle $\theta$. These inaccuracies are denoted $\delta R$ and $\delta\theta$, respectively. Measurement errors can be of two types:

- a systematic error, possibly stable and predictable, which can be corrected for during post-processing (e.g. an angle bias due to misalignment of the transducer during installation or the effect of sound refraction due to a depth-dependent sound speed profile);
- a random fluctuation, related to noise, movements of the support platform or to the fluctuating backscatter character of the seafloor itself.

In iso-velocity water, the sounding estimation errors due to an inaccuracy $\delta R$ of the range measurement, are given by

$$\delta z_R = \delta R \cos\theta$$
$$\delta y_R = \delta R \sin\theta$$

For an angle measurement error $\delta\theta$, we have

$$\delta z_\theta = R \sin\theta \; \delta\theta = H \tan\theta \; \delta\theta$$
$$\delta y_\theta = R \cos\theta \; \delta\theta = H\delta\theta$$

The main error term to consider is often the depth angular error $\delta z_\theta$ at shallow grazing angles, i.e. at large value of $\tan\theta$, see section 6.4.10 for a numerical example.
The prediction of the bathymetric measurement accuracy is an important research topic. Three main types of error, that effect the bathymetric measurements, can be distinguished:

- errors in the acoustic measurement itself (due to acoustic noise and the non-stable backscattered signal);
- movements of the support platform (due to the finite accuracy of the attitude sensors);
- inaccuracies in sound speed corrections.

The total estimation error can be modelled as the quadratic sum of these three components, thereby assuming independence.

The depth-dependent sound speed profile in the water column modifies the acoustic path due to refraction and thus affects the position of the depth measurements. A multi-beam

echo sounder system can account for this effect by calculating the acoustic ray paths using locally measured sound speed profiles or using profiles extracted from geographical/seasonal databases. This correction goes as follows:
For a given beam a sound ray is launched according to the beam angle, and followed as a function of time in the water column. This computation is stopped when the computed time equals the measured time for that beam depth measurement. The sound ray's position at this time defines the sounding point position, see Figure 26.

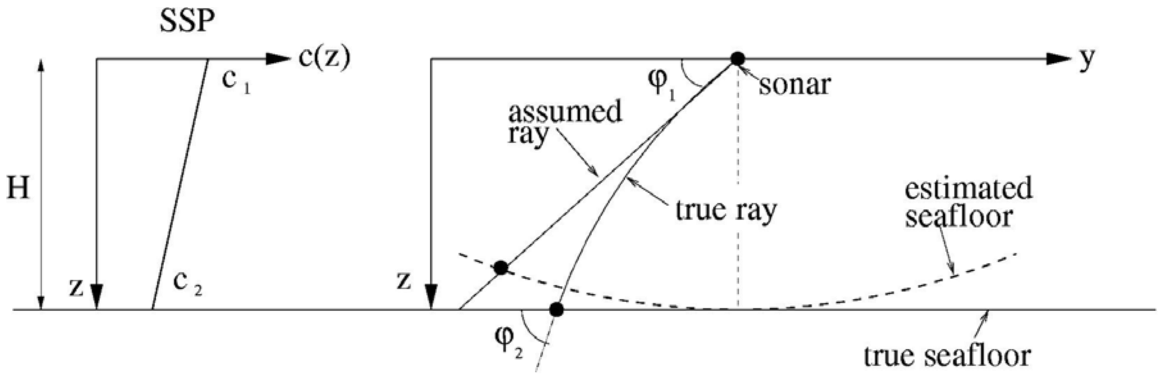


**Figure 26**

Let us illustrate this for a linear sound profile, both downward refracting and upward refracting. Then the sound speed profile is given as

$$c(z) = c_1 + g\ z$$

with $g$ the sound speed gradient, being either negative or positive. At $z = H$, the sound speed is $c(H) = c_2$. The sound ray launched at z = 0 (the sonar depth) and at an angle $\varphi_1$ with the horizontal undergoes circular refraction with radius of curvature $-c_1 / g \cos\varphi_1$, see chapter 3 (here, $\varphi = \pi / 2 - \theta$).
At a certain depth $z$, the angle with the horizontal is $\varphi$. The travel time of the ray from $z$ = 0 to depth $z$ is given as

$$t = \int \frac{ds}{c(z)}$$

with $ds = \sqrt{dy^2 + dz^2}$. As $dz = \tan\varphi\ dy$, we have $ds = dz / \sin\varphi$.

Further, from Snell's law

$$\frac{\cos\varphi_1}{c_1} = \frac{\cos\varphi(z)}{c(z)} = \frac{\cos\varphi(z)}{c_1 + gz}$$

we can derive

$$dz = \frac{c_1}{g}\frac{\sin\varphi}{\cos\varphi_1}d\varphi$$

Hence, the travel time up to depth $z = H$ becomes

$$t = \int_{\varphi_1}^{\varphi_2}\frac{1}{c_1}\frac{\cos\varphi_1}{\cos\varphi}\frac{1}{\sin\varphi}\frac{c_1}{g}\frac{\sin\varphi}{\cos\varphi_1}d\varphi = \frac{1}{g}\int_{\varphi_1}^{\varphi_2}\frac{1}{\cos\varphi}d\varphi = \frac{1}{g}\ln\frac{\tan\left(\frac{\pi/2-\varphi_2}{2}\right)}{\tan\left(\frac{\pi/2-\varphi_1}{2}\right)}$$

With this formula we can simulate the effect of refraction on the measured depth profile. We consider a perfectly flat and horizontal seafloor. For each beam, i.e. for $\varphi_1$ ranging from 90° (vertical beam) to say 15°, we calculate the travel time *t* to the seafloor (using the formula above). Assuming the system 'thinks' that there is no refraction, the sounding point position would be taken as

$$y = c_1 t\cos\varphi_1$$
$$z = c_1 t\sin\varphi_1$$

Figure 27 illustrates the effects for *H* = 150 m and $g = \pm 0.1\,\text{sec}^{-1}$. Note that the depth error for the outer beams is as large as 10 m.

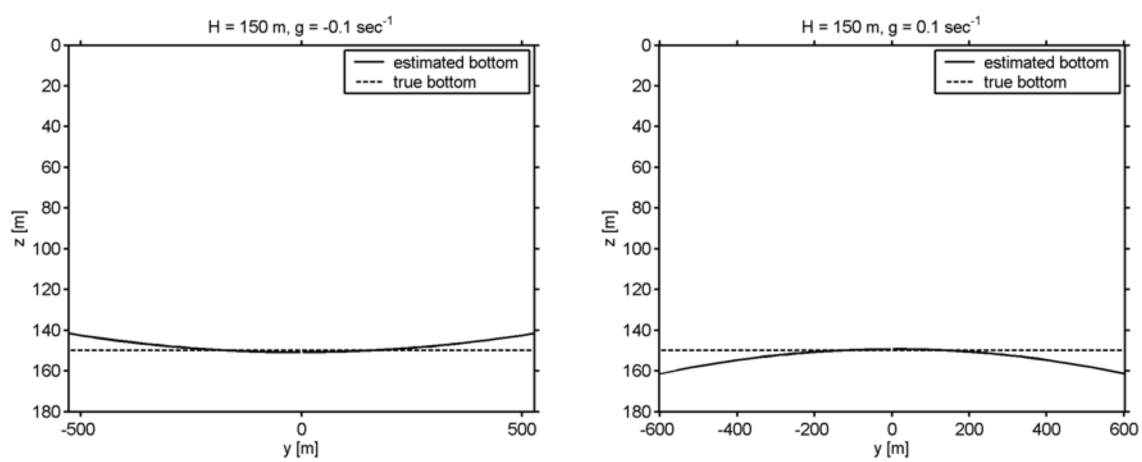


**Figure 27**

It is clear that errors in the average sound speed profile can yield appreciable depth measurement biases. In other words, systematic depth errors can occur if the average sound speed profile is not exactly known at the time of the depth measurements. In principle, one can however compensate for these deterministic effects. This requires the continuous availability of the prevailing (average) sound speed profile. The unavoidable random fluctuations around the average sound speed profile have negligible effect on the refraction of the acoustic rays, as the changes in direction around the mean path cancel each other out.

### 6.4.8 Resolution

The resolution formulas for a sidescan sonar are also applicable to a multi-beam echo sounder system. For the latter, however, we have to make a distinction between bathymetry and backscatter imaging.
The along-track resolution for bathymetry and imaging is given as

$$\delta x = R\theta_L$$

with $\theta_L$ the horizontal beam width or longitudinal aperture of the transducer.
The across-track resolution for backscatter imaging is the resolution of the time signal, i.e.,

$$\delta y = \frac{cT}{2\sin\theta}$$

At the vertical ($\theta \to 0°$) the across-track resolution for imaging becomes

$$\delta y = \sqrt{HcT}$$

The across-track resolution for bathymetry depends on the number of points averaged in the processing that give each depth measurement. It is at best equal to the resolution of the time signal (i.e. the signal footprint), given by the previous two equations for imaging. The resolution is at worst equal to the beam width $\theta_T$ (the transversal beam aperture) projected on the seafloor:

$$\delta y = \frac{H\theta_T}{\cos^2\theta}$$

In practice $\delta y$ will be in between a value according to this equation and a value equal to the signal footprint, depending on the processing details.

### 6.4.9 Repetition period and coverage

The 100%-coverage condition on the maximum velocity of the support platform is the same as that derived for the sidescan sonar, because the geometrical configuration is basically the same. Hence,

$$v \le \frac{c\theta_L}{2}\cos\theta_{\max}$$

Here we have assumed that the optimal ping repetition frequency consists in transmitting a signal as soon as the previous signal has been received, i.e., after a time corresponding to the propagation of the outer beam ($\theta = \theta_{\max}$).

Now, let us consider the global mapping of the deep oceans ($H$ = 4 km) and make an estimate of the time required to accomplish this task. Let's take $\theta_{\max}$ = 75° and $\theta_L$ = 1.5° for a typical deep water multi-beam echo sounder. Then the maximum speed $v$ with 100 % coverage is 5 m/s or 10 knots. The swathe of the system is $L = 2H\tan\theta_{\max} = 30$ km. The area covered per second is thus $vL = 0.15\ \text{km}^2/\text{sec}$, corresponding to 13000 $\text{km}^2$ per day. The surface of the Earth's deep ocean is around $350\text{x}10^6\ \text{km}^2$ and the time required to map all deep oceans is thus $2.7\text{x}10^4$ days = 74 years. This may sound high, but with more than 50 deep water multi-beam systems in service (situation in 2002), the global mapping task would be achievable in a year.

### 6.4.10 A note on the maximum reachable range

As discussed for the single-beam echo sounder in section 6.2.7, the maximum reachable range of a multi-beam echo sounder can be defined as the detection limit of the backscattered signal, as determined by the signal-to-noise ratio. However, specific data quality criteria can be imposed on the multi-beam system. Let us illustrate this with a simple example. Suppose that the main criterion is the hydrographic accuracy standard, which requires a depth accuracy of 0.5 % of the water depth $H$. Further, assume that the main measurement error is due to roll:

$$\delta z_{\text{roll}} = H\tan\theta\,\delta\theta_{\text{roll}}$$

Assume a roll measurement accuracy of $\delta\theta_{\text{roll}} = 0.1°$. This corresponds to a limit of 70.8° for $\theta$, which is independent of the possibility of signal detection beyond this angle. For a given water depth $H$, the corresponding maximum reachable range can be calculated according to $R_{\max} = H/\cos\theta_{\max}$.

### 6.4.11 Example

An example of bathymetry data acquired with multi-beam echo sounders is given in Figure 28.

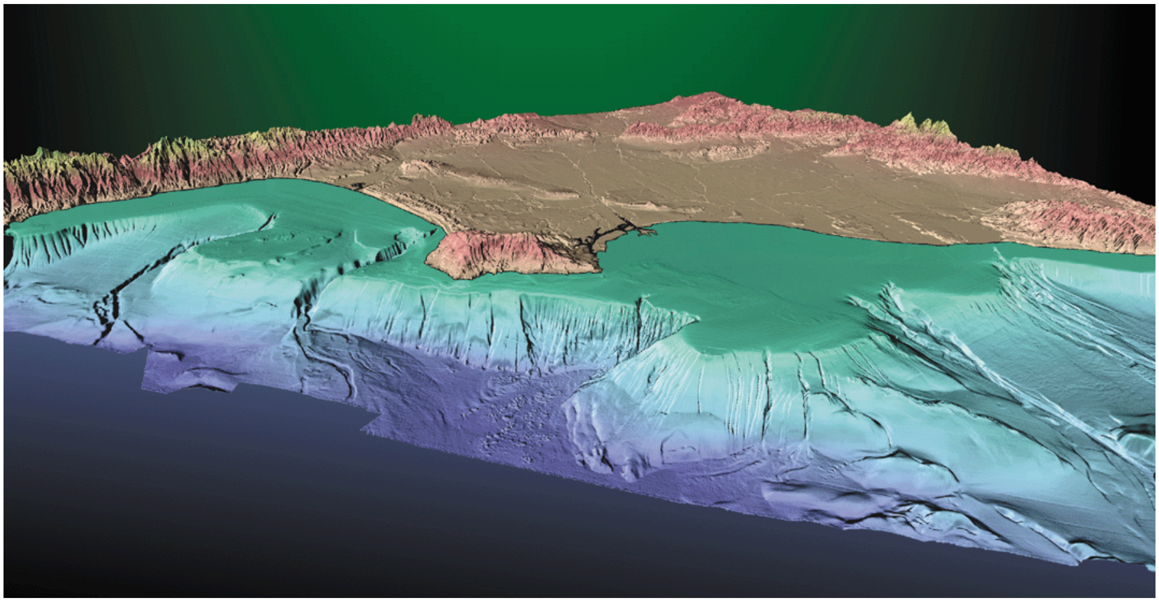

**Figure 28**