11 Sounding methods

11.1 Echo sounder operation

In bathymetry, the object to be positioned is frequently the seabed. Usually, the horizontal position of a surface vessel is obtained first, and then the distance between the vessel and the seabed, i.e., the depth, is determined. In modern hydrographic surveying, depth is determined from *observation of travel time* of acoustic waves. An acoustic pulse transmitted by a transducer travels through the column of water and is then reflected by the target (sea floor) back to the hydrophone. Depth is calculated from the measured travel time ΔT

$$\text{Depth} = c \cdot \frac{\Delta T}{2} \tag{11.1}$$

where c is the speed of sound in water.

A basic echo sounder, used to measure the pulse's two-way travel time through the water column, consists of the following components, as shown in Figure 11.1:

- A *transmitter* which generates pulses.

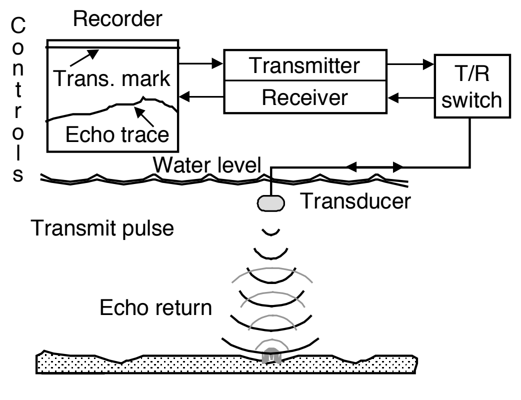


Figure 11.1: Basic echo sounder operation.

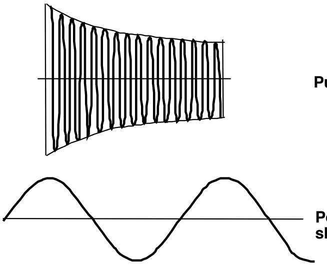


Figure 11.2: Acoustic pulse shape and envelope.

- A *T/R* (*transmitter/receiver*) *switch* which passes the power to the transducer.
- A *transducer*, mounted on the ship's hull, which converts the electrical power into acoustic power, sends the acoustic signal into the water, receives the echo, and converts it into an electrical signal.
- A *receiver* which amplifies the echo signal and sends it to the recording system.
- A *recorder* which controls the signal emission, measures the travel time of the acoustic signal, stores the data, and converts time intervals into ranges.

The *transmitter* is equipped with a quartz clock that oscillates in the range of 1-10 MHz, whose frequency is divided down to obtain the operating frequency of the transducer. The quartz clock is also used to measure time intervals between the transmission and the reception of acoustic signals. Modern echo sounders usually offer a choice of two to three transmitting frequencies, namely:

- *Low frequency* - effective for deep water because the attenuation is lower, but it requires a large transducer.
- *High frequency* - the transducer can be compact but the range is more limited due to a higher attenuation

The *T/R switch* is used to trigger a pulse with a specific length. Normally the pulse length varies from 0.1 to 50 ms. In shallow water, a single short pulse of length of 0.2 ms is transmitted and received before the next pulse is transmitted. In deep water, many pulses of lengths varying from 1 ms to 40 ms are generated and are in the water at any time. The variety of pulse length helps to overcome losses due to attenuation. The pulse shape and its envelope are shown in Figure 11.2.

The *receiver* amplifies the returning echo signal and sends it to the recording system. The receiver is equipped with a time varying gain (TVG), which is used to reduce the gain of the receiver immediately after transmission in order to filter out reverberation. Receiver gain returns as an exponential function of time. The receiver bandwidth must be wide enough to accommodate a Doppler shift if the transducer is not vertical (e.g., case of a speed log).

The *transducer* is mounted on the ship's hull and is in contact with water. Its functions are

- To convert electrical power into acoustic power.
- To send the acoustic signal into the water.
- To receive the echo of the acoustic signal.

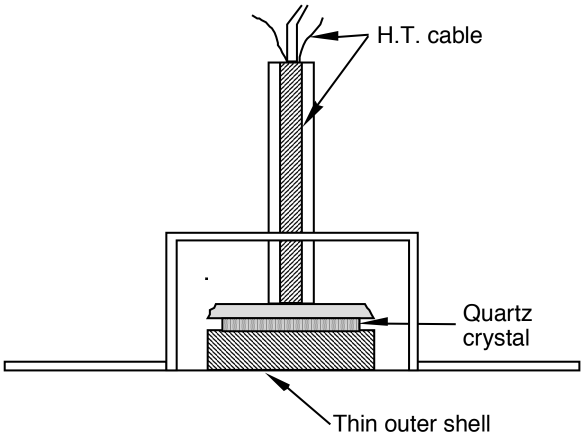


Figure 11.3: Piezoelectric transducer.

- To convert the acoustic signal into an electrical signal.

The electrical pulse from the transmitter causes the diaphragm of the transducer to vibrate. The vibrating diaphragm, in contact with water, generates an acoustic wave. The opposite process occurs when receiving signals, i.e., the vibrating diaphragm generates an electric current which is sent to the receiver. Transducers can be based on different principles. Three types of transducers are briefly presented.

A transducer of *magnetostrictive material* uses the property that the magnetostrictive material (e.g., nickel) changes its length in the presence of a magnetic field. A particular beam shape of the acoustic signal is obtained by configuring an array of elements according to specific patterns.

A *piezoelectric* transducer, see Figure 11.3, uses the property that certain crystals (e.g., ammonium dihydrogen phosphate) change length when a potential difference is applied to electrodes on the opposite faces of the crystal.

An *electrostrictive* transducer, shown in Figure 11.4, uses the property that ceramics change length when placed in an electric field. Ceramics can be molded in any desired shape. Elements are mounted between the face and the tail of a piston to obtain the desired beam width.

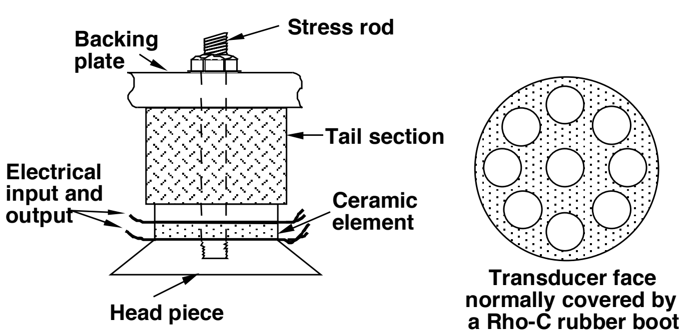


Figure 11.4: Electrostrictive transducer.

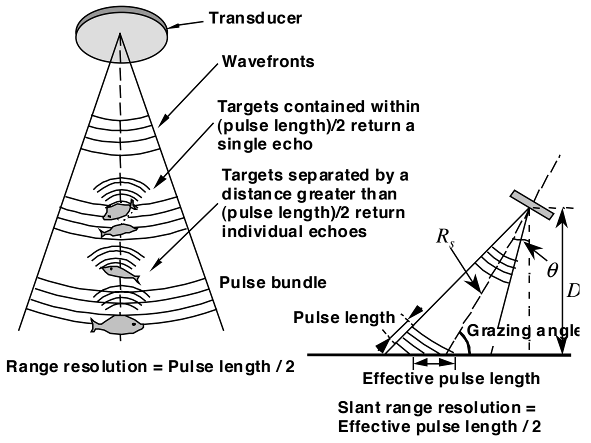


Figure 11.5: Resolution and incidence angle.

The resolution of an echosounder can define either its measuring precision or detection capabilities. It is a function of the following factors

- Pulse duration.
- Angle of incidence of the acoustic wave front on the target.
- Nature of the target.
- Beamwidth of the transmission.

The minimum distinguishability of an echosounder corresponds to 1/2 pulse length. If two objects less than half a pulse length apart are sensed by an acoustic wave, they will reflect as a single target. Two objects further apart from each other than half a pulse length will be recorded as two separate echoes. The concept is shown in Figure 11.5. For example, consider a pulse with a frequency f of 15 kHz and a duration of 1 ms. Given that the sound velocity c in sea water is approximately 1500 m/s, the wavelength $\lambda = c/f$ is 0.1 m, and the pulse length is 1.5 m. The resolution corresponding to 1/2 pulse length is then 0.75 m.

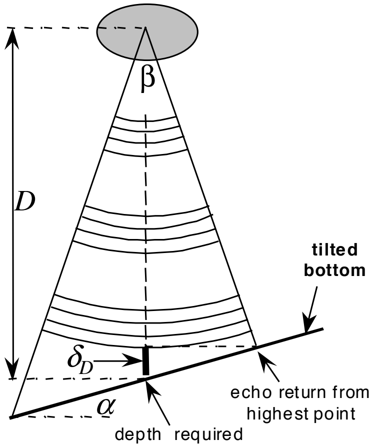


Figure 11.6: Effect of beamwidth due to tilted bottom.

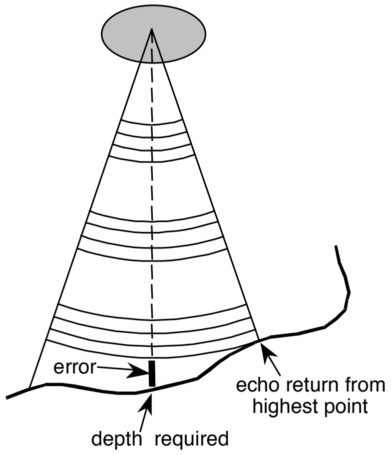


Figure 11.7: Effect of beamwidth due to irregular bottom.

A target will return more power to the transducer from those parts of it at right angle to the ray paths than from parts that will reflect the power away from the transducer. If the echosounder may be tilted by angle θ due to ship roll, the effects of this tilt are:

a. The resolution of the slant range R_s decreases because the effective pulse length L_{pe} increases.
b. The effect of the tilt angle θ on depth D (flat bottom case) is $D = R_s \cos\theta$ and the depth bias is $R_s(1-\cos\theta)$ if θ is not accounted for. The bias can be removed if θ is known. The effect of an error δR_s in the slant range R_s on D is $\delta D = \delta R_s \cos\theta$.

On the other hand, if the bottom is tilted by an angle α, the effect on D is $\delta D = (D - \delta D)\tan\alpha \tan\beta/2$, see Figure 11.6, which is approximately equal to $D\tan\alpha\tan\beta/2$. For example, for $\alpha = 10\partial$, $\beta = 20\partial$ and $D = 100\,\text{m}$, $\delta D \approx 3.1\,\text{m}$.

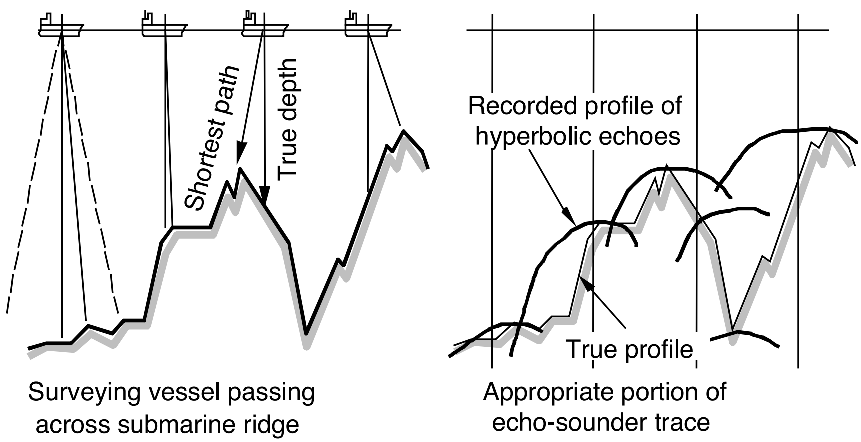


Figure 11.8: Echosounder beamwidth effect.

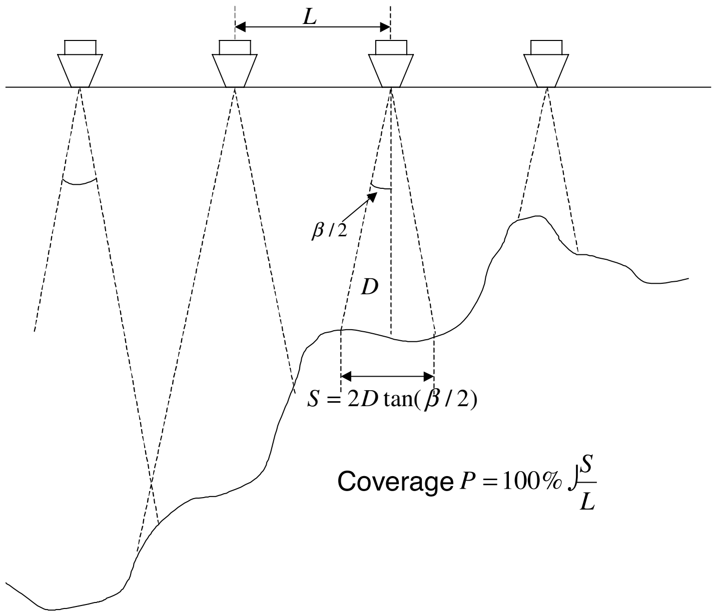


Figure 11.9: Seabed coverage versus beamwidth.

The echosounder has a specified beamwidth. It records the earliest return from its transmission, i.e., the echo having travelled the shortest distance. The effect depends on the actual beamwidth, the water depth and the tilt angle of the seabed, as shown in Figure 11.7. The recorded profile will be distorted and of an hyperbolic shape, as shown in Figure 11.8. The effect of the beamwidth also affects the seabed coverage, as illustrated in Figure 11.9.

11.2 Transducer beam pattern

It is effective to have the echo pulse directed to the target desired in order to increase power and establish the correct range to the target. The pattern of the beam for a transducer should ensure its directional response, i.e., a response as a function of the direction of the transmitted (or incident) sound wave in a specified plane at a specified frequency. Pattern control is important to

- Concentrate energy in a specified direction.
- Reduce noise and interference on receiving transducer.

A single point source radiates energy omni-directionally. In the case of transducers used for hydrography, energy is normally concentrated along the axis that is perpendicular to the radiating surface.

Transducers used in hydrography are designed to produce beams of acoustic power of various shapes. The shape of the beam is determined by the size and shape of the transducer, typically measured in wavelengths at the resonant/transmitting frequency.

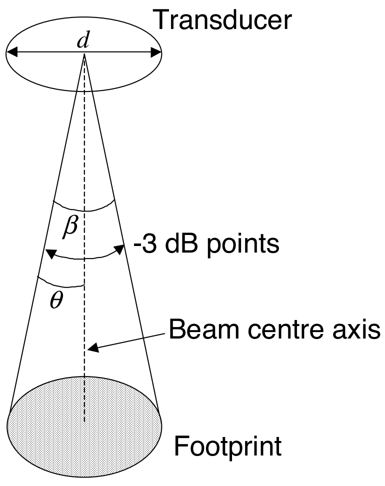


Figure 11.10: Transponder beamwidth for a circular transducer.

The beam pattern of *circular* transducers is of the shape of a cone whose vertex angle varies between 2° and 30°. Most of the energy of the beam is concentrated in the main lobe, whose limits are defined as -3 dB points. The angle θ between points at which the acoustic energy intensity has fallen to half (-3 dB point) of that along the main axis is called the *beam angle*, as shown in Figure 11.10. In other words, the intensity of the acoustic energy at the angular limit of the beam, P_2, is defined as half of the intensity P_1 at the centre of the beam

$$P_2 = \frac{1}{2} P_1 \Leftrightarrow 10 \log \frac{P_2}{P_1} = 10 \log 0.5 = -3 \text{ dB}$$

The *beamwidth* or *total beam angle* is 2θ or β. For a circular transducer, the beamwidth (in degrees) is roughly given as

$$\beta = 65 \frac{\lambda}{d} \tag{11.2}$$

where λ is the wavelength corresponding to the frequency of the transmitted signal and d the diameter of the radiating surface of the circular transducer. Both λ and d must be expressed in the same units. An important characteristic of an echosounder is the frequency of the transmission. The higher the frequency the shorter is the wavelength, and the narrower the beamwidth for a given transducer size, as shown in Figure 11.11 for the case of a circular transducer.

A *rectangular* transducer will produce a different beamwidth in each of its two principal axes. Consider a rectangular transducer of dimension L_1 (shorter dimension) by L_2 (longer dimension). The beam footprint will be narrow in the direction parallel

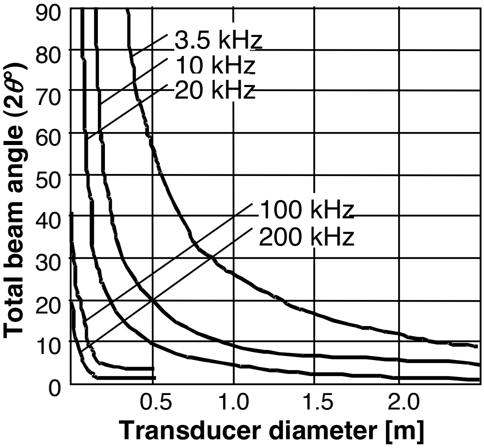


Figure 11.11: Beamwidth versus diameter for a circular transducer.

to the long direction of the transducer. By contrast, the footprint will be wide in the direction orthogonal to the long direction of the transducer (i.e., parallel to the short dimension of the transducer), as shown in Figure 11.12. The wide beamwidth β_1 and the narrow beamwidth β_2 of a rectangular transducer, both expressed in degrees, are given respectively by

$$\begin{aligned} \beta_1 &= 2\theta_1 = 50\frac{\lambda}{L_1} \\ \beta_2 &= 2\theta_2 = 50\frac{\lambda}{L_2} \end{aligned} \tag{11.3}$$

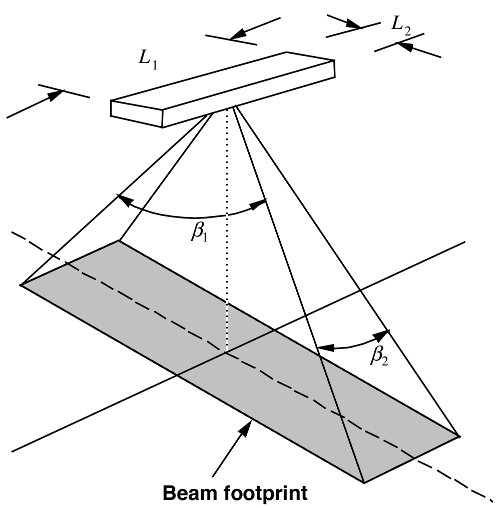


Figure 11.12: Beam shaping characteristics of a rectangular transducer.

11.3 Single beam echosounders

The beamwidth of conventional *single beam echosounders* (SBES) is usually of the order of 30°. However, narrow beam echo sounders with beamwidth of $\beta = 2\theta \leq 5\partial$ have also been available since the mid 1980's. Operation of a narrow beam echosounder requires the transducer to be mechanically or electronically stabilized for roll and pitch motion of the vessel. Narrow beam echosounders are used to:

- Obtain depths directly under the vessel, thus avoiding wide beam biases caused by underwater slopes. This depth is used either for safety of navigation or for sea floor mapping.
- Improve the quality of the data in terms of both resolution and accuracy. For instance, in order to meet the IHO Special and Order 1 requirements, see Section 8.3, a narrow beam or array of narrow beam echosounders can be used.

To produce a narrow beam, larger size transducers are needed than for a wide beam. The equipment becomes bulky and expensive. Narrow beam echosounders do not provide information off the sides of the ship. Sometimes they are used in conjunction with broad beam systems as a complementary source of data.

Two examples of typical circular transducers of narrow beam echosounders:

1) Frequency of 12 KHz, wavelength $\lambda = 0.125\,\text{m}$, beamwidth $\beta = 2\theta = 2\partial$. Diameter $d = 65\lambda / \beta = 4.06\,\text{m}$ (note that β is entered in degrees).
2) Frequency of 120 kHz, wavelength $\lambda = 0.0125\,\text{m}$, beamwidth $\beta = 2\theta = 2\partial$. Diameter $d = 0.41\,\text{m}$.

11.4 Multibeam echosounders

Multibeam echosounder (MBES) systems are used to increase bottom coverage and consequently, productivity. Each of the narrow beams produced yields a resolution of the bottom equivalent to that of a narrow single beam echosounder. The measurement accuracy is not better than that of single beam echosounders, however. In fact, accuracy decreases as the swath angle increases. MBES are divided into two groups, namely *swath* systems and *sweep* systems

A swath system produces multiple acoustic beams from a single transducer system (although dual transducer systems are used and, sometimes, the transmitter and receiver are separate). A sweep system simply consists of an array of single beam echosounders mounted on booms deployed on each side and perpendicular to the surface vessel. Most of this section will deal with swath systems, with an introduction to sweep systems at the end. The operation principle of the latter is much more straightforward than that of the former.

The development of deep water swath systems began in the 1970's. These systems, which permit effective and accurate bathymetric surveys of extensive areas, can also be used for other oceanographic applications such as geological mapping and other scientific investigations, EEZ surveys and surveying for cable laying. Shallow water swath MBES have evolved rapidly during the 1990's and they are being increasingly

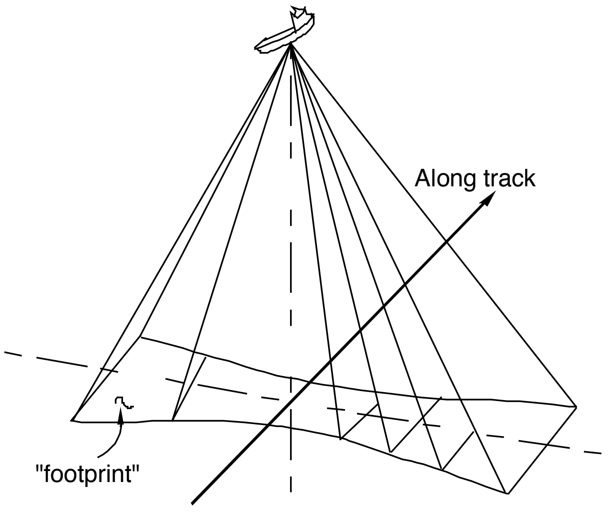


Figure 11.13: MBES footprints.

used for shallow water surveys, such as harbour and constricted waterway surveys where 100% coverage and a high accuracy are required. Adoption of the more stringent 1998 IHO Standards for hydrographic surveys is further accelerating the use of MBES systems for shallow water applications.

Certain swath systems have such a wide swath width that they can also be used simultaneously as sidescan sonars (see next section for principles). Swath MBES can be used in a surface vessel where it is mounted under the hull or beside the vessel, or in an under water vehicle such as a remotely operated vehicle (ROV).

A swath MBES transmits an acoustic pulse in a wide fan in one direction (fore-and-aft or athwartships). This results in a wide footprint in that direction. The back scattered signal is received by a transducer which segments the above wide footprint into multiple smaller beams, as shown in Figure 11.13. The width of these beams is of the order of one to a few degrees, depending on the system. In this manner a high number of depth soundings are generated for each pulse transmission. A lane of soundings is obtained from a single vessel's track, rather than a single line of soundings. The advantages over the use of a single beam echosounder are obvious, the major one being that 100% coverage of the bottom can be achieved in a relatively cost effective manner. This is important for harbour and constricted waterway applications.

The advantage of a MBES, as compared to a sweep system (multi-single beam) approach, is that similar or wider coverage is achieved even in shallow waters using a much more compact system. In deeper waters, the coverage is much wider and can be several times the water depth, depending on the MBES system specifications.

For each receive beam, there is a ΔT two-way travel time of the slant range measurement and a swath angle ψ measurement as shown in Figure 11.14. In the

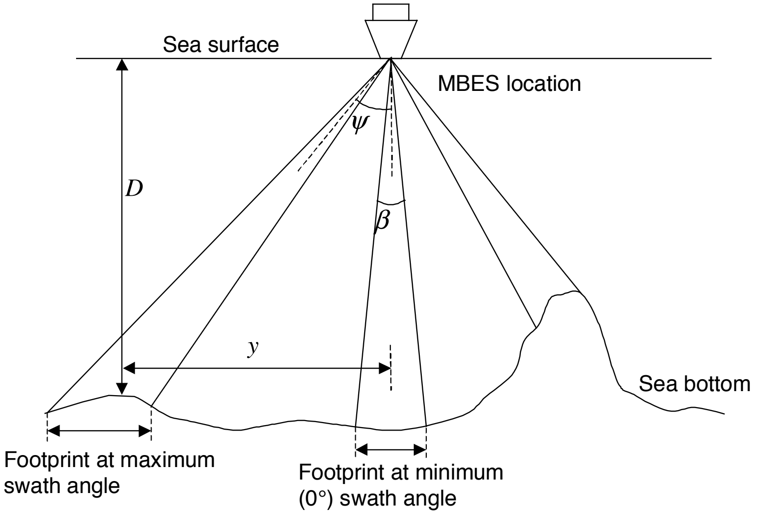


Figure 11.14: MBES footprint size versus swath angle ψ.

absence of errors and vessel's motion, these measurements can be converted into depth (D) and across-track positions (y) of the sounding as

$$\begin{aligned} D &= \frac{1}{2} c\Delta T \cos\psi \\ y &= \frac{1}{2} c\Delta T \sin\psi \end{aligned} \tag{11.4}$$

where c is the acoustic wave propagation in the medium. D and y can also be compensated for the effects of vessel pitching, yawing and rolling by using motion sensors of sufficient accuracy. Acoustic refraction can be compensated for by measuring the sound velocity profile in water, and by modelling the raypath of each beam in the model. The survey line spacing is selected such that neighbouring swaths are overlapping in order to avoid gaps. The ship's speed can also be selected such that there is 100% measurement overlap in order to enhance reliability.

An MBES can be mounted on a vessel permanently or temporarily. Deep water transducers are large (up to 5 m arrays) and mounting is more permanent. The ship's size has to be sufficiently large to support such transducers. Shallow water systems are much smaller (several dm) and can be mounted on survey launches. For portable use, a rig, which can be attached to the bow of a launch, can be used to mount the echosounder and motion sensor. Once the rig is calibrated, it can be moved from one vessel to another without the need for re-calibration.

The footprint of an MBES varies with swath angle. Let the beam width be β, as shown in Figure 11.14. For a vertical sounding, in which case the swath angle ψ is 0°, the footprint r, in the y-axis perpendicular to the ship is

$$r = 2D\tan(\beta/2)$$

For a swath angle $\psi \Sigma 0$, the footprint is approximately equal to

$$r \approx D\{\tan(\psi + \beta/2) - \tan(\psi - \beta/2)\}$$

As an example, let us consider the case of a deep water swath MBES system with a beamwidth of 2°×2°. The footprint at depth *D* of 500 m is therefore approximately 17 m. The system has a maximum swath angle of 140° (70° each side of the vertical axis). The maximum footprint for a depth of 500 m is therefore about 136 m. The footprint size increases with increasing depth.
In addition, the measured depth error of a footprint with a large swath angle is also larger than that with a small swath angle due to the effect of roll motion and acoustic refraction errors. In order to limit the footprint size and measured depth errors, many systems automatically reduce the swath angle as the depth increases.
The vessel's roll, pitch and yaw attitude motion parameters and heave (vessel's vertical motion) are required in real-time by the swath MBES. The accuracy requirements are function of the system's performance. For high performance systems, the roll and pitch parameters are usually required with an accuracy of 0.05° or 3 arcmins, while the heave is required with an accuracy of 5-10 cm. A three or four-antenna GPS system can deliver the roll and pitch components with the accuracy required. Difficulties can however arise with the rigidity of the multi-antenna GPS system with respect to the MBES transducer located in the water under or beside the vessel. As a consequence, the preferred solution is to use a motion sensor that contains an inertial measuring unit (IMU) and that can be located near the transducer. A mid-range IMU integrated with a DGPS system (which is nearly always used for positioning) can meet both the attitude and heave requirements. Heave compensators, which are essentially one-axis inertial accelerometers, can also be used to measure

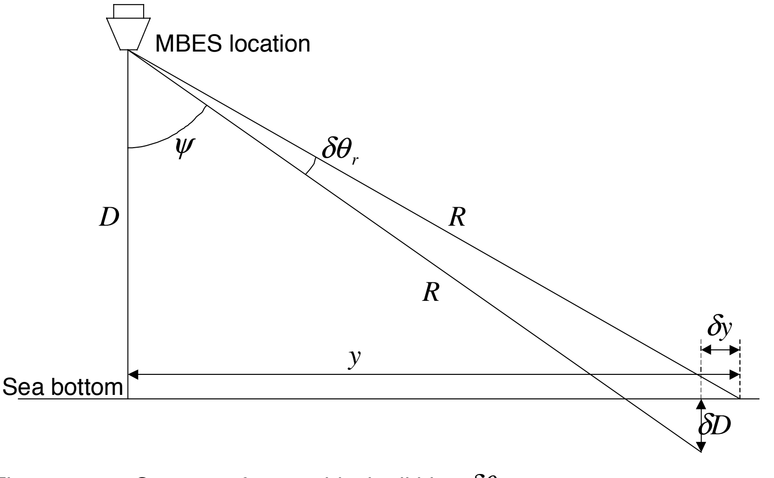


Figure 11.15: Geometry for a residual roll bias $\delta\theta_r$.

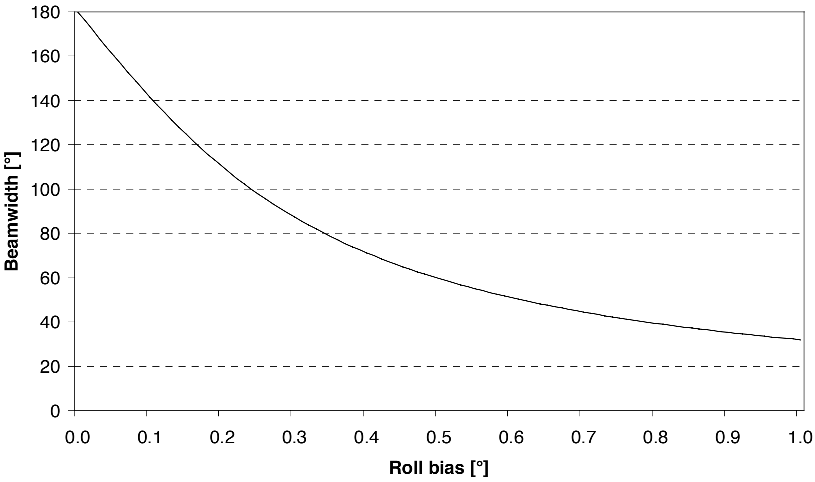


Figure 11.16: Beamwidth and residual roll bias, where the requirement is fulfilled that the resulting depth error is 0.5% of the depth or less.

heave.

The effect of a residual roll bias $\delta\theta_r$ is shown in Figure 11.15. While the swath angle is assumed to be ψ, in reality it is $\psi + \delta\theta_r$. Together with the observed slant distance $R = c \int dT / 2$, we may write

$$\begin{aligned} R &= \frac{D + \delta D}{\cos\psi} = \frac{D}{\cos(\psi + \delta\theta_r)} \\ R &= \frac{y - \delta y}{\sin\psi} = \frac{y}{\sin(\psi + \delta\theta_r)} \end{aligned} \tag{11.5}$$

where δD and δy are the depth error and the error in the error in the y-coordinate, respectively, due to the roll bias $\delta\theta_r$. For small $\delta\theta_r$ and neglecting second order terms, it follows from (11.5) that

$$\begin{aligned} \delta D &\approx D\delta\theta_r \tan\psi \\ \delta y &\approx -D\delta\theta_r \end{aligned} \tag{11.6}$$

Shown in Figure 11.16 is the maximum beamwidth as a function of residual roll bias, corresponding to the requirement that the depth error δD should be less than 0.5% of the depth D.

For a residual pitch bias $\delta\theta_p$ the situation is sketched in Figure 11.17. Its effect follows from

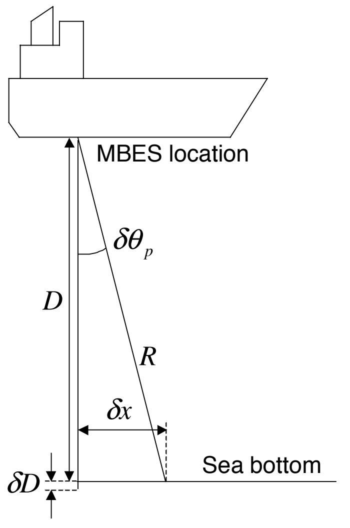


Figure 11.17: Geometry for a residual pitch bias $\delta\theta_p$.

$$
\begin{aligned}
R &= \frac{D+\delta D}{\cos 0} = \frac{D}{\cos\delta\theta_p} \\
\frac{\delta x}{D} &= \tan\delta\theta_p
\end{aligned}
\tag{11.7}
$$

where δx is the error in the direction perpendicular to the transmit beam. For small pitch biases, it follows from (11.7) that

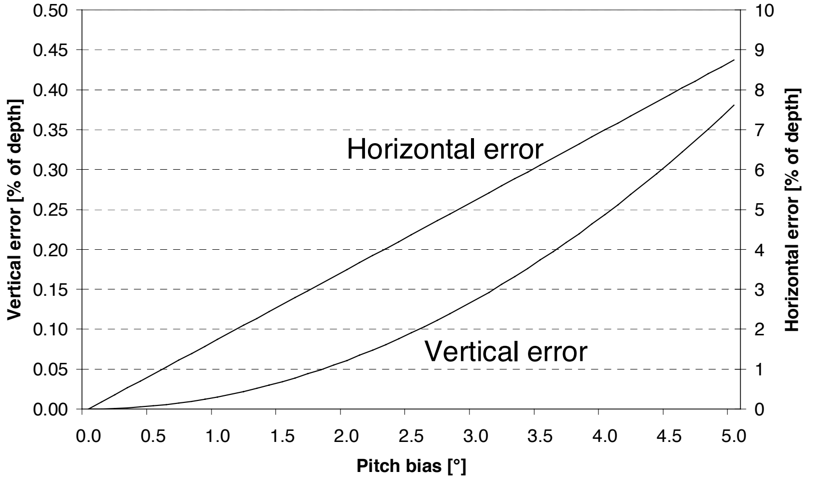


Figure 11.18: Horizontal and vertical positioning errors as a function of residual pitch bias $\delta\theta_p$.

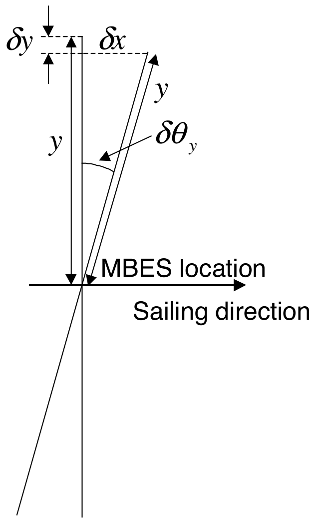


Figure 11.19: Geometry for a residual yaw bias $\delta\theta_y$.

$$\begin{aligned}\delta D &\approx \tfrac{1}{2} D\delta\theta_p^2 \\ \delta x &\approx D\delta\theta_p\end{aligned} \tag{11.8}$$

Shown in Figure 11.18 are the errors δD and δx as function of the residual pitch bias $\delta\theta_p$.
A residual yaw error $\delta\theta_y$, finally, results in an error in the *x*- and *y*-direction, as shown in Figure 11.19

$$\begin{aligned}\delta x &\approx y\delta\theta_y \\ \delta y &\approx \tfrac{1}{2} D\delta\theta_y^2\end{aligned} \tag{11.9}$$

These are the effects of residual angular ship motions. The total list of MBES errors and error sources is much longer. The most important are:
- System measurement errors, due to the system's electronics.
- Depth measurement error due to beamwidth (same as for single beam echosounders).
- Effect of beam angle error, due to the system's electronics; the effect of this error increases with the swath angle ψ. This error is therefore more significant than for single beam systems.
- Acoustic propagation errors: these errors increase with the swath angle due to the ray bending effect and are similar in concept to RF propagation in the atmosphere.
- Effect of attitude errors (roll, pitch and yaw); these errors increase with swath angle.
- Beam steering error due to surface sound speed error.

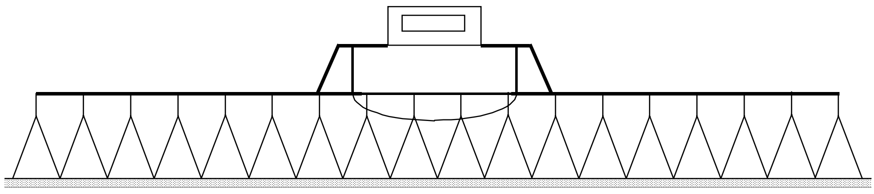


Figure 11.20: Vertical sweep system.

- Transducer misalignment error.
- Heave, dynamic draught and water level errors; same as for single beam echosounders.
- System calibration errors.
- Tides and/or other water level effects.

A vertical acoustic sweep system consists of a linear array of evenly spaced transducers mounted on booms attached perpendicularly to the vessel, as shown in Figure 11.20. These systems are used in critical shallow, calm water areas (harbours, channels, etc.) for 100% coverage. The coverage of the bottom is 100%, depending on transducer spacing and water depth. These systems are very accurate for IHO Special Order and Order 1 surveys where 100% coverage and high accuracy and resolution are required. The mobilization-demobilization logistics are complex due to the deployment of the booms and the use of these systems is usually limited to harbours and constricted waterways. In Canada, vertical acoustic sweep systems are used by the Canadian Coastguard (CCG) in the St. Lawrence navigation channel and the Canadian Hydrographic Service (CHS) for shallow waters in general.

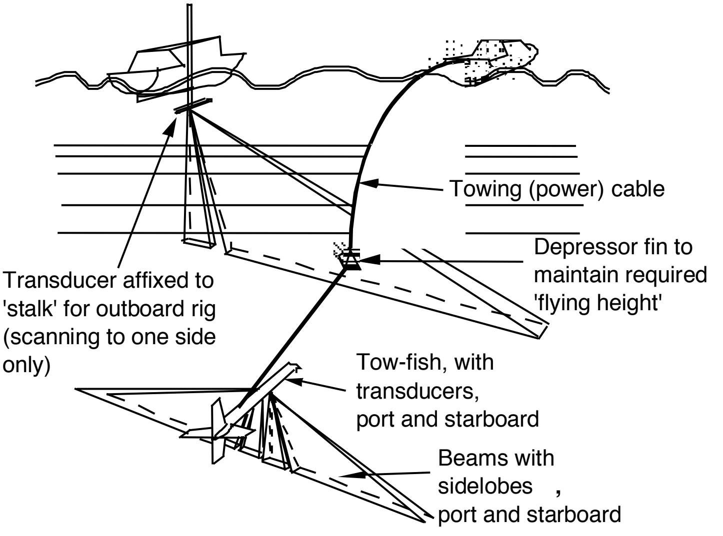


Figure 11.21: Sidescan sonar concept.

11.5 Sidescan and oblique sonars

A sidescan sonar is basically a transducer mounted obliquely with respect to the major axes of the ship. The sidescan sonar is primarily used for interpretation between sounding lines obtained with single beam echosounders. It can also be used to detect thin obstacles hazardous to navigation even when a multibeam echosounder is used. It is widely used for harbour and navigation channels to ensure obstacle detection between the sounding lines.

A single-sidescan is performed using a hull-mounted transducer to one side of the vessel's track while a dual-sidescan is performed using two transducers mounted obliquely on each side of the ship or on a towed-fish, as shown in Figure 11.21.

Two fish-mounted transducers (one on each side) are typically installed 10° below the horizon for good horizontal coverage, and therefore for good obstruction detection. The beam is rectangular shaped and the beamwidth is of the order of 30° in the vertical plane perpendicular to the vessel's heading, and 1° to 2° in the horizontal plane, as shown in Figure 11.22. Sidescan sonars can therefore cover wide areas and are useful to detect rough topographic irregularities.

The extent of coverage of the seabed by the sidescan sonar beam depends on:

- The beamwidth in the vertical plane.
- The tilt of the beam axis with respect to the horizontal.
- The height of the transducer above the seabed.
- The power of the acoustic transmission, frequency and of the echo.

The "flying" height of the towed fish configuration is selected for optimum results. The measured depth accuracy is affected by the same error sources affecting vertically mounted single beam sonars. However, the effect of the vessel's attitude parameters (roll, pitch and heading) plays a critical role.

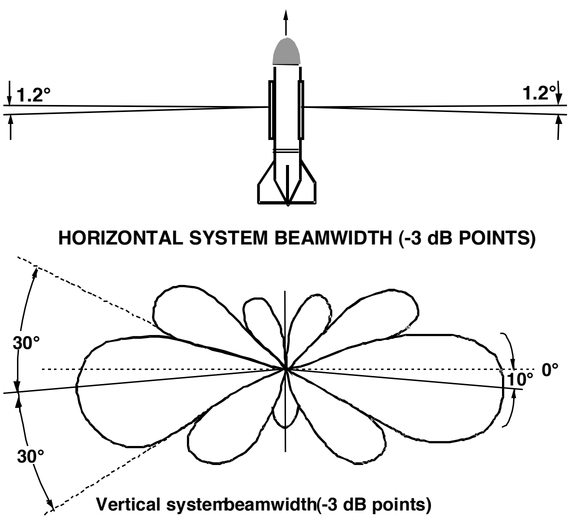


Figure 11.22: Side scan sonar transducer and beam patterns.

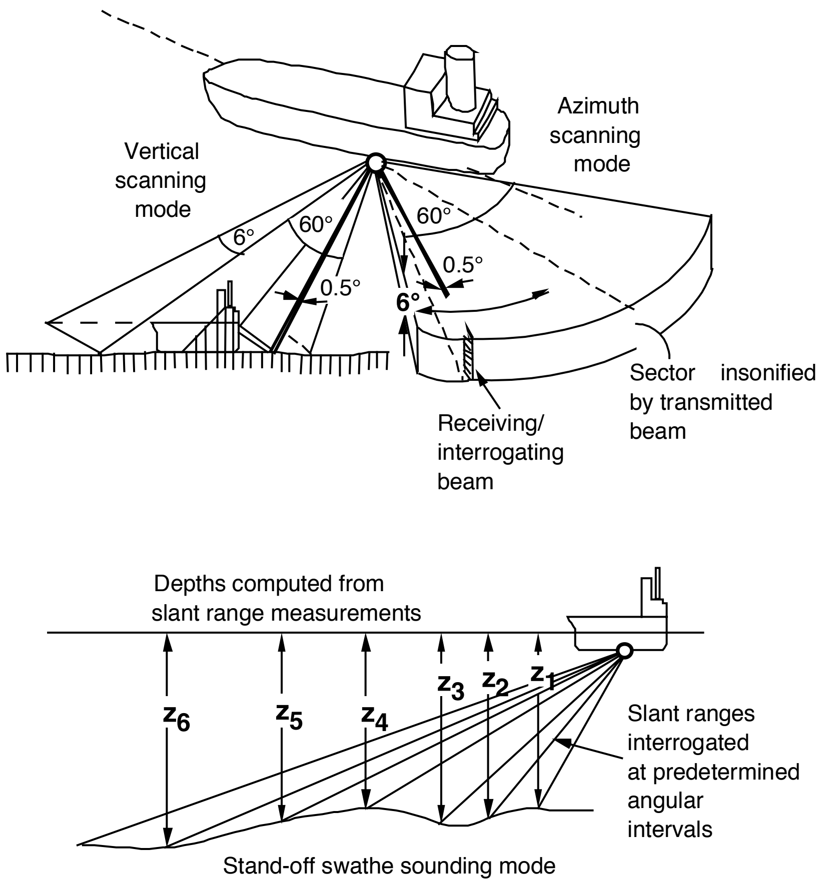


Figure 11.23: Oblique mounted sonar.

Towing a sidescan sonar is often impractical in confined areas such as ports. Another problem is multiple acoustic reflections from ships and other natural or man-made structures, due to their wide acoustic beams. For these reasons, swath MBES are replacing sidescan sonars in such constricted areas.

Oblique mounted sector scan sonars or sounders are used for seabed searches in "dangerous" shallow waters. The idea is that the vessel remains in safe water while mapping the seabed alongside. Both the vertical and azimuth scanning modes are being used in the system.

An example of an oblique system is shown in Figure 11.23. A transmitted beam of 60° × 6° is interrogated at a rate of 10 kHz by a focused array beam of 0.5° × 6°. The interrogation beam is steered across the transmitted sector with no physical rotation of the array.

The basic observable of a sidescan sonar is the two-way travel time. No information is available on the direction of the reflected signal. As a result, a sidescan sonar may not produce reliable images of areas that are not flat, see Figure 11.24. As discussed in

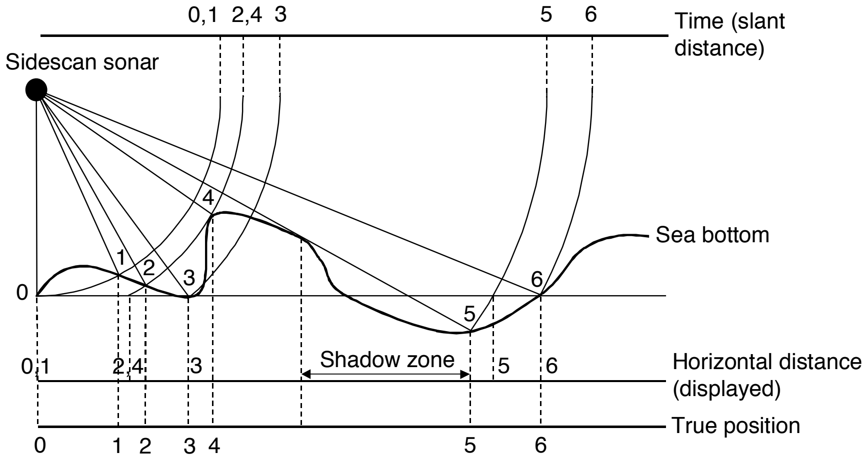


Figure 11.24: Sidescan sonar performance for a non-flat sea bottom. Due to the bottom relief, the image of the seafloor is distorted.

the previous section, a multibeam system is based on the computation of slant ranges for a number of predefined directions. An *interferometric* sidescan sonar, on the other hand, determines the direction of a signal from an observed difference in travel time. Such a system consists of a limited number of transducers (or transducer arrays, in order to get a narrow beam for each array), mounted at short distances from each other. To explain the principle of operation of an interferometric system, we will consider the simplified set-up of Figure 11.25. Two transducers, at distance Δx from each other receive a signal with an unknown angle of incidence θ. The signal at transducer i can be written as

$$p_e(r_i,t) = \frac{\hat{p}_e}{r_i}\cos(\omega t - kr_i) \tag{11.10}$$

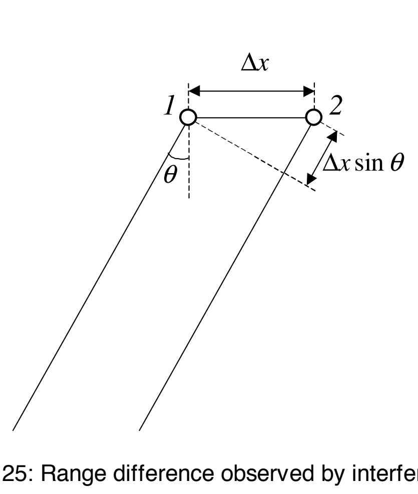


Figure 11.25: Range difference observed by interferometric sidescan sonar.

If the distance to the reflecting body is large enough to assume planar wavefronts, the range differenc between transducer *1* and *2* is equal to (see again Figure 11.25)

$$r_2 - r_1 = \Delta x \sin\theta \tag{11.11}$$

and the phase difference between them

$$\frac{2\pi}{\lambda}(r_2 - r_1) = \frac{2\pi}{\lambda}\Delta x \sin\theta \tag{11.12}$$

from which the angle θ can be determined. The phase difference is unambiguous when $\Delta x < \lambda/2$. However, for such short distances between transducers, it is not possible to precisely measure the phase difference. Resolution can be increased by increasing the distance Δx. Using more than two transducers at different distances, the ambiguities can be resolved. The exact configuration is usually not disclosed by manufacturers of interferometric sidescan sonar equipment.

11.6 Echosounding measurement corrections

All depths must refer to a *common datum*. Numerous corrections must be applied to the results of soundings in order to get chartered depths which refer to the defined datum. *Chart depth* is obtained as the sum of

- Observed depth (raw uncorrected sounding).
- Instrumental corrections.
- Sound velocity correction (discrepancy between actual and constant velocity used by the sounder to derive depth).
- Dynamic draft correction, which is the sum of

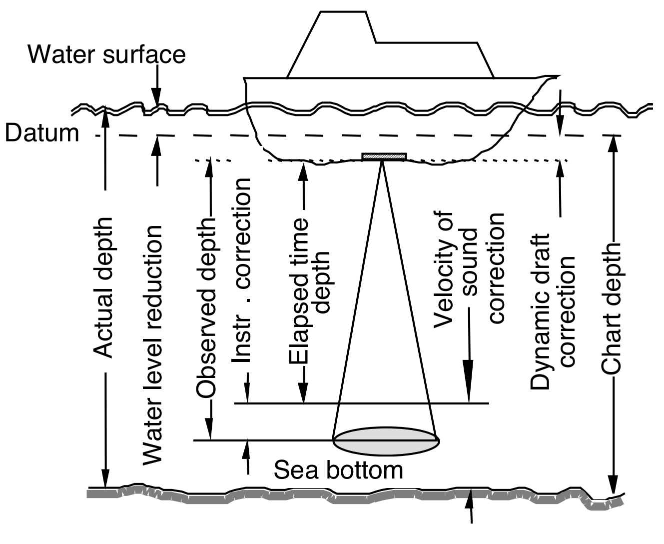


Figure 11.26: Depth measurement corrections.

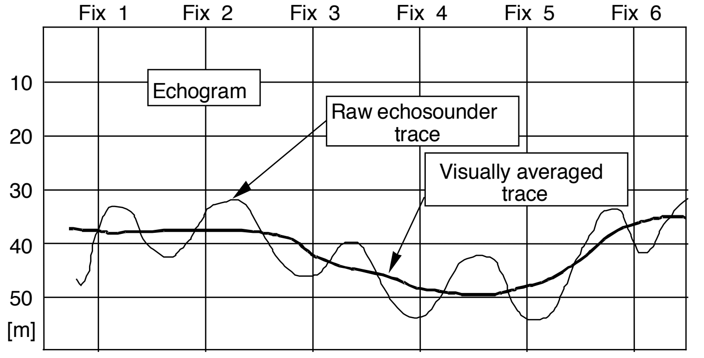


Figure 11.27: Heave compensation by averaging raw sounding data.

- Static draft (depth of transducer when the vessel is at rest).
- Settlement (difference between rest and underway positions).
- Squat (change in trim when underway).

э Water level (tidal correction).

The corrections are visualized in Figure 11.26.

The heave correction compensates for the vertical displacement of the sounding vessel from the mean water surface. It becomes very significant in shallow waters. The heave correction reflects the periodic features of waves, i.e., it has a period of 1 to 20 s and the wave amplitude is less than 20 m. When the sea bottom is regular, the sounding record can be scaled, averaged and heave corrections can be calculated. Irregular bottom causes problems in calculating heave corrections. With rough sea and irregular bottom, the heave is impossible to correct. In such conditions the sounding operations must be stopped. There are numerous ways to compensate or correct for heave:

1. Heave compensation by averaging the raw sounding data, shown in Figure 11.27.
2. Shore-based electro-optical method to correct for heave (for near-shore surveys), see Figure 11.28.
3. Use of a heave compensator. This is a vertically mounted accelerometer on a stabilized platform.
4. Use of precise DGPS. Carrier phase data observed at a high sampling rate (1 Hz or more) is used to average the height variations caused by heave motion.

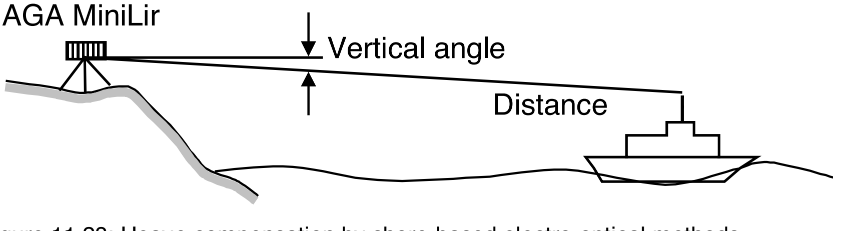


Figure 11.28: Heave compensation by shore-based electro-optical methods.

11.7 Airborne laser methods

In the mid 1960's the use of laser technology for measuring distances led to the experimental use of *airborne laser radar* (lidar) for determining topography. It was noticed that when the aircraft overflew a lake, the receiver showed a double return, which indicated that such a system could sense the surface and bottom and infer the water depth. A laser is the electromagnetic signal in the frequency band of the optical window of the electromagnetic (EM) spectrum.

Propagation of light in seawater, similarly to propagation of acoustic waves, depends on three basic state variables, namely temperature *T*, pressure *p* and salinity *S*. Seawater is somewhat transparent to EM radiation in the infrared and optical windows of the EM spectrum. *Transparency* is a function of the amount of material suspended in water. When no suspended material is present, attenuation is expressed as a function of absorption and scattering, with the absorption quantified by the *absorption coefficient k*. When suspended material is present then the absorption coefficient is replaced by the *extinction coefficient*. Due to absorption or extinction, the intensity of radiation *I* will decrease with the increasing path of the laser ray. The change *dI* in the intensity of radiation along the distance *dz* is proportional to intensity and thickness, and it is expressed by the following first order linear differential equation

$$dI = -kIdz \tag{11.13}$$

where *k* is either the absorption or the extinction coefficient. The coefficient *k* is assumed constant and has the dimension of the inverse of length (m^{-1}). The solution of the above differential equation is

$$I_z = I_0 e^{-kz} \tag{11.14}$$

where I_z is the intensity at distance *z* and I_0 is the intensity at the initial distance z_0.
For example, if $k = 1$ m^{-1}, the radiation intensity would drop to 1/*e* (37% of its initial value) after a travel distance of 1 m through the medium.

A distance equal to 1/*k*, at which the intensity is reduced by 1/*e*, is called the *attenuation length*. The fractional intensity remaining after 1 m is called the *transmission factor t*, and is expressed as

$$t = \frac{I_1}{I_0} = e^{-k} \tag{11.15}$$

The extinction coefficient *k* is characterized by the following properties:

- No significant variation with *T*, *S*, *p*.
- Nearly the same for filtered seawater and pure fresh water.
- It is a function of wavelength λ as shown in Figure 11.29.

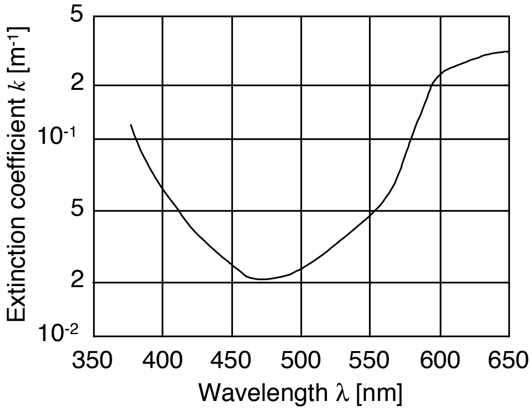


Figure 11.29: Extinction coefficient of pure water.

Dissolved material in water causes an increase of absorption. Suspended solid material increases scattering. Scattering also increases with decreasing wavelength λ. The maximum transparency is

- In pure water, at the wavelength $\lambda = 475$ nm (nanometre) corresponding to $k = 0.02\,\mathrm{m}^{-1}$, the mimimum value in Figure 11.29.
- In coastal water, at $\lambda = 550$ nm.

If $k = 0.02\,\mathrm{m}^{-1}$, then the fractional intensity after 1 m $t = e^{-k} = 0.98$. In the "clearest" water which occurs in sub-tropical regions, the extinction coefficient is twice as good as that of pure water. Coastal water may sometimes be practically opaque due to muddy bottom and biological activities.

The refractive index n_i for light propagating through a medium is defined as

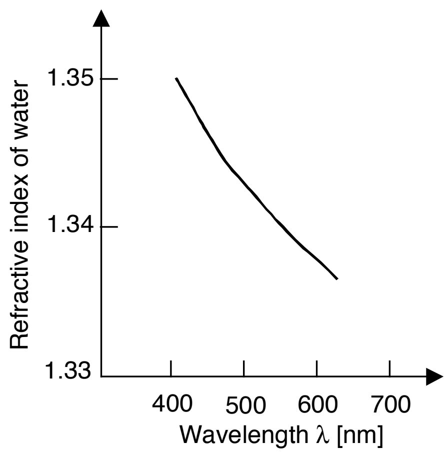


Figure 11.30: Refractive index of water as a function of wavelength for sodium light.

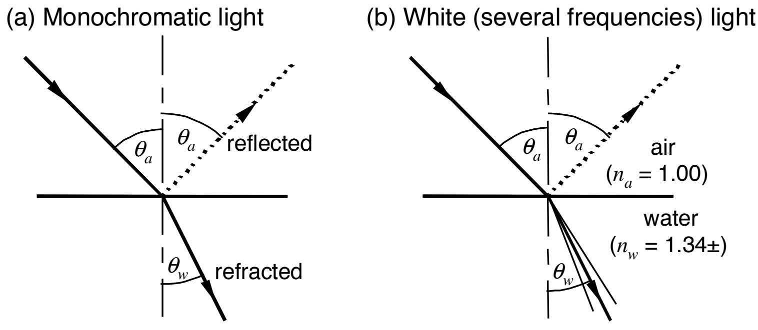


Figure 11.31: Snell's law at the air-water interface.

$$n_i = \frac{c_0}{c_i} \tag{11.13}$$

where c_0 is the speed of light in vacuo and c_i the speed of light in the medium. The refractive index n_w for the light propagating through water increases with S, T, p and decreases with increasing wavelength λ, as shown in Figure 11.30.

Snell's law states that the passage through a boundary between two media with refractive indices n_1 and n_2 is governed by the equation

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{11.14}$$

where θ_1 is the angle of incidence and θ_2 is the angle of refraction. For the passage through a boundary between air and water, the refractive indices are n_a and n_w and Snell's law is expressed as

$$n_a \sin\theta_a = n_w \sin\theta_w \tag{11.15}$$

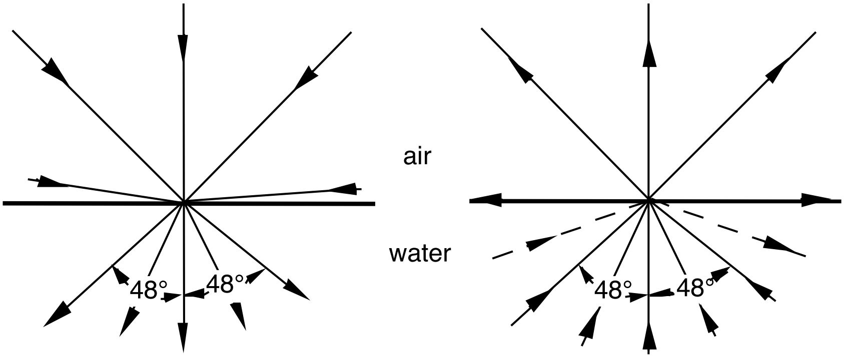


Figure 11.32: Critical angle of refraction for air-water interface.

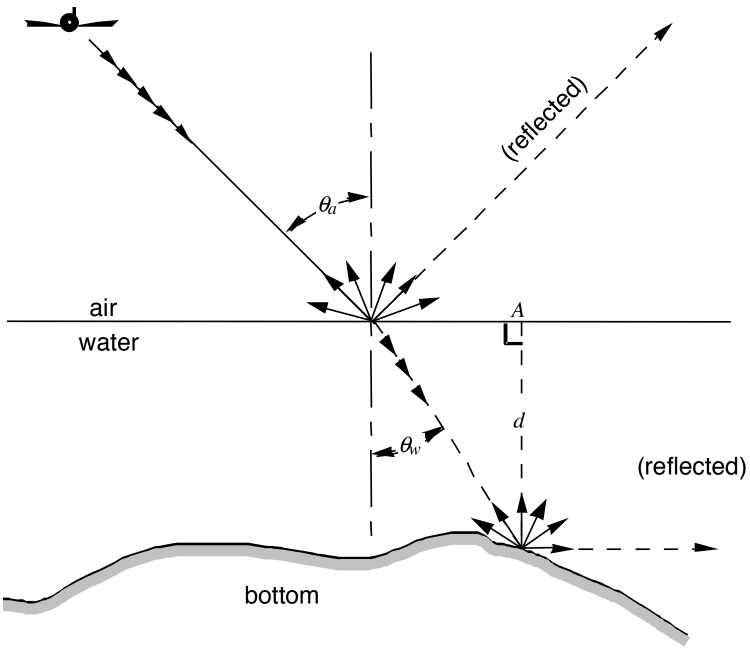
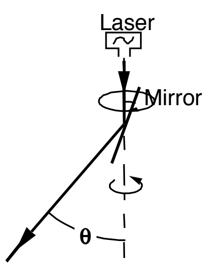


Figure 11.33: Airborne LIDAR bathymetry system concept.

as shown in Figure 11.31. The larger the angle of incidence, the larger the angle of refraction. With n_a / n_w being approximately 1/1.34, the critical refraction angle will occur when $\theta_a = 90\partial$ and $\sin\theta_a = 1$. In that case $\theta_w = \sin^{-1}(1/1.34) = 48\partial$. Thus, the light entering water through a horizontal surface will be refracted within a cone with edges of 48°, as shown in Figure 11.32.

Many countries have developed operational light detection and ranging (LIDAR) systems for airborne bathymetry in shallow waters. Using a laser airborne bathymetry system, the water depth in shallow waters (depth less than 50 m) is determined by measuring the arrival time difference between laser light pulses reflected from the surface and bottom. For mapping purposes, the horizontal position of the aircraft



Deflection of light path for rotary sweep scanning

Figure 11.34: Canadian Larsen system concept.

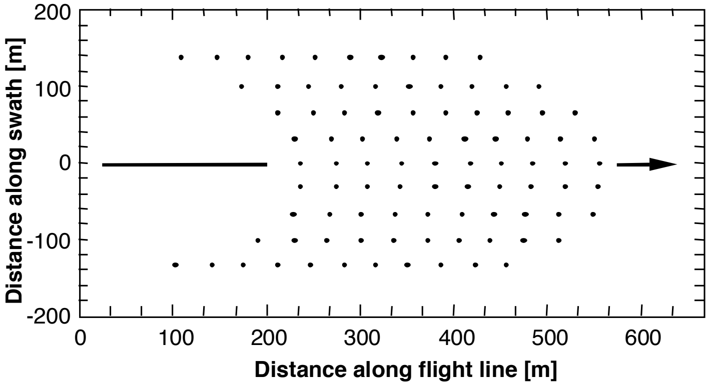


Figure 11.35: Grid produced by Canadian lidar system.

must be accurately determined throughout the operation. The use of GPS in differential mode has been a key factor in recent success. The laser airborne bathymetry system consists thus of a pulsed laser, and a positioning system, as shown in Figure 11.33. The height of the aircraft above water is measured separately.

The output of a pulsed laser creates a grid whose spacing determines the resolution of the survey. Two principles of scanning are used:

- Zero scanning angle - the laser is fired vertically (downward) at a high rate (much higher than 1 Hz). At 20 Hz, it would provide data every 2 m if the aircraft's horizontal velocity v = 40 m/s (144 km/h).
- Sweep scan - the optical axis of laser is fixed to the aircraft; the beam is deflected by a moving mirror.

The Canadian Larsen system uses a rotary sweep scanning method, see Figure 11.34, which results in the grid pattern shown in Figure 11.35.

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