Chapter 2 - Sonar Concepts

This chapter describes the components and operation of an echo-sounding system and the characteristics of its typical operating environment. It begins by introducing the most basic concepts associated with sonar technology. A simple single-beam echo sounder is then described in some detail to show the components and procedures common to all sonar systems. The limitations of this simple system are used as justification for the complexity of multibeam sonar.

Much of the terminology of sonar systems is introduced in this section. Where terms are used for the first time, they are *italicized*. Their meaning is in the context where they are used. For a formal list of the definitions of these and other terms, a glossary is included as an appendix to this document.

The Physics of Sound in Water

It is clear to anyone who has immersed himself or herself in a lake or ocean that sounds can be heard underwater. The sounds of waves, power boats, and other bathers can be heard with remarkable clarity, even at considerable distances. In fact, sounds move quite efficiently through water, far more easily than they do through air. As an example, whales use sound to communicate over distances of tens or even hundreds of kilometers. The ability of sound to travel over such great distances allows remote sensing in a water environment. Devices that use sounds in such an application fall under the family of instruments known as *sonars*. To understand sonars, you must first understand sound. In particular, you must understand how sound moves in water.

Sound travels in water in a moving series of pressure fronts known as a *compressional* wave. These pressure fronts move (or *propagate*) at a specific speed in water, the *local speed of sound*. The local speed of sound can change depending on the conditions of the water such as its salinity, pressure, and temperature, but it is independent of the characteristics of the sound itself—all sound waves travel at the local speed of sound. In a typical ocean environment, the speed of sound is in the neighborhood of 1500 meters per second (m/s). The section, "Detection Processing and Ray Calculation," in Chapter 4 describes some of the physics behind the differences in speed of sound and how sonars can adapt to them.

The physical distance between pressure fronts in a traveling sound wave is its *wavelength*. The number of pressure fronts that pass a stationary point in the water per unit time is the *frequency* of the wave. Wavelength, if measured in meters (m), and frequency, if measured in cycles per second (Hz), are related to each other through the speed of sound, which is measured in meters per second (m/s):

$$\text{speed of sound} = \text{frequency} \times \text{wavelength}$$

When a sound wave encounters a change in the local speed of sound, its wavelength changes, but its frequency remains constant. For this reason, sound waves are generally described in terms of their frequency.

A sound wave carries a certain amount of *acoustic energy*. This energy can be measured by a device called a *hydrophone*, which measures the oscillations in pressure as the pressure fronts of a sound wave pass. The size of these oscillations is the *amplitude* of the wave. The amplitude is related to the acoustic energy being transmitted in the wave—higher amplitude waves carry higher energy. Mathematically, the energy of a sound wave per unit time (called *power*) is proportional to the square of its amplitude.

Figure Chapter 2 - -1 shows schematically the components of a sound wave. A series of advancing pressure fronts, representing a traveling sound wave, are shown as a gray scale, with dark shades corresponding to high pressure and light shades corresponding to low pressure. The distance between the pressure fronts is the wavelength. The pressure fronts move with the speed of sound. Accompanying the gray scale is a measurement of the changes in pressure with time as seen by a stationary hydrophone in the water. The size of the oscillations in pressure is the amplitude, and the amount of time between peaks in the pressure is the inverse of the frequency, called the *time period*.

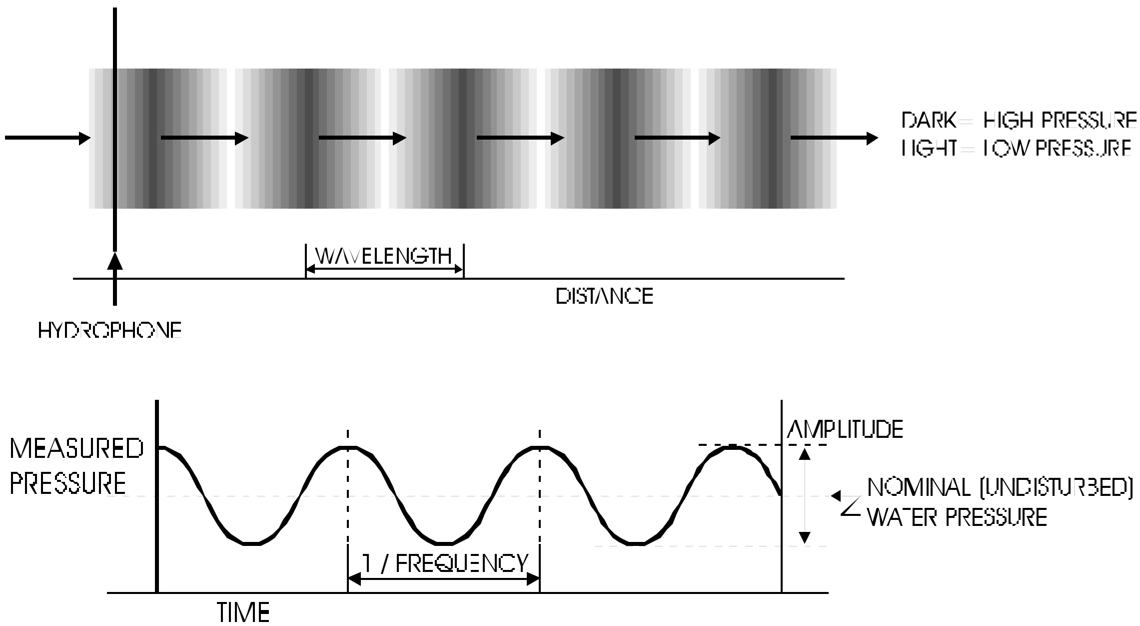

Figure Chapter 2 - -1: Components of a Sound Wave

As a sound wave propagates, it loses some of its acoustic energy. This happens because the transfer of pressure differences between molecules of water is not 100% efficient—some energy is lost as generated heat. The energy lost by propagating waves is called *attenuation*. As a sound wave is attenuated, its amplitude is reduced.

Sound waves are useful for remote sensing in a water environment because some of them can travel for hundreds of kilometers without significant attenuation. Light and radio waves (which are used in radar), on the other hand, penetrate only a few meters into water before they lose virtually all of their energy. The level of attenuation of a sound wave is dependent on its frequency—high frequency sound is attenuated rapidly, while extremely low frequency sound can travel virtually unimpeded throughout the ocean. A sound wave from a typical sonar operating at 12 kHz loses about half of its energy to attenuation traveling 3000 meters through water.

While acoustic energy travels well in water, it gets interrupted by a sudden change in medium, such as rock or sand. When a moving sound pulse encounters such a medium, some fraction of its energy propagates into the new material. How much of the energy is transmitted is dependent on a number of factors, including the *impedance* of the new material (a product of the material' s density and the speed of sound within it), the *angle of incidence* of the impinging pulse (the angle at which the sound pulse strikes the new medium), and the roughness of the new medium' s surface. The energy that is not transmitted into the new material must go back into the original medium—the water—as sound. Some amount of it is *reflected* off the surface of the material—essentially it bounces off in a direction that depends on the angle of incidence. The remainder is *scattered* in all directions. How much energy goes into reflection and how much goes into scattering depends on the characteristics of the material and the angle of incidence. The energy returned to the water (in other words, the energy that is not transmitted into the new medium) is called an *echo*. The echo maintains the frequency characteristics of the source wave. Figure Chapter 2 - -2 shows the components of an echo event on the ocean floor.

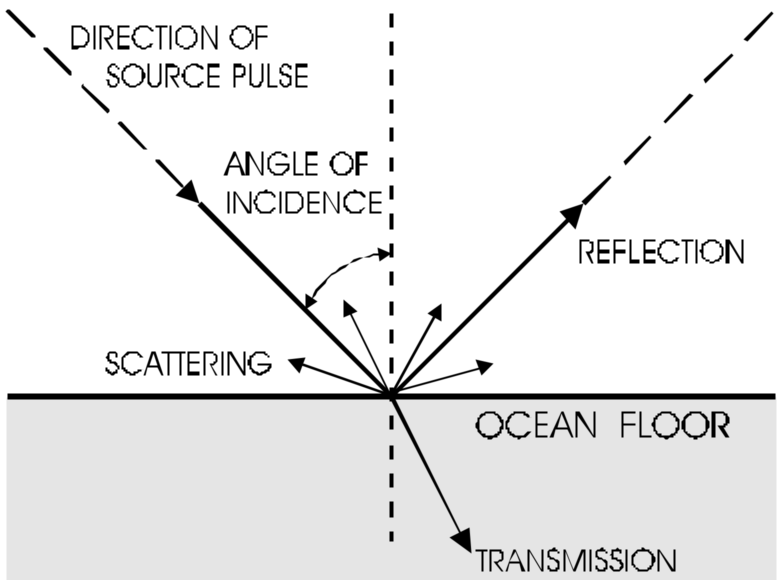

Figure Chapter 2 - -2: Components of an Echo Event on the Ocean Floor

The Principles of Sonar

A *sonar* is a device for remotely detecting and locating objects in water using sound. It does this by taking advantage of the behavior of sound in water. There are two basic types of sonar:

- *Passive sonars* are essentially "listening" devices that record the sounds emitted by objects in water. Such instruments can be used to detect seismic events, ships, submarines, and marine creatures—anything that emits sound on its own. Their utility is in disciplines other than sea floor measurement, and they are not covered in this document.

- *Active sonars* are devices that produce sound waves of specific, controlled frequencies, and listen for the echoes of these emitted sounds returned from remote objects in the water. Sonars that measure ocean depths are active sonars.

From this point on, this document only discusses active sonar devices used to remotely measure the depth of the ocean floor, a process called *echo sounding* or *bathymetry measurement*. The instruments that make these measurements are called *echo sounders*. The SEA BEAM 2100 system is a complex echo sounder, but basic principles of all echo sounders apply to it.

Echo sounders measure depth by generating a short pulse of sound, or *ping*, and then listening for the echo of the pulse from the bottom. The time between transmission of a pulse and the return of its echo is the time it takes the sound to travel to the bottom and back. Knowing this time and the speed of sound in water allows you to calculate the *range* to the bottom. For instance, if you find that it takes 10 seconds between when a ping is transmitted and when you hear its echo, then using a speed of sound of 1500 m/s, you know it traveled 10 sec × 1500 m/s = 15000 m. Because this is the "round trip" distance—to the target and back—the range to the bottom is half of 15000, or 7500 m. In general:

$$\text{range} = (1/2) \times \text{velocity} \times \text{echo time}$$

To produce a sound wave, an echo sounder uses a device called a *projector*. A projector can be anything that is capable of producing a sound in water, and there are many forms of them tailored to specific applications. One type of projector system detonates explosive charges underwater—such devices are called "boomers." "Sparkers" use high energy electrical discharges to create plasma bubbles. "Air guns" use compressed air to create a collapsing bubble underwater. These devices are used primarily for seismic surveys. They are limited in that the amplitude, frequency, and duration of the sound pulses they create cannot be maintained from one ping to the next.

Bathymetric sonars require projectors that can repeatedly produce acoustic pulses with precise, controllable, and repeatable characteristics. They use projectors constructed of piezo-electric ceramic, a material that changes its size minutely when a voltage is applied to it. An echo sounder can use particular voltages to cause the piezo-electric projector to oscillate, transmitting a pressure wave with specific frequency characteristics into the water. Such a projector is analogous to a common loudspeaker, which converts electrical signals into oscillations of a cloth or paper membrane, transmitting energy into air in the form of sound waves.

A sound pulse generated in water expands spherically from its source—its energy travels equally in all directions. As the sphere of a pulse front expands, its energy is being spread over a larger and larger area (the surface of the expanding sphere), causing a drop in energy per unit area. This drop in energy is called *spreading loss*. The pulse also suffers from some attenuation, or *absorption loss*. Collectively, spreading loss and absorption loss are called *transmission loss*. The total amount of transmission loss that affects a sound wave is dependent on the distance it travels—the farther a wave propagates, the weaker it gets.

When a sound wave strikes a portion of the ocean bottom, it is said to *illuminate* or *ensonify* that part of the bottom. What happens to the acoustic energy at this point can be very complex. A portion of the energy is transmitted into the sea floor. How much energy is transmitted depends on the bottom material. Sand and silt absorb energy fairly easily. On the other hand, rocks and metal objects absorb minimal acoustic energy. The bulk of the energy that cannot be absorbed by the ensonified target is reflected or scattered back into the water. The fraction of incident energy per unit area that is directed back in the direction of the projector is called the *backscattering strength* of the bottom.

After echoing off the bottom, the return sound pulse endures more transmission loss. The echo sounder detects what is left of the return pulse using a hydrophone. Hydrophones do what projectors do in reverse—they convert the physical oscillations that they experience when sound waves impinge upon them into voltages. Hydrophones are analogous to microphones in that they convert sounds transmitted through the air into electrical signals. Because of the similarity of their functions, the projectors and hydrophones in a sonar system are often the same pieces of hardware. The term *transducer* refers to both hydrophone and projector devices.

In every stage of this process—ping generation, propagation, echoing, and reception—there are sources of sound that add themselves to the final signal received. These include, but are not limited to, ocean sounds (waves, for example), marine creatures, and shipboard sounds from the survey vessel and other vessels. There are also spurious signals that enter the signal from the sonar electronics. Collectively, the magnitude of these unwanted signals is called the *noise level*. The noise level limits the maximum range of any remote sensing instrument. In a noiseless world, the tiniest sonar echo from the sea floor could be detected. While a ping and its echo have transmission losses that make them weaker and weaker, they never actually drop to zero. However, in the real, noisy world they will eventually become so weak that they are indistinguishable from the noise level, and are thus undetectable. The *signal-to-noise ratio* is the ratio of the received signal strength to the noise level. It gives a measure of the detectability of a signal. The minimal signal-to-noise ratio required for a signal to be detectable depends on the specific application.

The Sonar Equation

Sonar engineers often keep track of all of the factors involved in the acoustic echoing process with the *Sonar Equation*. This equation expresses what is called the *Signal Excess* (*SE*), the strength of the measured echo return, in terms of the quantities described above—Transmission Loss (*TL*), Backscattering Strength (*BS*, often called *target strength* when used in the detection of discrete objects such as a mine or a submarine), the Target Area (*TA*), and Noise Level (*NL*). It also includes the *transmitted Source Level* (*SL*), which is a measure of the amount of acoustic energy put into the water by the projector. By convention, all quantities are in decibels (dBs):

$$SE = SL - 2TL + BS - NL + TA$$

The sonar equation can appear in different forms and may have additional terms. It clearly represents many of the factors involved in echo sounding and how they relate to one another. The sonar equation thus comes in handy during the design process or for predicting performances during many "what if" scenarios. Figure Chapter 2 - -3 follows the path of a ping from projector to the ocean floor and back to a hydrophone to show where each element of the sonar equation comes into play. The interested reader will find more information on sonar equations in the book, *Principles of Underwater Sound* by Robert J. Urick. 3rd edition: McGraw Hill, 1983.

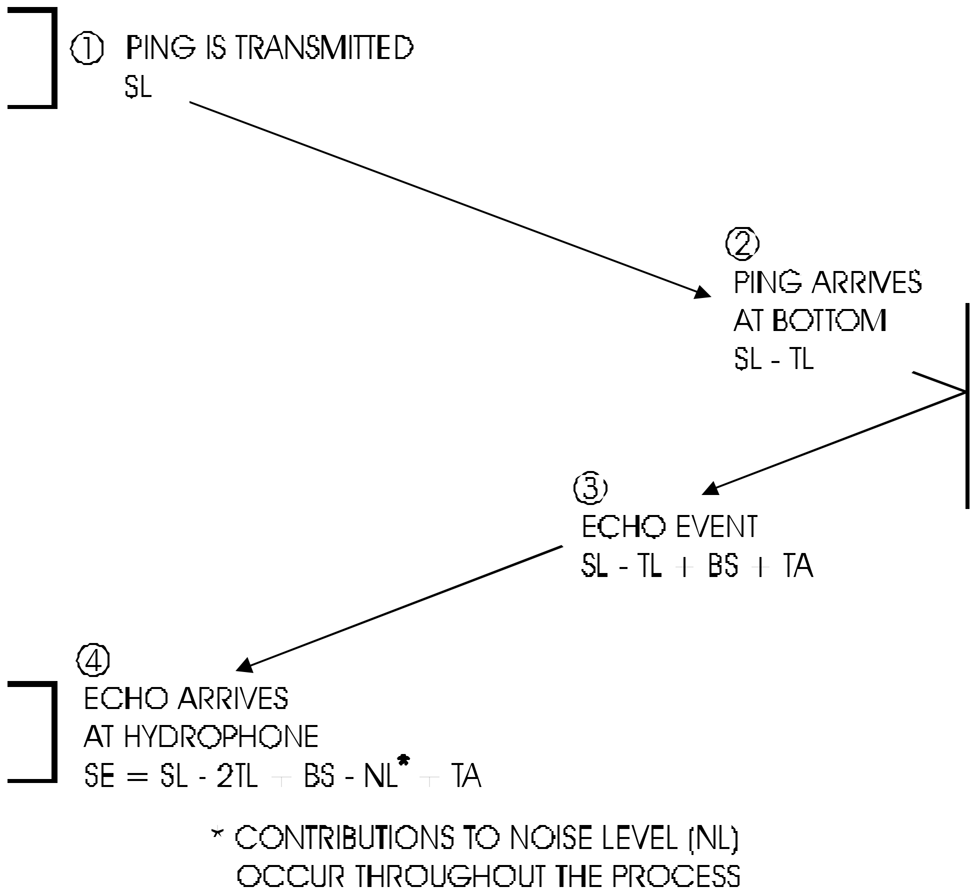

Figure Chapter 2 - -3: Path of a Ping

A Single-Beam Depth Sounder

The earliest, most basic, and still the most widely used echo sounding devices are *single-beam depth sounders*. The purpose of these instruments is to make one-at-a-time measurements of the ocean depth at many locations. Recorded depths can be combined with their physical locations to build a three-dimensional map of the ocean floor. In general, single-beam depth sounders are set up to make measurements from a vessel while it is in motion. While single-beam depth sounders have many limitations (discussed in this document), it is useful to understand how they work as a prelude to understanding a multibeam sonar.

A single-beam depth sounder system consists of four basic components: a Transmitter, a Transducer, a Receiver, and a Control and Display system. These components are depicted schematically in Figure Chapter 2 - -4. In order to collect a series of depth measurements as a ship travels, the operations of the single-beam depth sounder are performed in a continuous cycle, called the *ping cycle*.

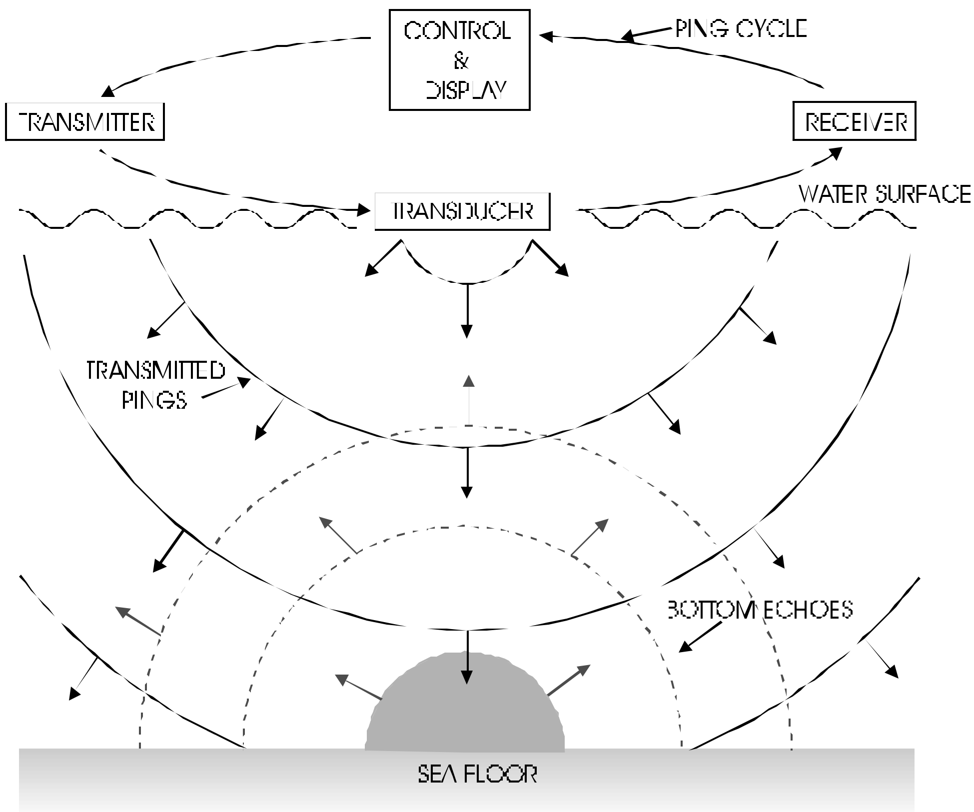

Figure Chapter 2 - -4: Components of a Single-Beam Depth Sounder System

The ping cycle is governed by the Control and Display system. In a single cycle, the Control and Display system signals the Transmitter system to produce a sound pulse (or ping). The Transmitter generates an oscillating electric signal with frequency characteristics that can be uniquely distinguished. The Transducer converts the electrical energy into sound waves. In this capacity it is being used as a projector. The oscillating electric signals are converted into mechanical vibrations that are transmitted into the water as an oscillating pressure or a sound wave. Upon its return as an echo from the sea floor, the sound pulse is received and converted back into electrical signals by the Transducer acting as a hydrophone. The Transducer passes on all received electrical signals to the Receiver system, where they are amplified and passed through a detection scheme to determine when an echo arrives. The time between transmission and reception is used by the Receiver system to compute a range or depth. This depth is reported and recorded by the Control and Display system. The Control and Display system then triggers the next ping. The amount of time required between the ping transmissions is called the *ping time* or *ping interval*. Using a continuous ping cycle, a series of depth measurements are taken and logged.

Why Multibeam? The Limitations of a Single-Beam Depth Sounder

While simple and inexpensive to build, and easy to use and understand, the single-beam echo sounder has a number of critical limitations that make it an inappropriate instrument for large-scale bathymetric survey work. These limitations have been the driving incentive behind the development of the more complex and expensive multibeam sonars such as the SEA BEAM 2100.

The purpose of a large-scale bathymetric survey is to produce accurate depth measurements for many neighboring points on the sea floor such that an accurate picture of the geography of the bottom can be established. To do this efficiently, two things are required of the sonar used: it must produce accurate depth measurements that correspond to well-defined locations on the sea floor (that is, specific latitudes and longitudes); and it must be able to make large numbers of these measurements in a reasonable amount of time. As you will see, the single-beam echo sounder falls short in both areas.

Echo Location Questions – Where is the Bottom?

The most basic function of an echo sounder is to measure the range to the ocean floor accurately. In a bathymetric survey, a sonar is most useful if it measures the range to a specific location on the bottom, ideally at a point directly below the vessel doing the survey.

Using the single-beam echo sounder described above, you might assume that the time of the first echo from a ping determines the range to the bottom directly below the survey vessel. In the situation pictured in Figure Chapter 2 - -4 this is certainly the case—the earliest echo is from directly below the sonar, because that is where the ping first encounters the bottom. However, Figure Chapter 2 - -4 is drawn with an ideal, flat bottom. You can easily imagine a situation where the first echo might not be from a point directly below. Figure Chapter 2 - -5 shows a survey vessel over an irregular sea floor, where a bottom feature behind the vessel is closer to the sonar than the bottom directly below. Pings from the single-beam echo sounder, which spread out spherically from the sonar—equally in all directions—strike the bottom first at this point. There is no way for an operator on the survey vessel to know that the first return echo is not from the bottom directly below. This situation will produce an inaccurate measurement of the depth at this location.

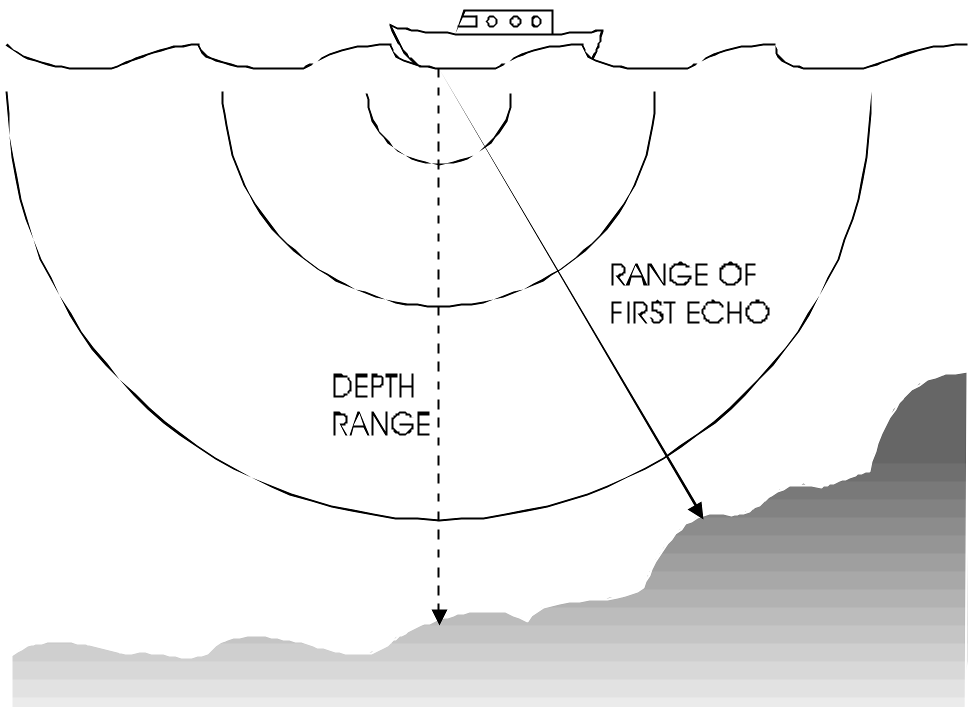

Figure Chapter 2 - -5: Surveying an Irregular Sea Floor

A single-beam echo sounder can be designed such that it deals with this problem to some degree. It does this by introducing some *directivity* to the ping. Effectively, the bulk of the acoustic energy in the ping is focused within a narrow solid angle, or *beam* (how this is done is covered in Chapter 3). The ping then ensonifies only a small patch of the bottom, and the first returned echo can be assumed to come from this area. Figure Chapter 2 - -6 shows how a narrow-beam echo sounder can be used to produce a more accurate depth measurement of an irregular sea floor.

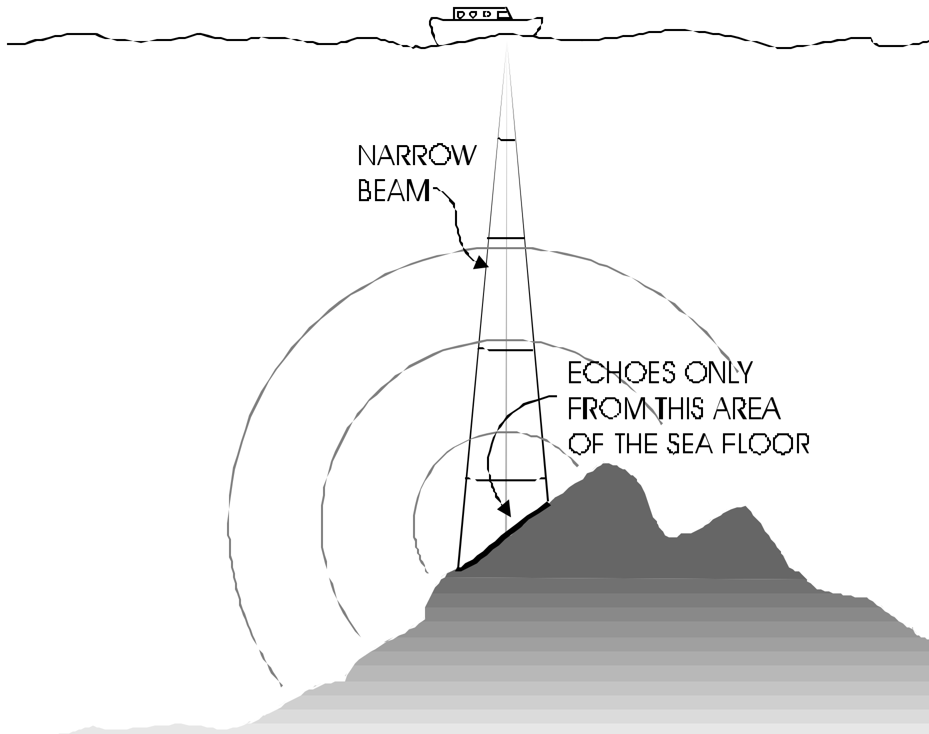

Figure Chapter 2 - -6: Using a Narrow-Beam Echo Sounder on an Irregular Sea Floor

However, the narrow beam does not completely solve the problem for two reasons. First, since the transducers are mounted on the hull of a ship, which is subject to wave motion, the narrow beam illuminates scattered areas of the ocean floor (see Figure Chapter 2 - -7). This is what is known as an *unstabilized* beam. The magnitude of this problem depends on the severity of the weather, but it can be quite large. Roll and pitch angles of tens of degrees in moderately heavy seas are not uncommon in the open ocean. Secondly, beams are made narrower by making the transducer face larger. For example, a circular 12 kHz transducer with a 30° beam width has a diameter of roughly 25 cm, but requires a diameter of roughly 295 cm for a 2.5° beam. These larger transducers are more expensive to manufacture.

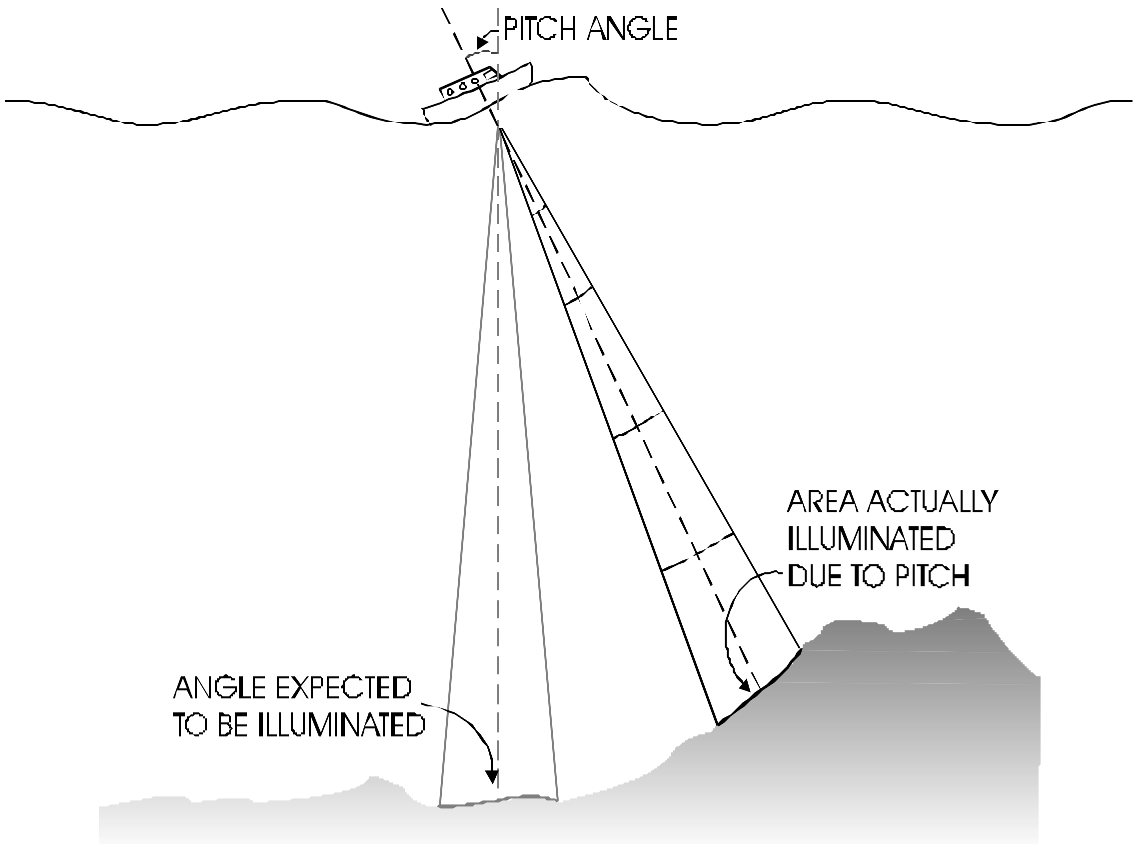

Figure Chapter 2 - -7: Ship Motion Effects on an Unstabilized Beam

The solid angle size of the beam determines how accurately a narrow beam sonar can determine the location of depths on the bottom. An observer recording an echo from such a sonar can determine only that the bottom is located somewhere within that angle at the computed range. For a simple sonar there is no way of extracting any more accurate information from the system. The size of the beam solid angle determines the *resolution* of a sonar. The term resolution may apply to the angle itself, or to the physical size of the area on the bottom the beam ensonifies. Note that in the latter definition, the resolution is not fixed—it depends on depth. The deeper a ping goes, the larger an area its fixed solid angle will intersect (see Figure Chapter 2 - -8). In general, the area of the ensonified bottom is proportional to the beam solid angle and to the square of the depth.

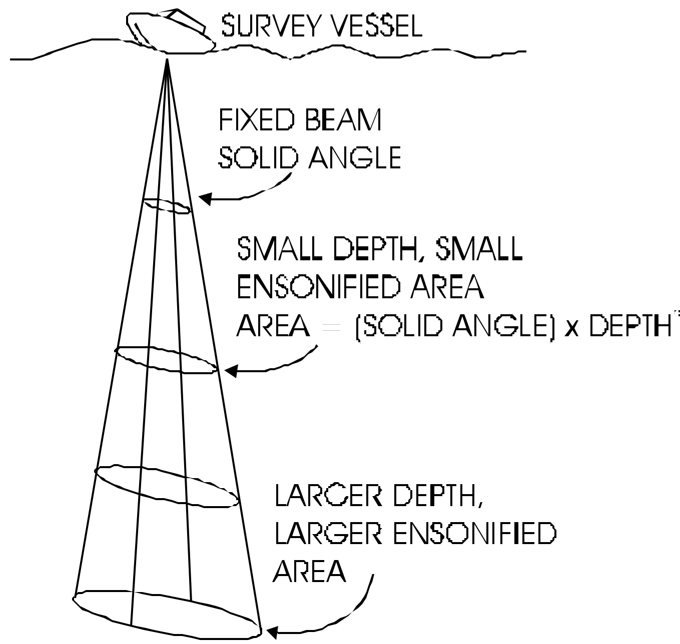

Figure Chapter 2 - -8: Dependence of Ensonified Area on Depth

Survey Speed

To be cost-effective, a bathymetric survey must be completed in a reasonably short amount of time. For a survey to be performed properly, it must have a dedicated survey vessel, and, quite simply, ships are very expensive to operate. This is particularly true in a deep sea environment, where a survey vessel must be large enough to ride out the worst ocean weather and must have a dedicated staff to run and maintain it for days or weeks at a time. In the business of bathymetric surveying, time is equal to money in a very real sense.

A single-beam echo sounder is not a time-efficient survey instrument because it makes only one depth measurement at a time. The area of the bottom ensonified by the sonar' s beam is the only part of the sea floor that can be considered "mapped" in a ping. Additional pings must be used to map all neighboring points. Recall that in the ping cycle, a ping echo must return before the next ping can be transmitted. This effectively removes the size of the time interval between pings from your control—it is dependent on the depth and the speed of sound. If a sonar has a very narrow beam, which provides highly accurate locations for its depth measurements, the mapping process will require many individual measurements and take a very long time. The process can be speeded up by using a sonar with a larger beam that maps a larger area with each ping, but with poorer bottom resolution.

The Multibeam Solution

A *multibeam sonar* is an instrument that can map more than one location on the ocean floor with a single ping and with higher resolution than those of conventional echo sounders. Effectively, the job of a narrow single-beam echo sounder is performed at several different locations on the bottom at once. These bottom locations are arranged such that they map a contiguous area of the bottom—usually a strip of points in a direction perpendicular to the path of the survey vessel. This area is called a *swath*. The dimension of the swath in the *acrosstrack* or *athwartship* direction (perpendicular to the path of the ship) is called the *swath width*, and it can be measured either as a fixed angle or as a physical size that changes with depth. The swath of a multibeam sonar is depicted in Figure Chapter 2 - -9.

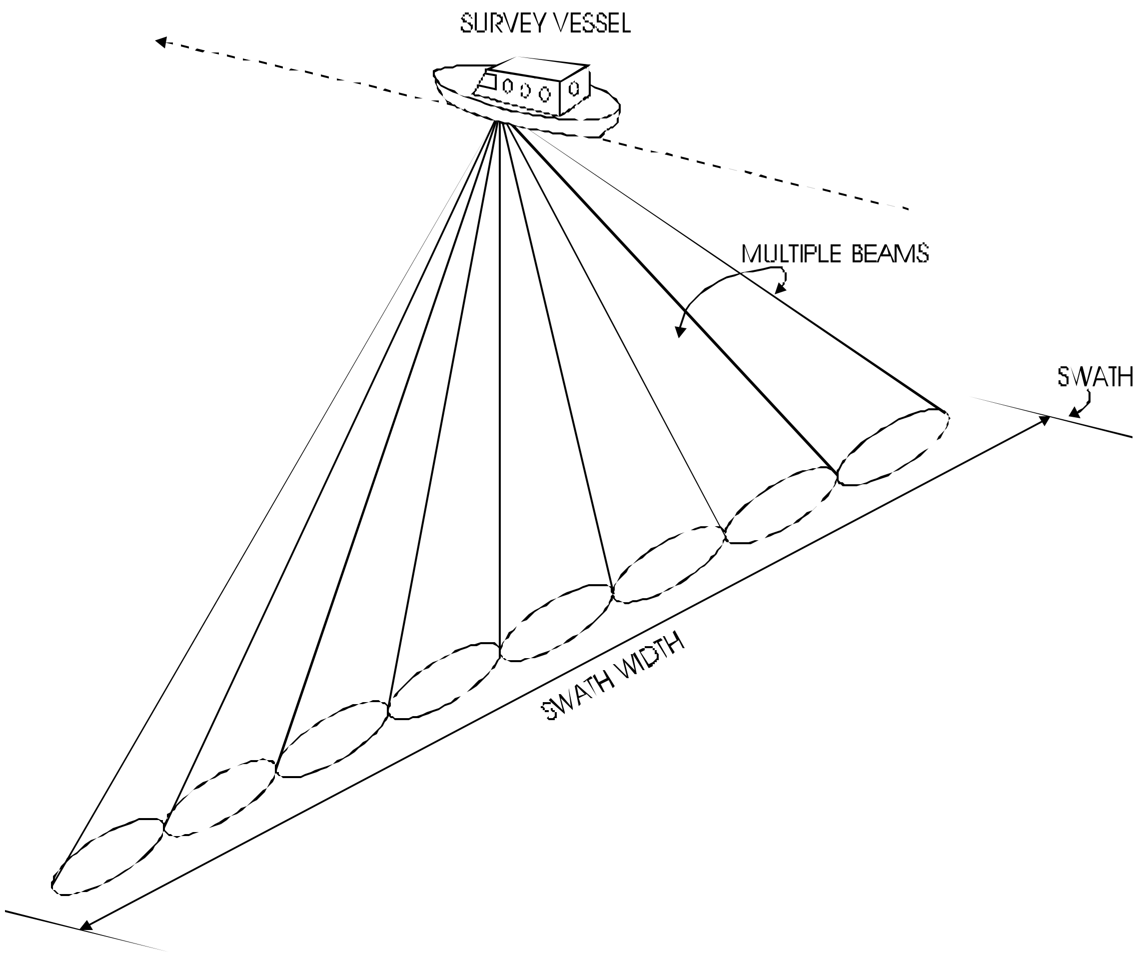

Figure Chapter 2 - -9: Multibeam Sonar Swath

Clearly, this is highly advantageous. Multibeam sonars can map complete swaths of the bottom in roughly the time it takes for the echo to return from the farthest angle. For a 120°-swath system, this time is twice the ping cycle time of a single-beam sounder, but such a system typically provides over 100 soundings as opposed to only one. Because they are far more complex, the cost of a multibeam sonar can be many times that of a single-beam sonar. However, this cost is more than compensated by the savings associated with reduced ship operating time. As a consequence, multibeam sonars are the survey instrument of choice in most mapping applications, particularly in deep ocean environments where ship operating time is expensive.

The SEA BEAM 2100 is a multibeam sonar system. It maps up to 151 sounding points at 1° intervals with each ping, and can cover areas tens of kilometers wide in depths of a few kilometers. How this is accomplished is the subject of the rest of this document.

