Multibeam Sonar

Theory of Operation

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Table of Contents

Chapter 1 - Introduction

Chapter 2 - Sonar Concepts

Chapter 3 - Introduction to Multibeam Sonar: Projector and Hydrophone Systems

Chapter 4 - Detection Processing and Range Calculations

Chapter 5 - Sidescan Sonar

Glossary of Terms

List of Figures

Chapter 1 - Introduction

Echo sounding is a technique for measuring water depths by transmitting acoustic pulses from the ocean surface and listening for their reflection (or echo) from the sea floor. This technique has been used since the early twentieth century to provide the vital depth input to charts that now map most of the world's water-covered areas. These charts have permitted ships to navigate safely through the world's oceans. In addition, information derived from echo sounding has aided in laying trans-oceanic telephone cables, exploring and drilling for off-shore oil, locating important underwater mineral deposits, and improving our understanding of the Earth's geological processes.

Until the early 1960s most depth sounding used single-beam echo sounders. These devices make a single depth measurement with each acoustic pulse (or ping) and include both wide and narrow beam systems. Relatively inexpensive wide-beam "unstabilized" sounders detect echoes within a large solid angle under a vessel and are useful for finding potential hazards to safe navigation. However, these devices are unable to provide much detailed information about the sea bottom. On the other hand, more expensive narrow-beam "stabilized" sounders are capable of providing high spatial resolution with the small solid angle encompassed by their beam, but can cover only a limited survey area with each ping. Neither system provides a method for creating detailed maps of the sea floor that minimizes ship time and is thus cost-effective. The unstabilized systems lack the necessary spatial resolution, while the stabilized systems map too little area with each ping.

In 1964, SeaBeam Instruments—at the time the Harris Anti-Submarine Warfare Division of General Instrument Corporation—patented a technique for multiple narrow-beam depth sounding. The first such systems to use this technique were built by SeaBeam for the US Navy and were known as Sonar Array Sounding Systems (SASS). SASS employed two separate sonar arrays oriented orthogonal to one another—one for transmitting and one for receiving—an arrangement called a Mills Cross Array. The arrays and the associated analog electronics provided 90 1°-wide unstabilized beams. Roll and pitch compensation produced 60 1°-wide stabilized beams, which permitted mapping a 60° "fan" of the sea floor with each ping. This system allowed survey vessels to produce high-resolution coverage of wide swaths of the ocean bottom in far less ship time than would have been required for a single-beam echo sounder, greatly reducing the costs of such mapping endeavors.

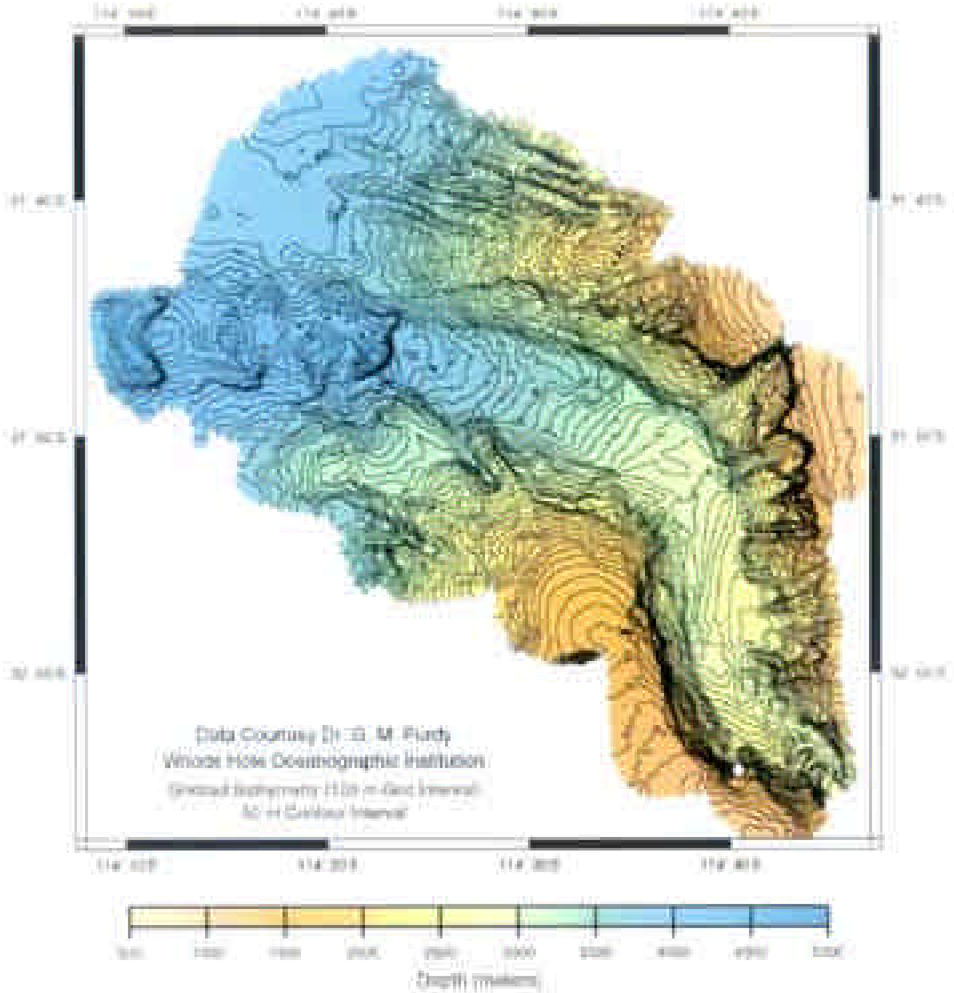

Figure Chapter 1 - -1: Contour Map of Perth Canyon

Most multibeam bathymetry systems still use the Mills Cross technique for beam forming. However, as faster computers and Large Scale Integrated (LSI) digital chips have become available, most of the signal processing, including beam forming, moved from analog signal processing into the digital (discrete) signal processing (DSP) domain using digital signal microprocessor (DSPμP) chips. The availability of fast DSPμPs has also permitted the implementation of sophisticated detection algorithms. As a result, survey vessels today can do on-board real-time multibeam processing and display of bathymetry data in a manner impossible only a few years ago. Figure Chapter 1 - -1 shows a sample of a high-quality ocean floor map produced by a SEA BEAM 2100 Multibeam Survey System, the latest generation of multibeam sonar from SeaBeam Instruments.

The SEA BEAM 2100 system represents the culmination of over a third of a century of design, development, and production experience by SeaBeam Instruments in the area of multibeam bathymetric systems. With added sophistication, this latest generation multibeam sonar system has added capabilities and complexity. It is necessary to have a basic theoretical understanding of the way multibeam bathymetry systems in general, and the SEA BEAM 2100 in particular, work in order to both:

- Operate the system in a manner that maximizes coverage and data quality
- Evaluate the system performance for signs of system degradation

Organization of this Document

This manual provides a general explanation of the way a multibeam sonar system works and describes in detail the implementation of multibeam technology represented by the SEA BEAM 2100 system.

Chapter 2, "Sonar Concepts," introduces the concepts and definitions involved in echo sounding, using a description of a simple single-beam echo sounder as an example. Characteristics of the creation and transmission of acoustic pulses in water and their echoes off the ocean bottom are discussed. This chapter also explains some of the limitations of a single-beam sonar.

Chapter 3, "Introduction to Multibeam Sonar: Projector and Hydrophone Systems," describes the Mills Cross technique, including the processes of beam forming and beam steering and how it is applied to sonar and to the SEA BEAM 2100 in particular. The chapter discusses how systems that employ the Mills Cross technique can make up for many of the short-comings of single-beam echo sounders.

Chapter 4, "Detection Processing and Range Calculation," describes how the SEA BEAM 2100 extracts signals and determines the location of the sea floor from multibeam echoes. The processes used for ship motion compensation and the formation of stable beams and the implementation of sound velocity profiles are discussed.

Chapter 5, "Sidescan Sonar," discusses sea floor imaging using sidescan sonars and how the SEA BEAM 2100 can be used simultaneously as a depth-finding and sidescan sonar.

A glossary of the terminology of multibeam sonar technology is included as an appendix.

Scope of this Document

Multibeam technology involves a number of disciplines including underwater acoustics, digital signal processing, and detection theory statistics. Many excellent texts are available that provide in-depth mathematical treatment of each of these fields. The purpose of this document is not to cover all related topics in rigorous mathematical detail, but instead to present you with a simple, clear understanding of the fundamental concepts required to develop the full potential of a multibeam sonar system. Ideas are presented in a graphical and descriptive way, with minimal use of complex mathematics. Where appropriate, references to texts are provided so you can pursue topics in greater detail. While directed at users of the SEA BEAM 2100 system in particular, most of the concepts explained in this document are common to all multibeam sonars, so much of this information can be applied to any commercially available multibeam system.

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*.

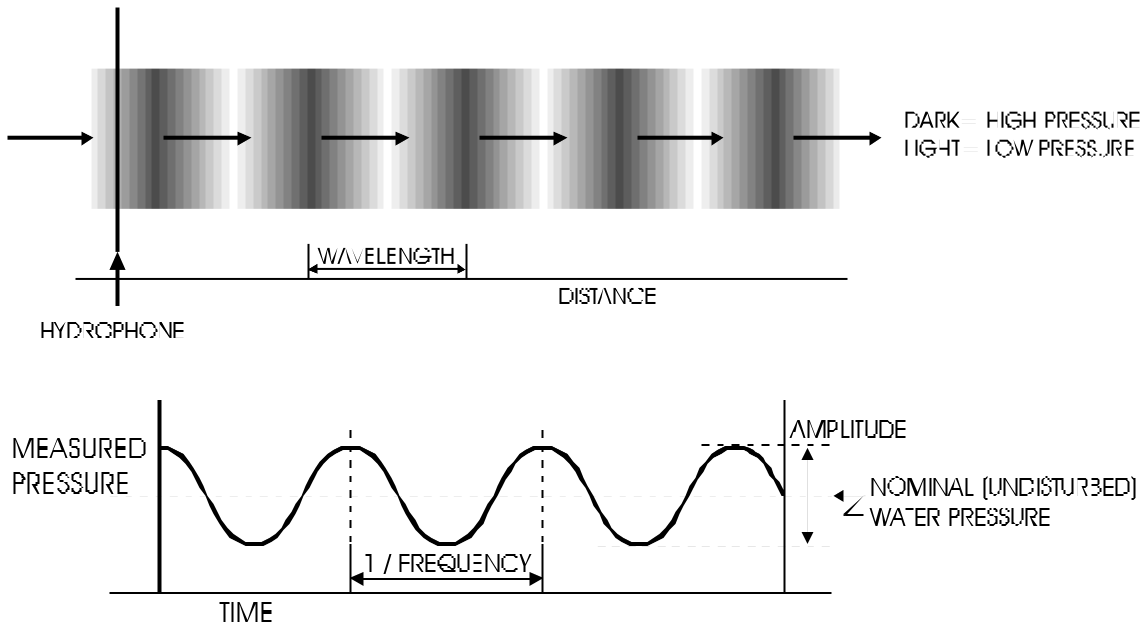

Figure Chapter 2 - -1: Components of a Sound Wave

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.

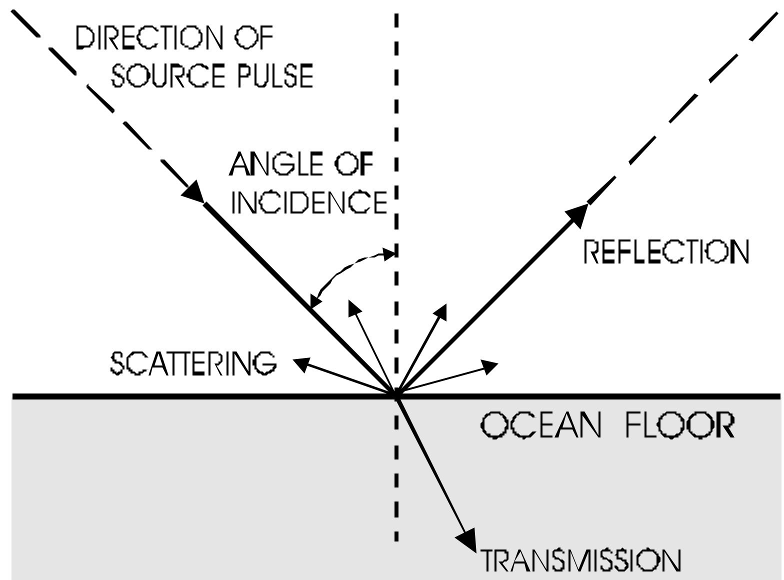

Figure Chapter 2 - -2: Components of an Echo Event on the Ocean Floor

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.

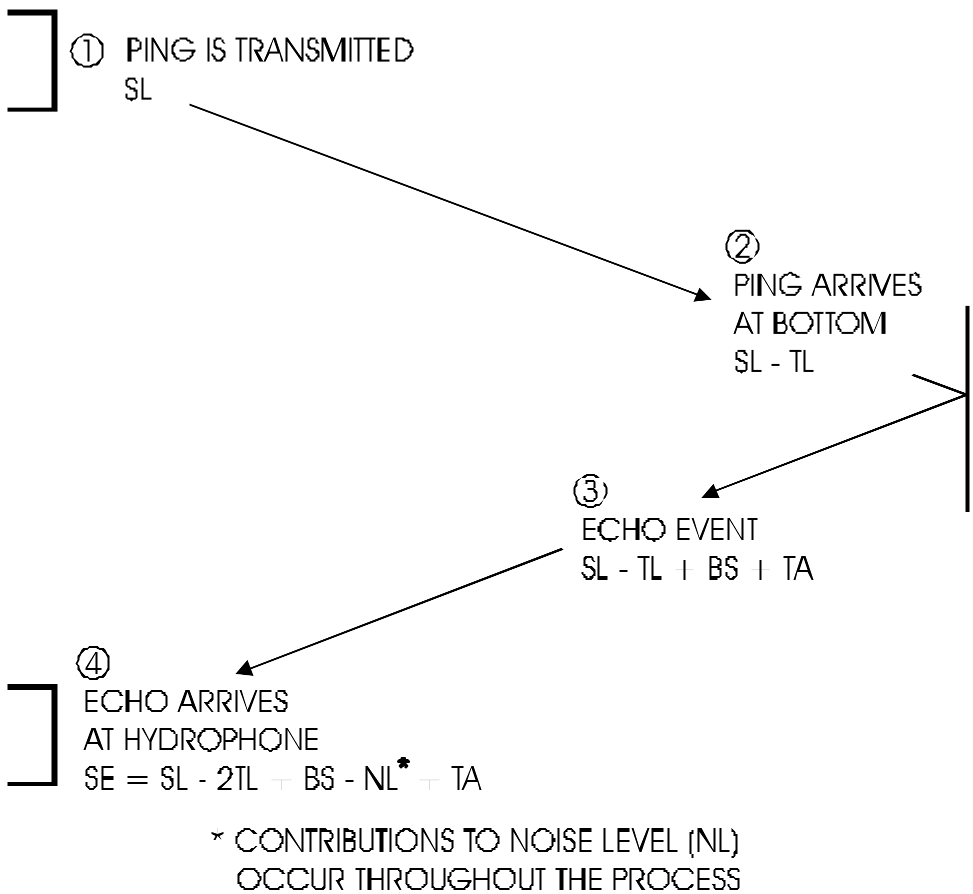

Figure Chapter 2 - -3: Path of a Ping

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*.

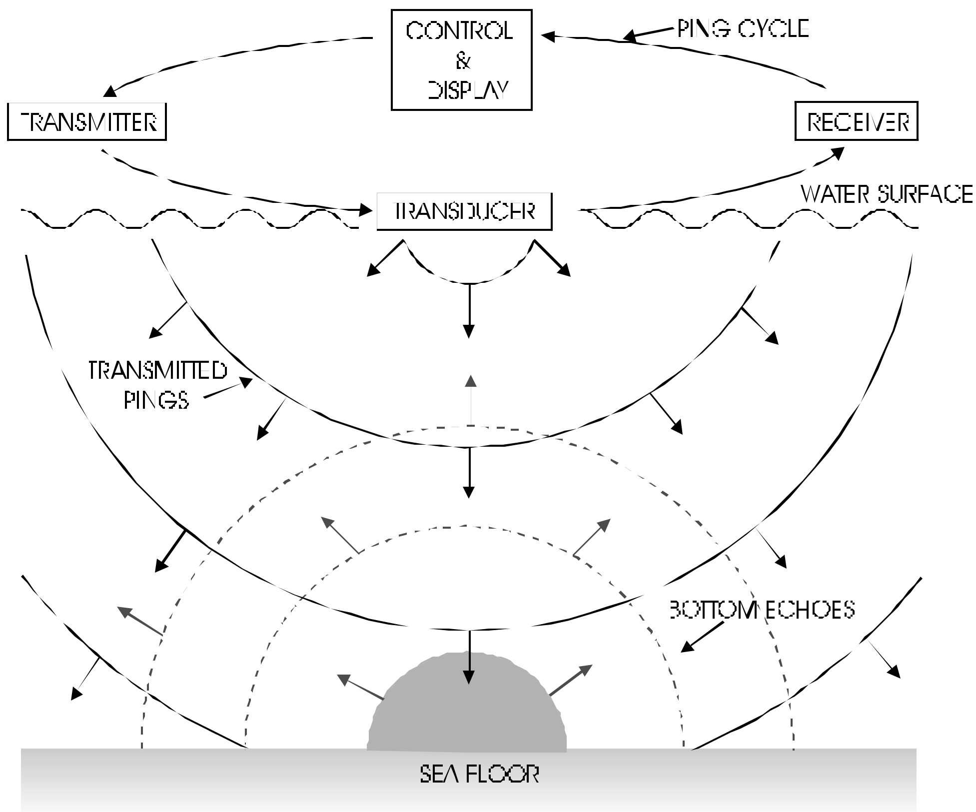

Figure Chapter 2 - -4: Components of a Single-Beam Depth Sounder System

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.

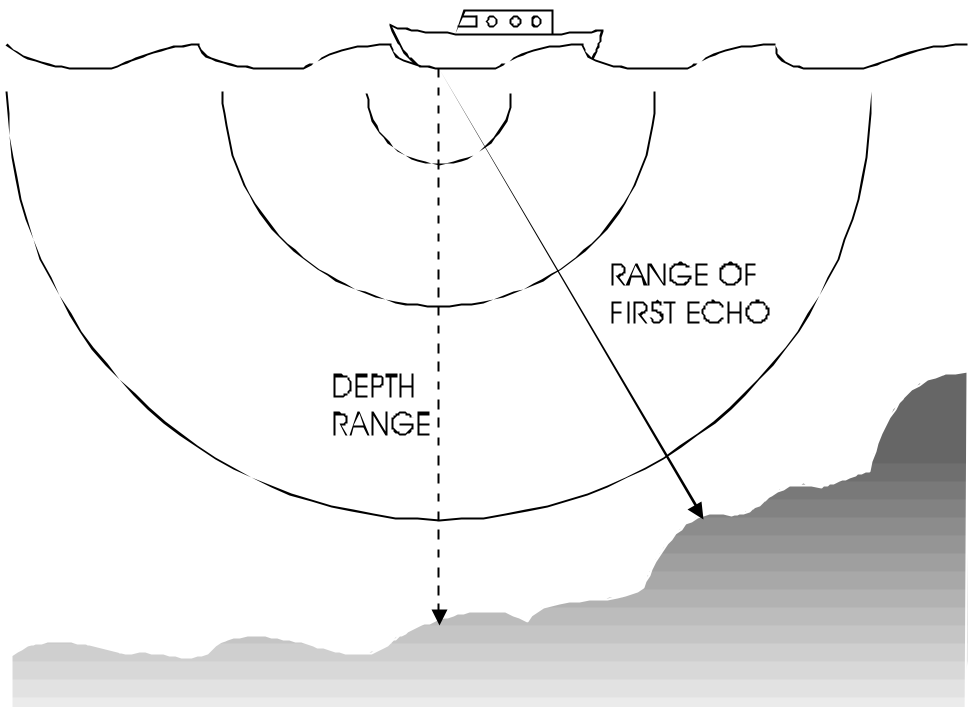

Figure Chapter 2 - -5: Surveying an Irregular Sea Floor

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.

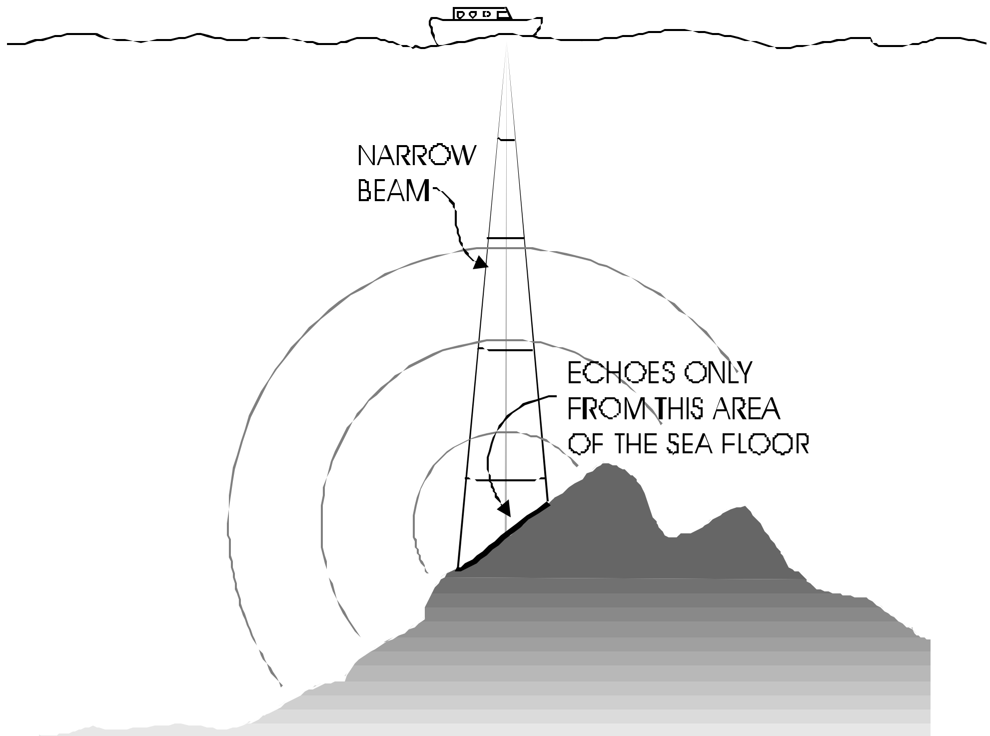

Figure Chapter 2 - -6: Using a Narrow-Beam Echo Sounder on an Irregular Sea Floor

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.

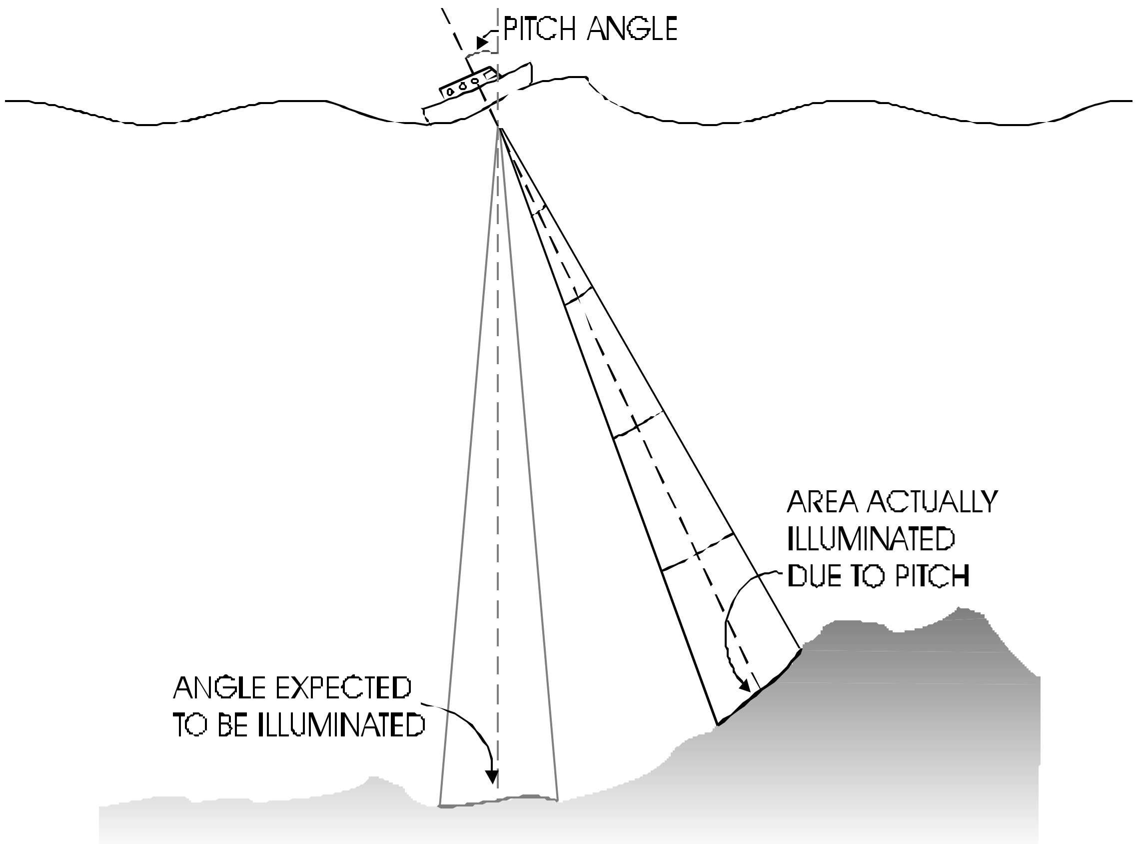

Figure Chapter 2 - -7: Ship Motion Effects on an Unstabilized Beam

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.

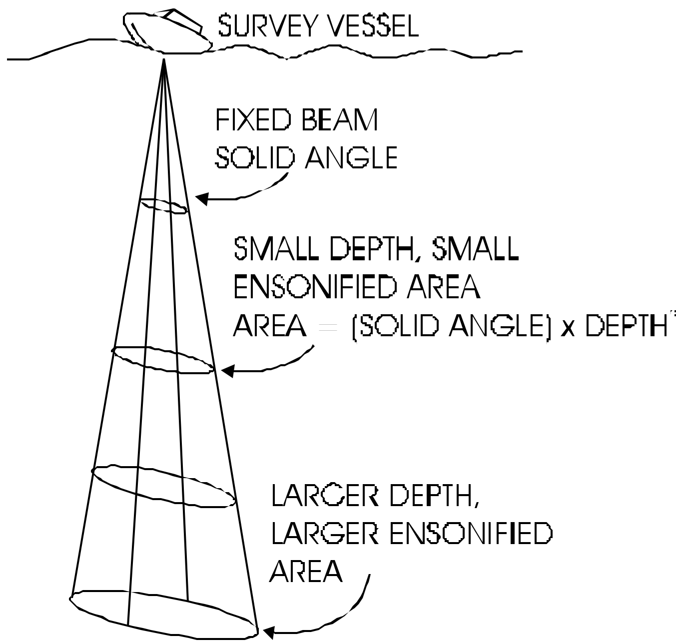

Figure Chapter 2 - -8: Dependence of Ensonified Area on Depth

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.

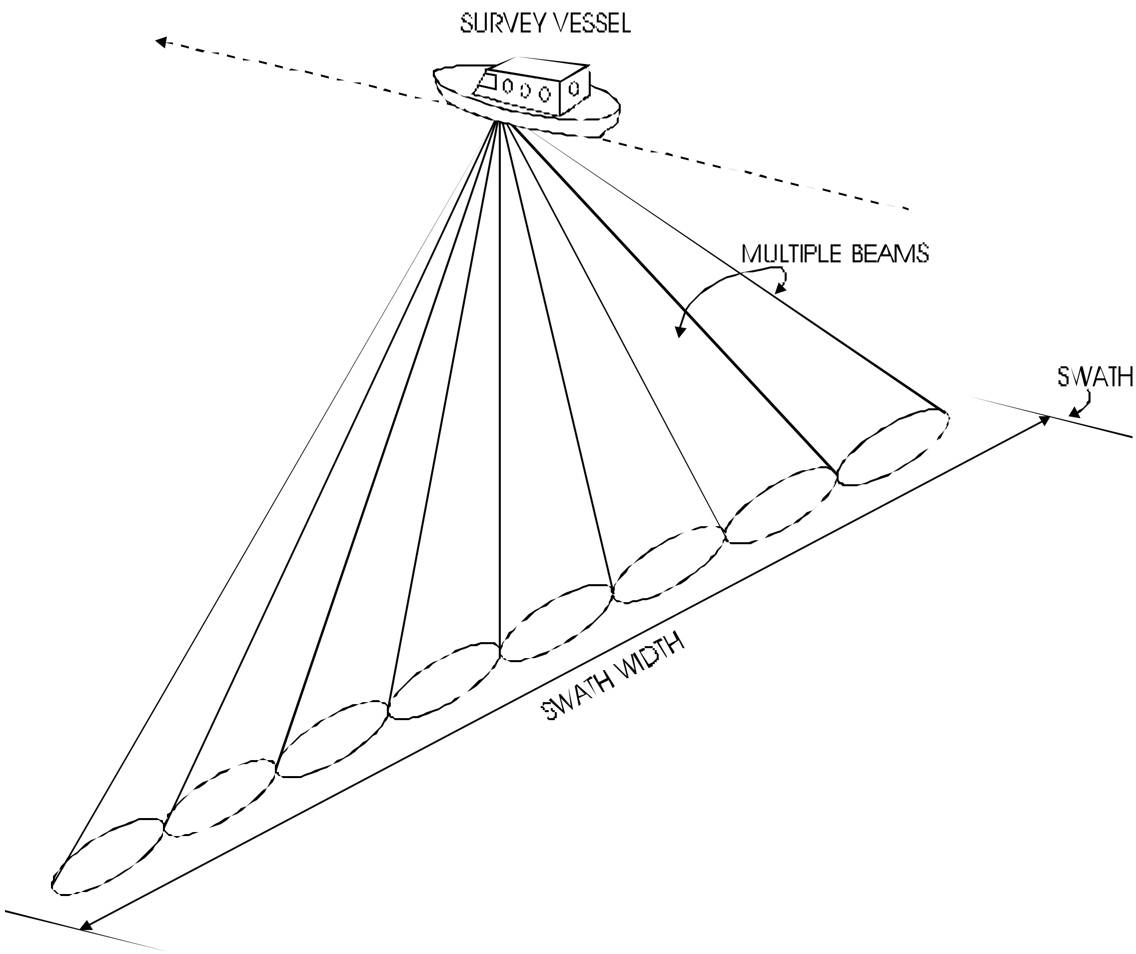

Figure Chapter 2 - -9: Multibeam Sonar Swath

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.

Chapter 3 - Introduction to Multibeam Sonar: Projector and Hydrophone Systems

The previous chapter examined how multibeam sonar can be used to make up for many of the short comings of single-beam sonar. It introduced the concept of directivity and narrow projector beams. This chapter describes how

- groups of projectors, called *projector arrays*, and groups of hydrophones, called *hydrophone arrays*, can be used to produce narrow transmit and receive beams, a process called *beam forming*
- these narrow beams can be targeted at specific angles using *beam steering* processes
- a hydrophone array can be used to simultaneously record sound from many steered beams
- projector and hydrophone arrays are combined in a *Mills Cross* arrangement
- all of these techniques are employed in the SEA BEAM 2100 system

Projector Arrays and Beam Forming

Recall from the section, "A Single-Beam Depth Sounder," in Chapter 2, that a ping from a simple single-beam echo sounder expands spherically with uniform amplitude as it propagates through water, spreading its acoustic energy equally in all directions. This symmetric spreading is called an *isotropic expansion*, and the projector that produces it is called an *isotropic source*. A good example of a wave with isotropic expansion is the circular pattern produced when a small stone is dropped in a quiet pond (see Figure Chapter 3 - -1).

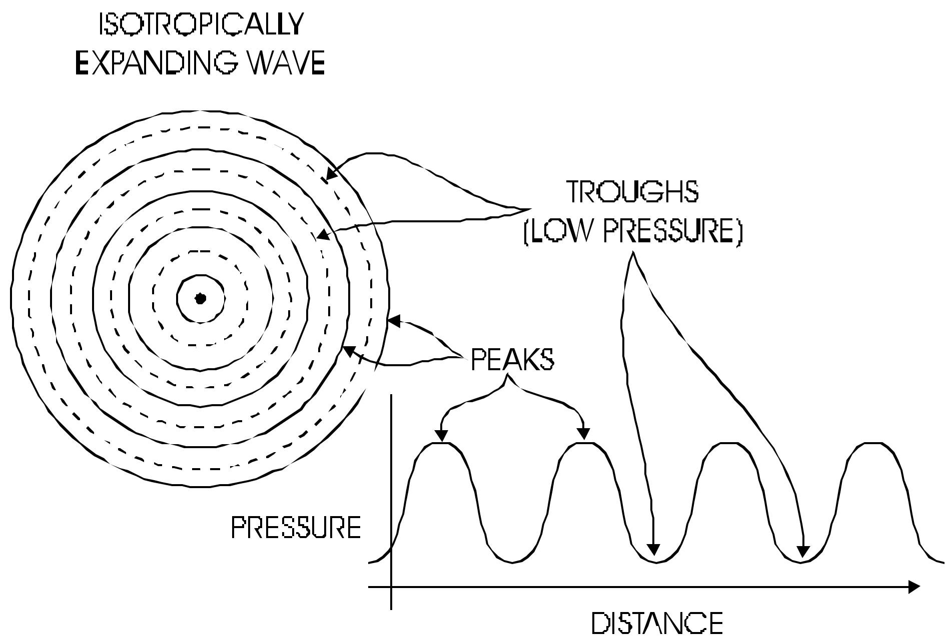

Figure Chapter 3 - -1: Isotropic Expansion

An isotropic source is not ideal for a depth-sounding sonar for two reasons:

- The spherically expanding pulse strikes the ocean floor in all directions. There is no way to determine the direction of the return echoes, so no detailed information about the bottom can be discerned.
- The power of the transmitted pulse is sent equally in all directions, so much of it is squandered, ensonifying areas that may not be interesting.

Fortunately, groups of isotropic sources, called *projector arrays*, can be used to transmit non-isotropic waves or sound waves whose amplitude varies as a function of angular location (still spreading spherically), allowing projected pulses to have a degree of directivity. Directed pulses can be used to ensonify specific areas on the ocean floor, causing stronger echoes from these locations. Ranges can then be found to those locations, generating more detailed information about the bottom.

Recall from the section, "The Physics of Sound in Water," in Chapter 2, that a sound wave is composed of a series of pressure oscillations. The circular solid lines in Figure Chapter 3 - -1 represent high pressure *peaks*. Spaced half-way between these lines are low pressure *troughs* represented by dashed lines. Alone, an ideal single-point projector always produces an isotropically expanding wave. Operating at a constant frequency, it creates a continuous series of equally spaced, expanding peaks and troughs, which look similar to what is pictured in Figure Chapter 3 - -1.

If two neighboring projectors are emitting identical isotropically expanding signals, their wave patterns will overlap and *interfere* with each other. This situation is depicted in Figure Chapter 3 - -2. At some points in the surrounding water, the peaks of the pattern from one projector will coincide with peaks from the other, and will add to create a new, stronger peak. Troughs that coincide with troughs will create new, deeper troughs. This is called *constructive* interference. At other points, peaks from one projector will coincide with troughs of the other and will effectively cancel each other. This is called *destructive* interference.

In general, constructive interference occurs at points where the distances to each projector are equal, or where the difference between the two distances is equal to an *integer* number of wavelengths. Destructive interference occurs at positions where the difference between the distances to the projectors is half a wavelength, or half a wavelength plus an integer number of wavelengths (1.5, 2.5, 3.5, and so forth). If a hydrophone is placed at the positions of constructive interference, a combined wave would be measured with an amplitude twice that of the signals emitted by each projector individually. A hydrophone placed at a position of destructive interference would measure nothing at all. Where are these places?

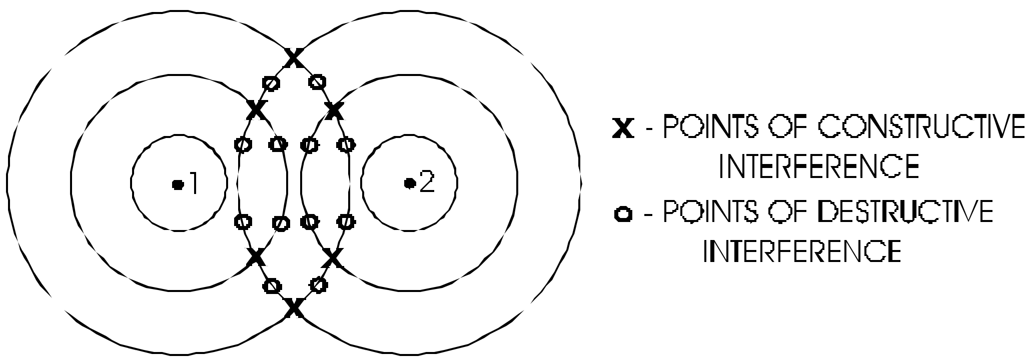

Figure Chapter 3 - -2: Constructive and Destructive Interference

In Figure Chapter 3 - -3, two projectors P_1 and P_2 are separated by a distance d (referred to as the *element spacing*). Consider a point located distance R_1 from P_1 and R_2 from P_2. If this point is located anywhere on the perpendicular bisector of line P_1P_2, then R_1 and R_2 are equal. Any point along this line will witness constructive interference.

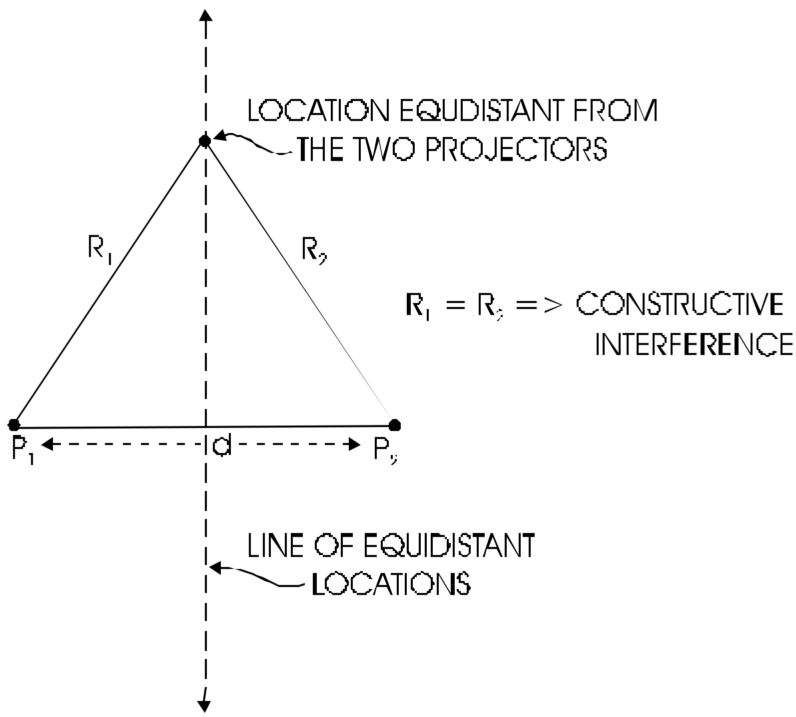

Figure Chapter 3 - -3: Positions of Constructive Interference (Example 1)

The locations of other constructive interference are less obvious, but they can be found with some simple geometry. In Figure Chapter 3 - -4, two projectors P_1 and P_2 again have a spacing d. Consider a point at a location R_1 from P_1 and R_2 from P_2. The direction to this location (labeled R_0 in the figure) intersects a line perpendicular to the spacing d with an angle θ_0. Next, assume that the point you are considering is very far away compared to the spacing of the projectors—meaning that R_1 and R_2 are much larger than d. For a typical operating environment for a sonar, this is a good approximation—projectors are spaced centimeters apart (d = cm) and the ocean floor they are ensonifying is hundreds or thousands of meters away (R_0 = 100 m to 1000 m, meaning R_0/d = 1000 to 10000). This is called the *far field* approximation, and it is necessary to keep computations simple. In this situation, the lines R_0, R_1, and R_2 are treated as parallel, and all intersecting angles θ_0, θ_1, and θ_2 as equal.

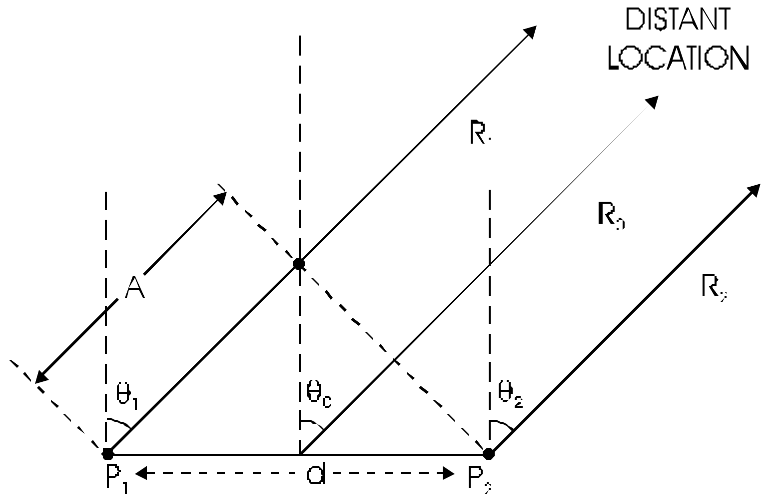

Figure Chapter 3 - -4: Positions of Constructive Interference (Example 2)

The difference between R_1 and R_2 is the line segment labeled A in Figure Chapter 3 - -4. If all angles are equal, this distance is:

$$A = d \times \cos(90 - \theta_0), \tag{3.1}$$

or more simply:

$$A = d \times \sin \theta_0. \tag{3.2}$$

Recall that constructive interference occurs when A is an integer number of wavelengths:

$$A/\lambda = 0, 1, 2, 3, 4, \dots\dots\dots\text{etc.}, \tag{3.3}$$

where λ represents wavelength.

Substituting Equation 3.2 for A:

$$(d/\lambda) \times \sin \theta_0 = 0, 1, 2, 3, 4, \dots\dots\text{etc.} \tag{3.4}$$

Similarly, destructive interference will occur where:

$$(d/\lambda) \times \sin \theta_0 = .5, 1.5, 2.5, 3.5, \dots\dots\text{etc.} \tag{3.5}$$

From these equations you can see that locations of constructive and destructive interference are dependent on the projector spacing d, the wavelength of the sound emitted λ, and the angle θ_0 to the location. Both d and λ remain constant for a typical sonar installation—the only remaining variable is θ_0. This indicates that two projectors in the configuration described will transmit constructively interfering (that is, high amplitude) waves in certain *directions*, while in others it will transmit nothing due to destructive interference. Knowing d in terms of λ, you can determine which directions will have constructive and destructive interference.

A typical sonar spacing *d* is λ/2—half a wavelength—because the angles at which destructive and constructive interference occur are most advantageous. Using *d*/λ = l/2 in the Equations 3.4 and 3.5 yields:

Constructive interference: θ = 0, 180

Destructive interference: θ = 90, 270

So, the two projector arrays will transmit the highest energy sound in the directions θ = 0, 180, and no sound at all in the directions θ = 90, 270 (see Figure Chapter 3 - -5). The emission of this system can be measured with a hydrophone located at different angles around it. At 0 and 180, it measures maximum amplitude, while at 90 and 270 it measures nothing. At angles in between, there is a mix of constructive and destructive interference leading to intermediate amplitudes. By positioning a hydrophone at a set radius and many different angles around a projector array, you can record the amplitude of emitted sound in different directions. Figure Chapter 3 - -6 plots measured amplitude as a function of angle for a two projector array. Figure Chapter 3 - -6 is a polar plot—amplitudes are measured along radial lines from the center. The amplitude plot is what is known as a *beam pattern*, or *array pattern* (and sometimes a *power pattern*). It clearly shows that the bulk of the energy emitted by the two projector array propagates perpendicular to the axis of separation of the projectors.

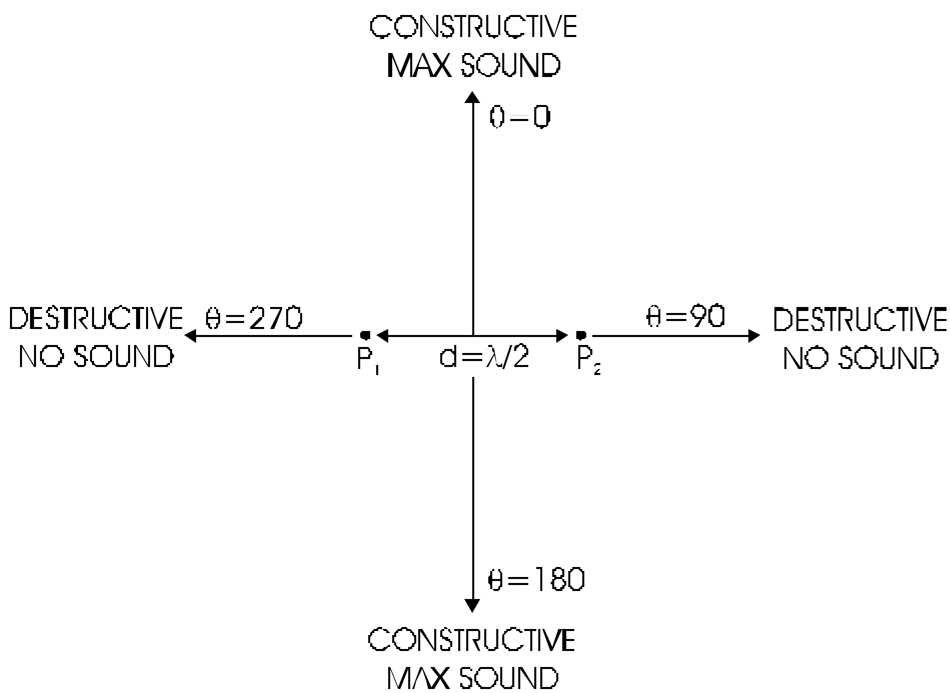

Figure Chapter 3 - -5: Directions of Constructive and Destructive Interference for Two Projectors with Spacing l/2

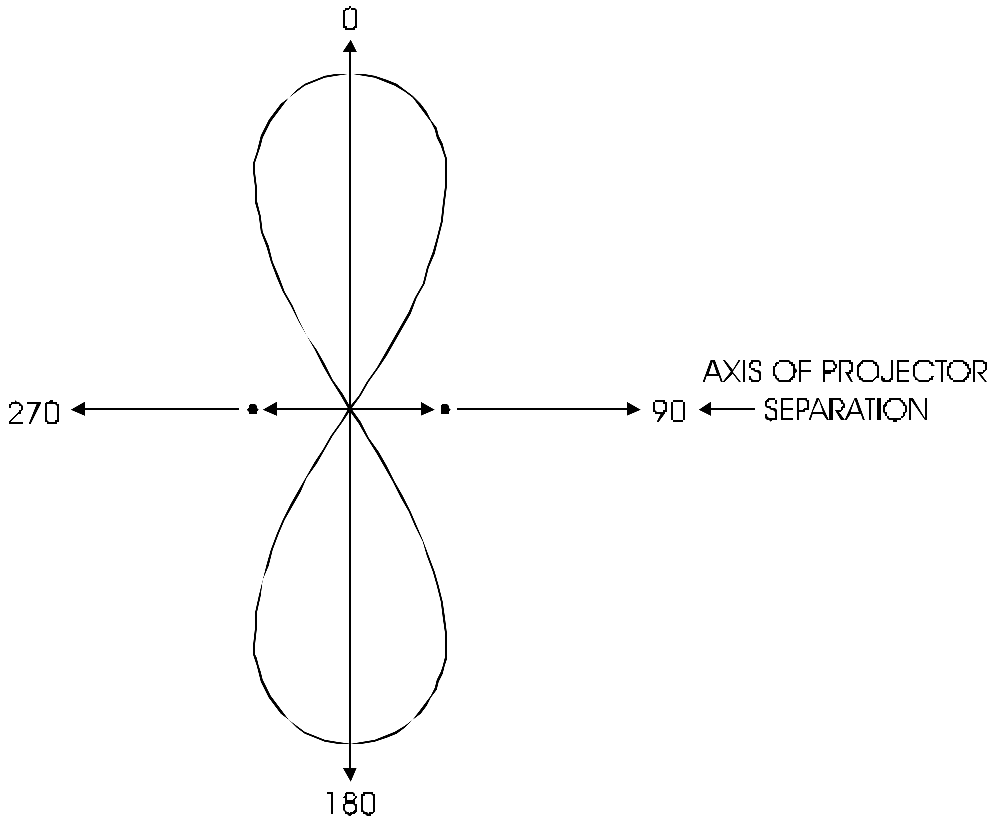

Figure Chapter 3 - -6: Beam Pattern for Two Hydrophones with Spacing l/2

Remember that projectors operate in a three-dimensional environment. To accurately represent the beam pattern of a two-projector array, Figure Chapter 3 - -6 should be rotated around the axis of separation of the projectors, about which it is symmetric (see Figure Chapter 3 - -7). Because three-dimensional drawings of beam patterns are difficult to interpret, the patterns are usually drawn in two-dimensions. For those beam patterns with an axis of symmetry, a two-dimensional drawing provides a complete description. More complex patterns that are not symmetric about an axis are usually represented by multiple drawings showing the cross-section of the pattern at different angles.

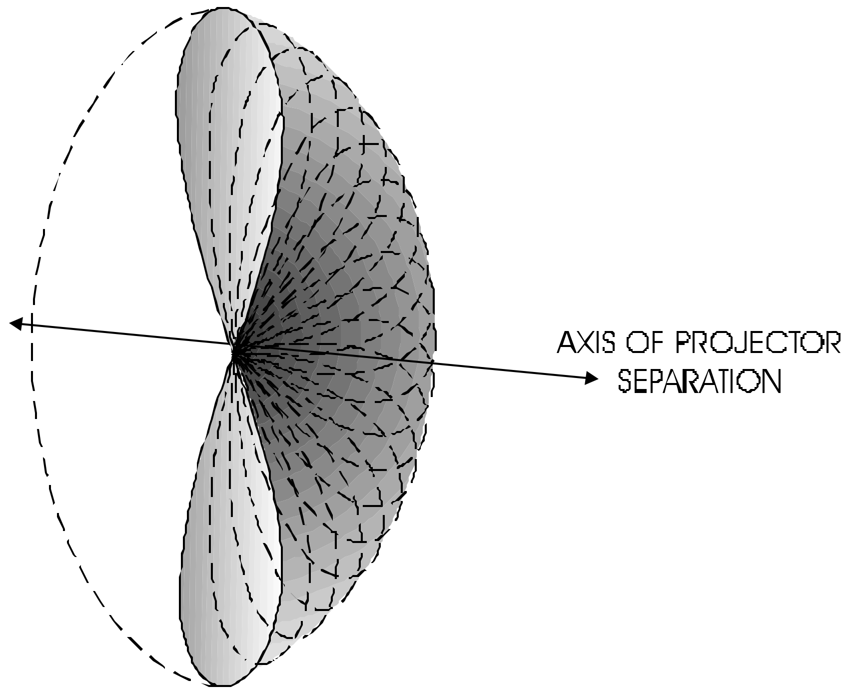

Figure Chapter 3 - -7: Three-Dimensional Beam Pattern for Two Projectors with Spacing l/2

One useful way of interpreting Figure Chapter 3 - -6 is as a plot of the angles at which the energy of an acoustic pulse is directed. In the figure, the highest level of acoustic energy is directed perpendicular to the axis of projector separation. Objects in these directions are ensonified with the most energy and return the strongest echoes. Objects in other directions return significantly weaker echoes. This selective projection of energy is called *directivity*. The beam pattern provides a measure of the directivity of a system—projector arrays that direct the bulk of their energy at a very narrow range of angles are said to have a high directivity.

Real projector arrays generally have more than two projector elements and have complex beam patterns. One common array configuration is a simple extension of the two projector array—an arrangement of many projectors in a straight line called a *line array*. The beam pattern of a multiple-element line array is pictured in Figure Chapter 3 - -8. Although detailed mathematics are required to compute this pattern, it is essentially just an extension of the reasoning used to find the two-projector array pattern. This complex beam pattern can be used to point out the features of all such patterns.

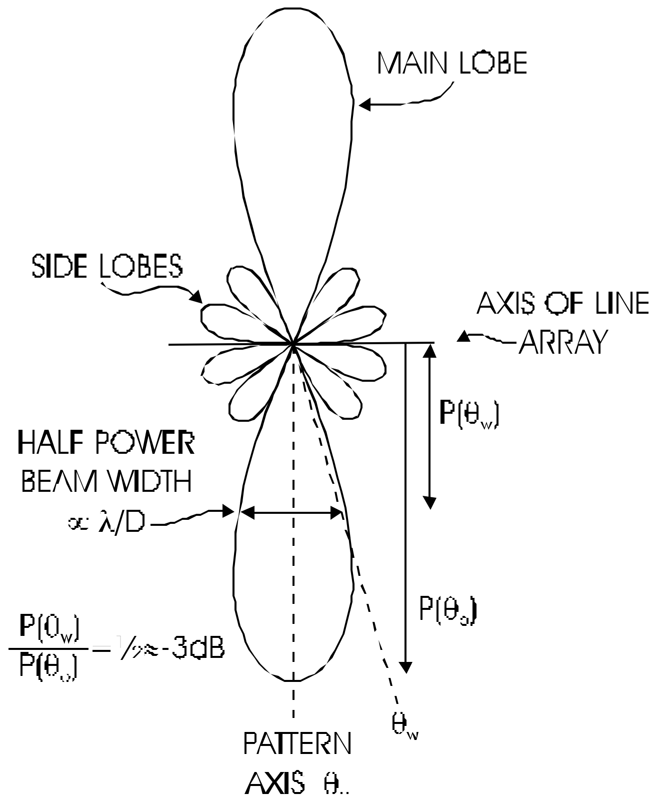

Figure Chapter 3 - -8: Beam Pattern of a Multiple-Element Line Array

The bulk of the energy in the line array beam pattern is in what is called the *main lobe*. The direction of the peak energy projection—the center of the main lobe—is called the *maximum response axis* (MRA) of the beam pattern. The *width* or *beam solid angle* of the main lobe, which is a measure of the pattern's directivity, is twice the angle from the axis to the *half power point* on the pattern—the angle at which the projected power is exactly half that of the axis. This is referred to as the beam width measured to the -3 dB point, where the projected power is -3 dB that of the axis (these points are almost equal, as -3 dB corresponds roughly to 1/2).

The main lobe of the line array pattern is narrower than that of the two-projector array pattern. In general, the larger an array or projector system is in a dimension, the narrower the main lobe of the beam it projects in perpendicular directions will be. A good first approximation for the width of the main lobe of a pattern of a system with size D (which can be the physical size of the transducer in a single-projector system, or $(N - 1) \times d$, the total length of N elements in an array with spacing d) transmitting at a wavelength λ is:

$$\text{half power beam width (degrees)} = 50.6 \times \lambda/D \qquad (3.6)$$

Equation 3.6 illustrates some of the design considerations involved in building a sonar system. If a high-resolution sonar system is desired, a narrow beam is needed. The width of the beam can be reduced by building larger projectors and arrays, but there are physical limits on both. Alternatively, shorter wavelengths can be used. However, shorter wavelength sound, which is also higher frequency, suffers greater attenuation in water as discussed in the section “The Physics of Sound in Water.” The attenuation can be compensated for by raising the transmitted power, but there are limits to the amount of power a single projector can cleanly transmit into water.

On either side of the main lobe are a series of *side lobes* where partial constructive interference takes place. In general, the purpose of the array is to ensonify targets in the direction of the main lobe. The side lobes are an annoyance—not only is some of the projector energy being squandered in these directions, but there might be echoes from them as well, and these may be confused with the echoes from the target in the main lobe. The nearest set of side lobes on either side of the main lobe are called the *first side lobes*, and subsequent sets are called the second side lobes, third side lobes, and so on. The strength of side lobes is measured as a fraction of the power projected into them divided by the power projected into the main lobe, and is called the *side lobe level*. These numbers are given in dB. For an array in which all projectors emit the same power level, the first side lobe level is roughly -13 dB.

Side lobes in the beam patterns of projector arrays are unavoidable, although the energy that is projected into them can be reduced by projecting stronger signals from the individual elements in the center of an array than from those on the edges. This technique is called *shading*, and the fraction of energy that is projected by each projector element divided by the energy projected by the peak element is called its *shading value*. There are a variety of algorithms used to determine what shading values should be applied to each array element. Different combinations of shading values produce different side lobe structures. One popular shading scheme, called *Dolph-Chebyshev* shading, can be used to bring all side lobe levels to a uniform value. In theory, this side lobe level can be any value, but practical considerations limit side lobe reduction generally to a maximum of -40 dB. Although it can be used to reduce the side lobes, shading also causes the width of the main lobe to be larger, decreasing the directivity of the system (and nullifying some of the advantage of the large array). A comparison of the approximate widths of the main lobes of different array sizes both unshaded (-13 dB first side lobe levels) and with Chebyshev shading to obtain -35 dB side lobe levels is given in Table Chapter 3 - -1. Discovering the proper balance of shading, array size, and array elements that yields high directivity with minimal side lobes is a complex art.

Table Chapter 3 - -1: Main Lobe Width Comparisons

	Beamwidth	
Array Elements	**Unshaded**	**Chebyshev (-35 dB)**
20	5.1°	6.8°
40	2.5°	3.3°
48	2.1°	2.8°
80	1.3°	1.6°
96	1.1°	1.4°

Hydrophone Arrays

The previous section described how arrays of projectors can be used to generate narrow beams of sound that will ensonify small patches of the sea floor. Hydrophones as well as projectors can be formed into arrays. Where projector arrays transmit sound into narrow beams, hydrophones arrays are used to receive sound from narrow beams.

It is easy to see how this works. In Figure Chapter 3 - -9 through Figure Chapter 3 - -14, a line array of hydrophones is examined in two situations. In Figure Chapter 3 - -9, a source perpendicular to the axis of the line array is producing sound waves. The source of these sound waves is in the far field, such that the wave fronts striking the hydrophone array are a series of parallel lines. Each hydrophone in the array is making an independent measurement of the wave. The signal measured by each hydrophone as a function of time can be plotted in what is called a signal *trace*. Figure Chapter 3 - -10 shows signal traces for three of the hydrophones. Because the parallel waves are striking these hydrophones at exactly the same time, these three plots are identical—measured peaks and troughs occur at the same times. The three measurements are said to be *in phase*. Summing the three hydrophone traces results in a trace with the same frequency but three times the amplitude (pictured in Figure Chapter 3 - -11)—the measurements of the three hydrophones add *constructively*. Collectively, the hydrophone array is highly sensitive to sounds from this direction.

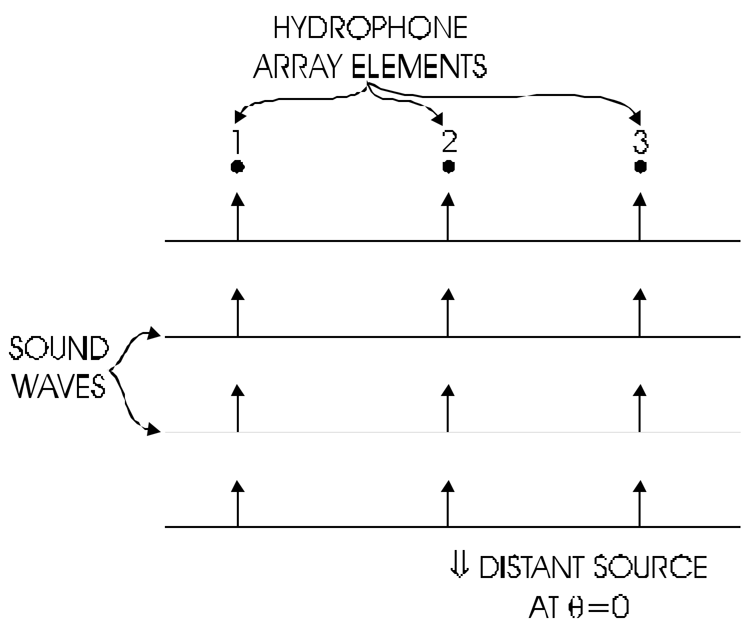

Figure Chapter 3 - -9: Hydrophone Array with a Perpendicular Source

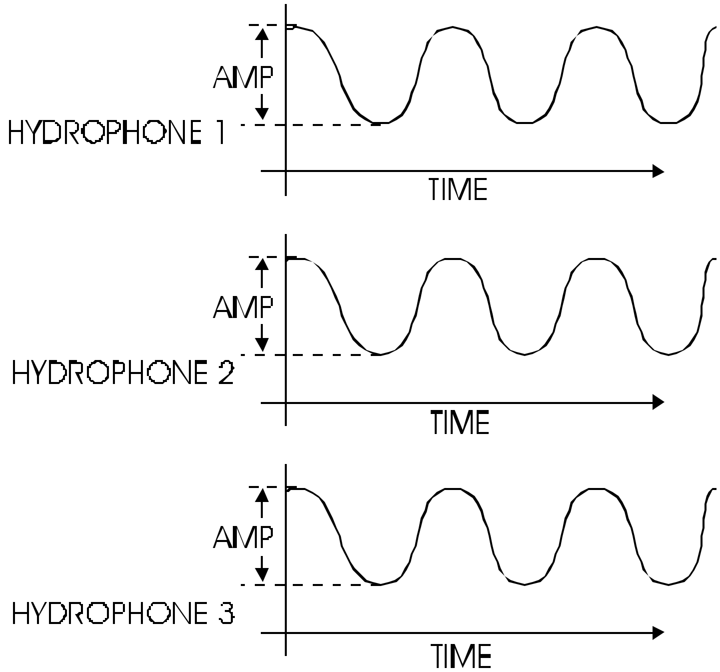

Figure Chapter 3 - -10: Hydrophone Traces for a Perpendicular Source

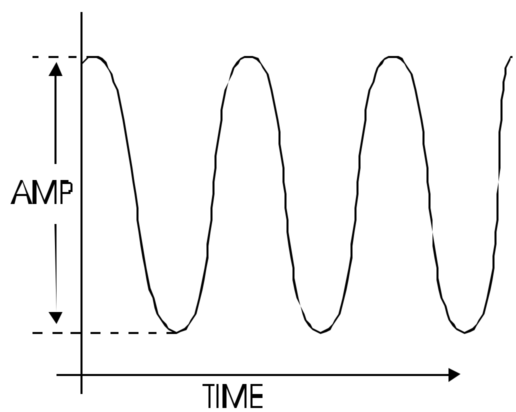

Figure Chapter 3 - -11: Sum of Hydrophone Traces for a Perpendicular Source

Figure Chapter 3 - -12 shows the same hydrophone array receiving sound waves from a source at an angle θ off the perpendicular. Due to the angle of the source, the parallel waves from this source strike the hydrophones in the array at different times. This causes the hydrophone traces to look different—peaks and troughs occur at different times as pictured in Figure Chapter 3 - -13. The three measurements are said to be *out of phase*. The sum of the three hydrophone traces has peaks and troughs eliminating each other—they add *destructively* (see Figure Chapter 3 - -14). Collectively, the hydrophone array is not sensitive to sounds from this direction.

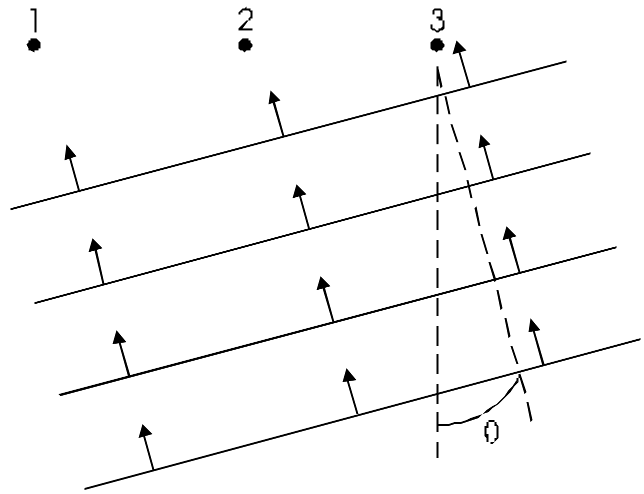

Figure Chapter 3 - -12: Hydrophone Array with Waves from an Angled Source

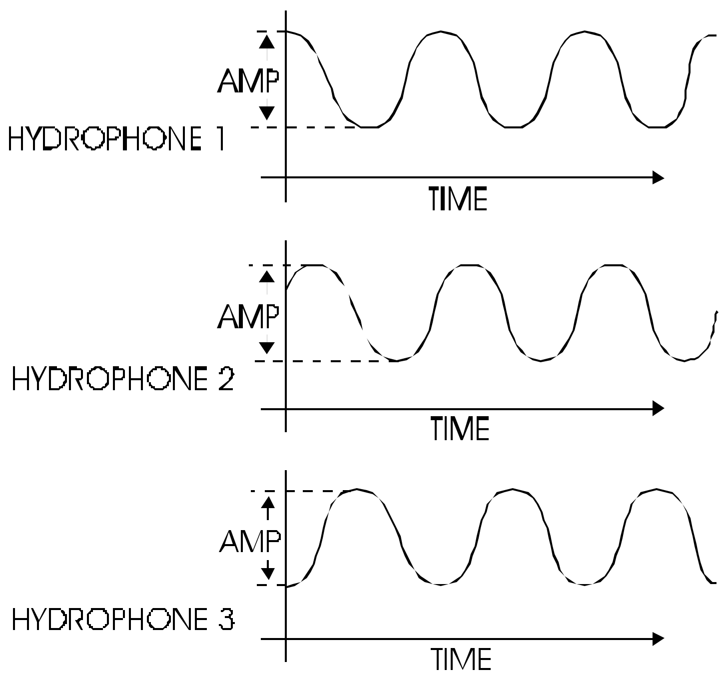

Figure Chapter 3 - -13: Hydrophone Traces for an Angled Source

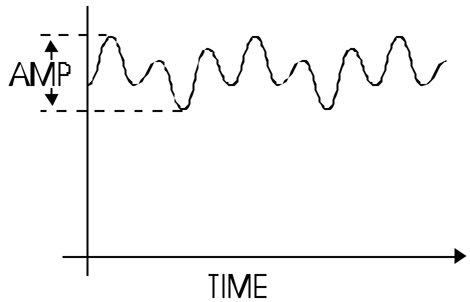

Figure Chapter 3 - -14: Sum of Hydrophone Traces for an Angled Source

Placing a projector at many distant (far field) points around the hydrophone array, and recording the sum of what the hydrophone elements measure, generates a familiar pattern. Figure Chapter 3 - -15 shows the pattern that would result from such a series of measurements for a line array of hydrophones. As in the case of the projector arrays, these pictures, called beam patterns, share many of the same features and terminology associated with projector arrays—main lobes, side lobes, axis, shading, and beam widths are all defined the same way. In fact, if you were to measure the beam patterns of an array of transducers operating as a projector array and then as a hydrophone array (recall that they can act as both), the patterns would be identical. This is called the *principle of reciprocity* because the hydrophone arrays follow exactly the same rules that projector arrays do.

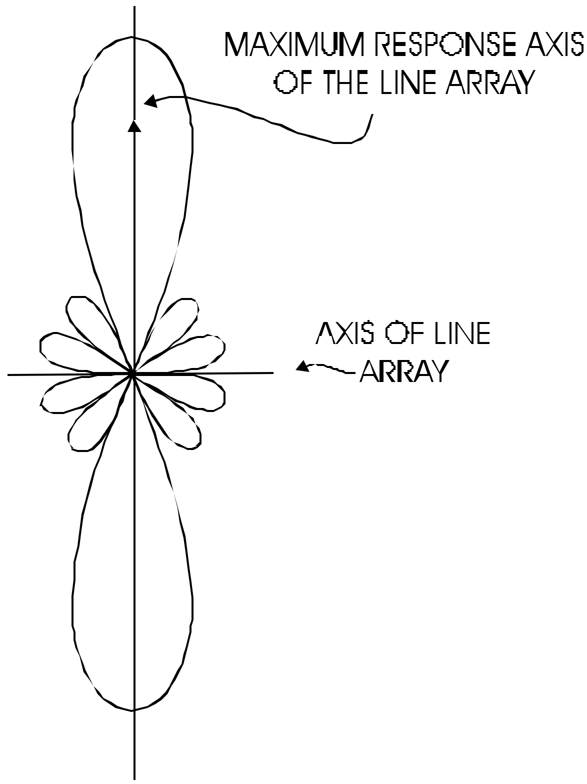

Figure Chapter 3 - -15: Beam Pattern for a Line Array of Hydrophones

In short, the important points to remember about the beam patterns of both projector and hydrophone arrays are the following:

- The larger an array is in a dimension, the narrower its main lobe will be in the plane perpendicular to that dimension.
- The width of the main lobe is measured at the half power point.
- Side lobes are undesirable, but unavoidable.
- Side lobes can be reduced through techniques such as shading at the cost of widening the main lobe.
- The beam pattern of a transducer array acting as projectors is the same as that of it acting as hydrophones.

Beam Steering

The previous section described how an array of hydrophones can be used to receive sound preferentially from specific perpendicular directions. This section describes how an array can be altered to receive preferentially from any of a number of directions. This technique is called *beam steering*. Effectively, it allows the angle of the axis of the beam pattern, pictured in Figure Chapter 3 - -15, to be changed.

Consider, once again, a line array receiving sound from an arbitrary angle θ off the perpendicular (see Figure Chapter 3 - -16). Recall that the sound from this angle arrived at the elements of the hydrophone array out of phase, causing the signals at the different hydrophones to add destructively. The reason for this is that the sound waves must travel different distances to reach each hydrophone. In Figure Chapter 3 - -16, sound waves first strike the hydrophone labeled 3. They must travel the distance labeled *A* before reaching hydrophone 2, and distance *B* before reaching hydrophone 1. These distances can be computed using the spacing between the hydrophones (both assumed in this case to equal *d*, although this is by no means a requirement):

$$A = d \times \sin\theta \qquad (3.7)$$

$$B = 2d \times \sin\theta$$

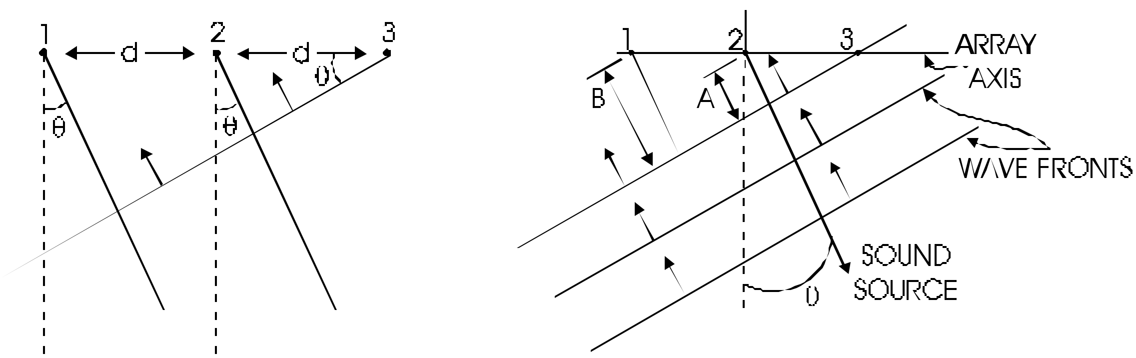

Figure Chapter 3 - -16: Wavefronts Striking a Hydrophone Array from a Source at Angle q

The extra times required for the wave front to reach each hydrophone are given by the distances divided by the local sound speed *c*:

$$T_2 \text{ (time to hydrophone 2)} = A / c = (d \sin\theta) / c \qquad (3.8)$$

$$T_1 \text{ (time to hydrophone 1)} = B / c = (2d \sin\theta) / c$$

Knowing these time differences you can cause the hydrophone array to have maximum sensitivity at angle θ by summing the individual hydrophone readings slightly offset in time such that the wave fronts constructively interfere. In this example, you would sum the reading of hydrophone 3 with the reading of hydrophone 2 delayed by T_2 and the reading of hydrophone 1 delayed by time T_1. This is called introducing a *time delay*. It causes the main lobe of the beam pattern to shift such that its axis is at angle θ from the perpendicular (see Figure Chapter 3 - -17). By applying time delays, or alternatively equivalent *phase delays* to hydrophone readings and summing them (a concept covered in the description of SEA BEAM 2100 processing), an array can be “steered” to maximize its sensitivity to any angle θ.

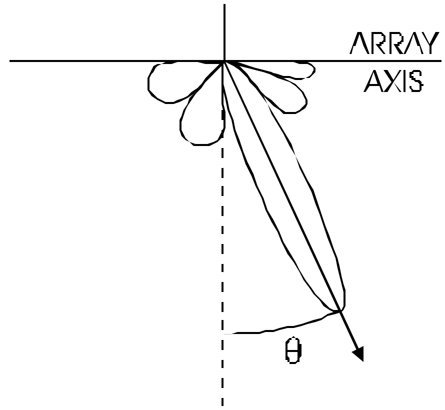

Figure Chapter 3 - -17: Main Lobe Shifted to Angle q **by Introducing a Time Delay**

Note that in steering a hydrophone array to be sensitive to a particular angle, nothing about the array itself is changed—only the interpretation of the data it records is altered. By changing the data processing, the same array can be steered to observe any of a large range of angles. In fact, using the same recorded data from the elements of the hydrophone array, different data processing can be used to examine the sounds coming from different angles *simultaneously*. In this way, a hydrophone array can be used to examine the echoes from a single ping at many different locations.

The product of this process—the series of beam-steered traces $B_{\theta 1}(t)$, $B_{\theta 2}(t)$, ... $B_{\theta M}(t)$—can be treated as a series of independent measurements of signals from different angles between θ_1 and θ_M. Effectively, beam steering is used to create a series of “virtual” hydrophone arrays, each sensitive to a different angle (see Figure Chapter 3 - -18).

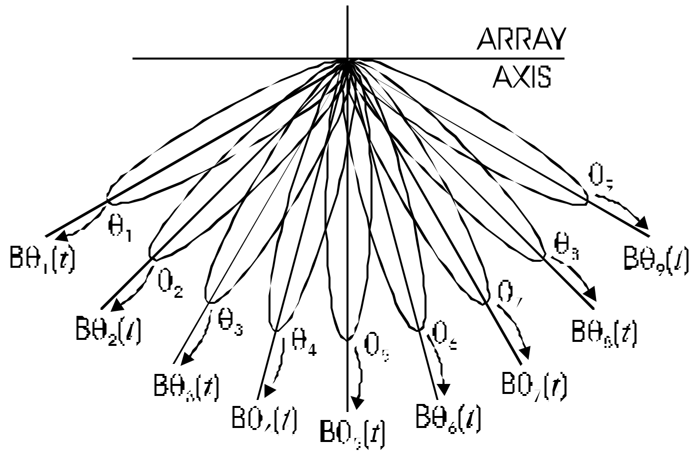

Figure Chapter 3 - -18: Hydrophone Array Processing Used to Observe Different Beam Patterns Simultaneously

The Mills Cross Technique

Recall that each of the beam patterns in Figure Chapter 3 - -8, Figure Chapter 3 - -15, Figure Chapter 3 - -17, and Figure Chapter 3 - -18 are two-dimensional representations of three-dimensional patterns. The true beam pattern in each of these situations can be seen by rotating the figure about the axis of the line array (see Figure Chapter 3 - -6 and Figure Chapter 3 - -7). A projector line array transmits sound preferentially in all directions perpendicular to the axis of the array, ensonifying a strip of the ocean bottom (see Figure Chapter 3 - -19). Similarly, a hydrophone array aligned parallel to the projector array receives echoes from all locations along a similar strip of the ocean floor. If you want to accurately locate echoes on the ocean floor, this is not very useful! The projector array will cause echoes all along the ensonified strip, and the hydrophone array will pick up echoes from a similar strip. There will be no way of telling where the echoes are occurring along these strips.

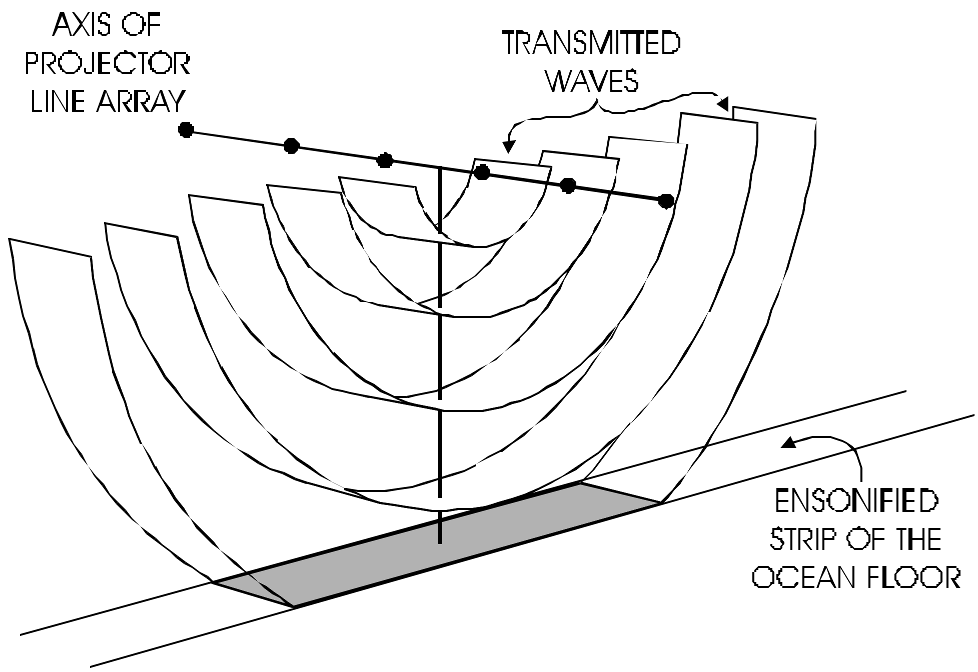

Figure Chapter 3 - -19: Projector Array Ensonifying a Strip of the Ocean Floor

If, however, the projector and hydrophone arrays are perpendicular to each other, the strip of the ocean floor ensonified by the projectors will intersect with the strip of the ocean floor observed by the hydrophones. This occurs in only a small area with dimensions that correspond approximately to the projector and hydrophone array beamwidths (see Figure Chapter 3 - -20). While echoes occur along the entire ensonified area, and sound may be received from the entire observed area, the only part of the bottom both ensonified by the projector array and observed by the hydrophone array beam is the area where the two strips overlap. The amplitude trace from the hydrophone array will contain only those echoes from the transmitted ping that occur in this area. The perpendicular arrangement of the projector and hydrophone line arrays is called a *Mills Cross*, named after a pioneering radio astronomy instrument built in New South Wales, Australia.

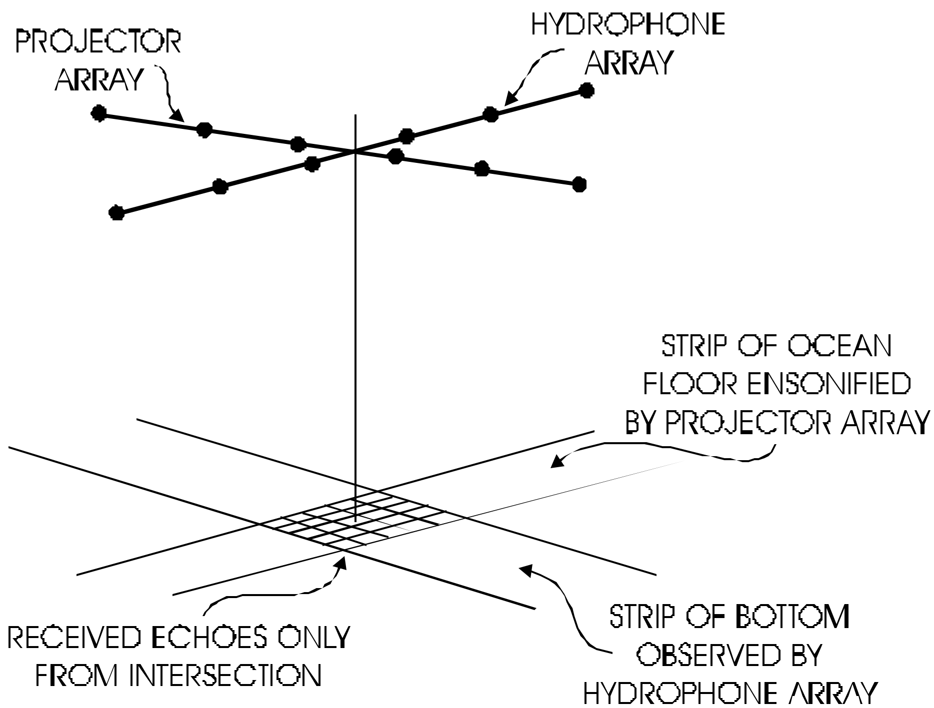

Figure Chapter 3 - -20: Projector and Hydrophone Arrays Arranged in a "Mills Cross"

Recall that beam steering can be used to observe echoes generated from multiple angles with the hydrophone array. These different angles observe parallel strips of the bottom, which in the Mills Cross arrangement, will intersect with the ensonified area in a series of small patches (see Figure Chapter 3 - -21). In this way, the multiple steered beams can be used to receive the echoes from discrete locations all along the ensonified area, allowing the sonar to determine ranges to a strip of locations with each ping. This technique is used by all modern multibeam sonar systems.

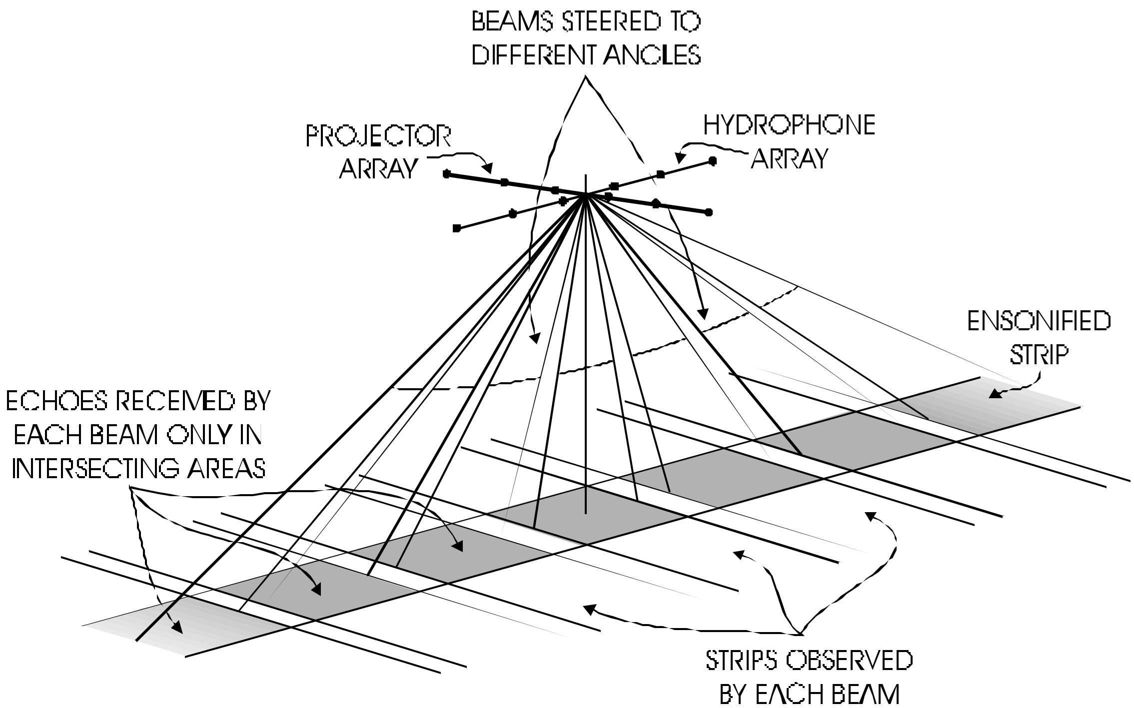

Figure Chapter 3 - -21: Mills Cross with Multiple Steered Beams

The Mills Cross Applied in the SEA BEAM 2100 System

The SEA BEAM 2100 multibeam sonar utilizes the Mills Cross technique to produce high-resolution maps of the ocean floor. This section describes the projector and hydrophone array configurations used by the 2100, the beams formed by those systems, and how beam steering is accomplished.

The SEA BEAM 2100 Projector and Hydrophone Arrays

The SEA BEAM 2100 12 kHz projector system consists of a line of 10 to 14 projector elements mounted along the keel of its survey vessel. Because it is far longer in the *alongtrack* direction (parallel to the ship's keel and its direction of motion) than in the *acrosstrack* or *athwartship* direction (perpendicular to the ship's keel), the complete projector array is similar to a line array. It projects a beam that is narrow in the alongtrack direction (roughly 2 degrees), and wide in the acrosstrack direction, illuminating a wide swath of the bottom. Dolph-Chebyshev shading techniques are used to even the illumination in the acrosstrack direction, reducing side lobe levels to between -25 and -30 dB, depending on the number of projector elements. A cross-section of the beam pattern of the SEA BEAM 2100 projector array at 12 kHz is depicted in Figure Chapter 3 - -22. This pattern has been tailored such that more energy is directed towards the wide acrosstrack directions where return signals usually arrive with lower signal-to-noise levels. Less energy is directed near the vertical where backscattering strengths are usually high and travel distances are shorter.

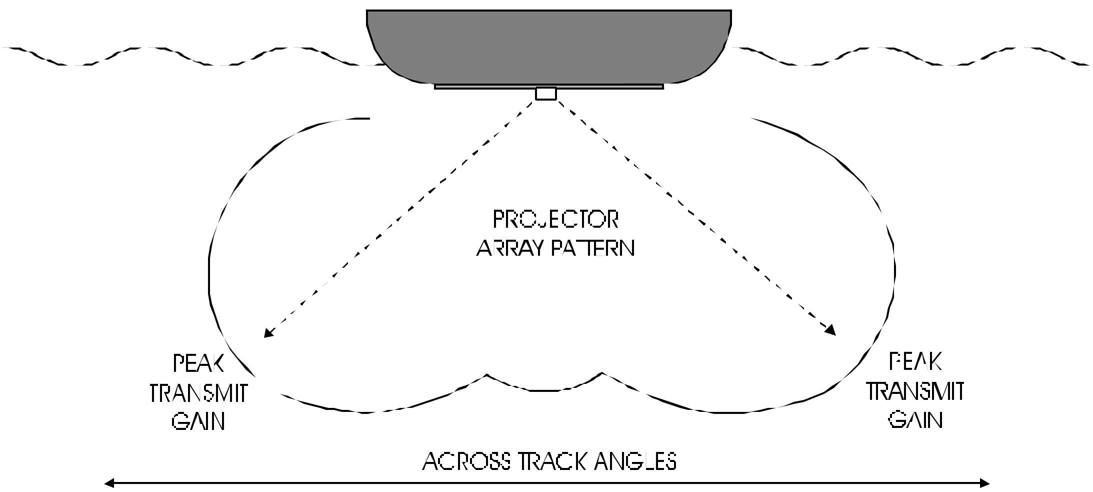

Figure Chapter 3 - -22: Projector Array Pattern

The SEA BEAM 2100 hydrophone array is mounted in the athwartship direction, forming the Mills Cross. It consists of between 48 and 80 hydrophones, depending on the installation, and can either be mounted in a "flat" configuration if the survey vessel has a flat bottom, or in a "V" configuration if the survey ship has v-shaped bottom (see Figure Chapter 3 - -23). In the flat configuration, the received echoes of the entire array are processed together, while in the "V" configuration the two sides of the array are processed separately. The reasons for this are related to the high-speed data processing shortcuts used in beam steering.

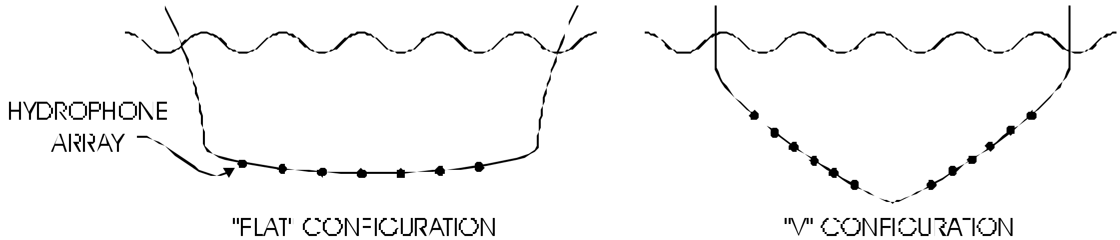

Figure Chapter 3 - -23: "Flat" and "V" Configurations for Hydrophone Arrays

SEA BEAM 2100 Beam Steering

The data from the hydrophones is used to form a maximum of 151 steered beams, which have beam widths in the athwartship direction of approximately 2 degrees, and spacing of roughly 1 degree between their axes. Beam steering is accomplished through digital signal processing.

Each element *i* of the *N* elements of the hydrophone array (*N* for the SEA BEAM 2100 is between 48 and 80) records a signal trace $S_i(t)$. It is important to understand the relationship between the measurement $S(t)$ and the amplitude $A(t)$ of a signal. The amplitude $A(t)$ measures the change in signal strength. It does not measure the oscillations of a wave that are observed by instantaneous measurements. Consider the signal segment pictured in Figure Chapter 3 - -24.

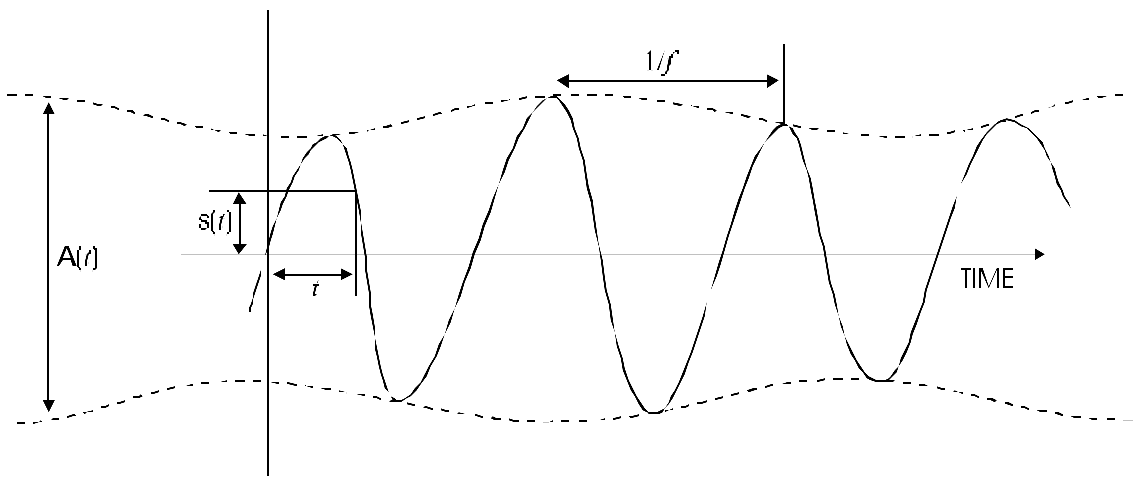

Figure Chapter 3 - -24: Instantaneous Measurements $S(t)$ of a Signal with Amplitude $A(t)$

The amplitude $A(t)$, which changes with time, is represented by the dashed lines. Within the envelope of the changing amplitude, the signal oscillates with its frequency f.

$S(t)$ is an instantaneous measurement of this signal made at time t. Knowing the frequency of the signal and its amplitude $A(t)$ at time t, the instantaneous signal measurement is given by:

$$S(t) = A(t) \cos(2\pi f t) \tag{3.9}$$

This equation can be rewritten in terms of the phase $\phi(t)$ of the signal at time t:

$$S(t) = A(t)\cos(\phi(t)) \tag{3.10}$$

where:

$$\phi(t) = 2\pi ft \tag{3.11}$$

or equivalently:

$$S(t) = A(t)e^{j\Phi(t)} \tag{3.12}$$

The phase $\phi(t)$ is simply a measure of where a signal is in its oscillations. An instantaneous measure of a signal will yield $S(t)$, as described above, but what you are really interested in is $A(t)$, the amplitude. If measurements of $S(t)$ and $\phi(t)$ are made simultaneously, $A(t)$ can be extracted using Equation 3.12.

The SEA BEAM 2100 measures both signal strength $S(t)$ and phase $\phi(t)$. Both pieces of information are converted from continuous analog signals to a series of discrete digital measurements through the analog-to-digital converters. These measurements are made at the *sampling rate*, which is between 1 and 3 milliseconds. All of the signal and phase data for all hydrophones from one of these samples is called a *time slice*.

To form a steered beam, the signals from the hydrophones $S_1(t)$ through $S_N(t)$ must be combined with the correct adjustments for the path differences between different elements. Recall from Equation 3.7 that the path difference of a signal from steered beam angle θ between two elements of an array spaced d apart is given by:

$$d \sin\theta \tag{3.13}$$

If the N hydrophones are numbered $i = 0$ through $i = N - 1$, the path differences required to properly combine the signals of each are given by:

$$id \sin\theta \tag{3.14}$$

For computational purposes, it is easier to speak in terms of the *phase difference* between hydrophone elements rather than the path difference. The phase difference is a measure of the fractional number of wave oscillations that occur in the path difference. The phase difference in one complete oscillation or cycle is 2π. The fractional difference in phase caused by the path difference $id \sin\theta$ is given by:

$$\frac{2p}{l} id \sin q \tag{3.15}$$

The in-phase signal received from an angle θ by each hydrophone is the measured signal adjusted by the appropriate phase delay. Using Equations 3.9 and 3.15, you can find the signal of hydrophone element i with the appropriate phase delay required to form a steered beam at angle θ, called $B_i(q)$, in terms of the instantaneous measurements S_i and ϕ_i within a time slice:

$$B_i(\theta) = A_i e^{j(\Phi + \frac{2\pi}{\lambda} id \sin\theta)} \tag{3.16}$$

$$= A_i e^{j(\Phi_i)} e^{j(\frac{2\pi}{\lambda} id \sin\theta)} \tag{3.17}$$

$$= S_i^{j(\frac{2\pi}{\lambda} id\sin\theta)} \tag{3.18}$$

The combined steered beam at angle θ for a particular time slice is found by summing the contributions of all hydrophones, with appropriate shading coefficients s_i:

$$B(\theta) = \sum_{i=0}^{N-1} s_i S_i e^{j\left(\frac{2\pi}{\lambda} id\sin\theta\right)} \tag{3.19}$$

The calculations required to form M steered beams from the data of N hydrophones within one time slice can be represented using matrix algebra. The phase delay required for hydrophone i at a beam steered to angle θ_m as D_{mi} is defined as:

$$D_{mi} \equiv e^{j(\frac{2\pi}{\lambda} id\sin\theta m)} \tag{3.20}$$

Then the operation required to find a steered beam becomes:

$$B(\theta_m) = \sum_{i=0}^{N-1} s_i S_i D_{mi} \tag{3.21}$$

The logic required to form M steered beams can then be expressed as a matrix multiplication:

$$\begin{bmatrix} B(\theta_1) \\ B(\theta_2) \\ . \\ . \\ B(\theta_M) \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & . & . & D_{1N} \\ D_{21} & D_{22} & & & D_{2N} \\ . & & & & . \\ . & & & & . \\ D_{M1} & D_{M2} & . & . & D_{MN} \end{bmatrix} \times \begin{bmatrix} S_1 \\ S_2 \\ . \\ . \\ S_N \end{bmatrix}$$

To create M steered beams out of data from N hydrophones requires on the order of $M \times N$ operations. These computations must be completed for each time slice in real time—before data appears from the next time slice. The time between time slices is only a few milliseconds—far too short for the matrix multiplication to be performed. Fortunately, some computation short cuts can be used.

Equation 3.19 is similar to a familiar equation—that of a *Fast Fourier Transform* (FFT[1]):

$$H_k = \sum_{i=0}^{N} h_i e^{j\left(\frac{2\pi ik}{N}\right)} \tag{3.22}$$

where k is an integer.

This is a useful similarity if we make the substitutions:

[1] The subject of FFTs is vast and deep. Interested readers will find more information in *Discrete-Time Signal Processing* by A. V. Oppenheim and R. W. Schafer: Prentice Hall, 1989.

$$H_k \equiv B(\theta_k)$$

$$\frac{2\pi}{N} ik = \frac{2\pi}{\lambda} id \sin\theta_k \tag{3.23}$$

Equation 3.19 can be used to find $B(\theta)$ at any arbitrary θ. However, the FFT can be used only to solve for angles θ_k where the substitution in Equation 3.23 holds true. Solving this equation for θ_k:

$$\theta_k = \sin^{-1}\left(\frac{\lambda}{d} \cdot \frac{k}{N}\right) \tag{3.24}$$

From Equation 3.24, you can see that the beam steering angles that emerge from the FFT processing will be limited to a discrete set of angles which will depend on λ/d and on *N*, the number of hydrophones in the array. These angles can be found using values of *k*, which range from -*N*/2 to *N*/2 - 1. Using a hydrophone spacing *d* of λ/2, a 48-hydrophone installation would yield angles of:

k	beam angle
0	0°
1	± 2.4°
2	± 4.8°
3	± 7.2°
4	± 9.6°
5	± 12.0°
etc.	

Recall that θ is measured such that 0.0 is perpendicular to the hydrophone array.

For certain sizes of *N* (preferably powers of 2), special techniques for solving FFTs are available. Fortunately, *N* is not strictly limited to the number of physical hydrophones in an array. Equation 3.22 and FFT processing work fine if the value of h_i (corresponding to signal S_i and shading s_i) is 0. The SEA BEAM 2100 adds a number of "virtual" hydrophones with S_j and s_j equal to 0 in order to trick the FFT into processing data with *N* a power of 2. This is also done to increase beam density.

The FFT computations, which are performed on high-speed digital signal processors (DSPs), allow the SEA BEAM 2100 beam steering to be accomplished in real time. The FFT processing produces a time series of amplitudes for beams with axes at the beam steering angles. Echoes recorded from these time series would correspond to locations on the sea floor to which each of these angles was pointing. These data must be translated into measurements of ocean depths. The processing required to do this translation is the subject of the next chapter.

Chapter 4 - Detection Processing and Range Calculations

The SEA BEAM 2100 employs the beam steering technique described in Chapter 3 to convert the amplitude and phase information recorded by the hydrophone array into the amplitudes of echoes observed by the array at discrete angles.

This chapter outlines the additional processing that is performed to convert the steered beam data into usable output.

Processing Steps

The data processing stream of the SEA BEAM 2100 is best understood in terms of its timing. Data is collected by the individual elements of the hydrophone array in *analog* form—each hydrophone reports continuous voltages representing the amplitudes and phases of incoming signals. These continuous signals are converted to discrete *digital* signals by the analog-to-digital converters (see Figure Chapter 4 - -1). The digital data takes the form of multiple voltage readings, each representing the value of the continuous analog signal at a precise instant in time. Collectively, all of the instantaneous signal and phase information from all hydrophones in one of these precise time instants is called a *time slice* of data. Time slices are separated in time by the *sampling interval*, which for the SEA BEAM 2100 is either 4/3 or 8/3 milliseconds depending on the *pulse length* or duration of the pulse.

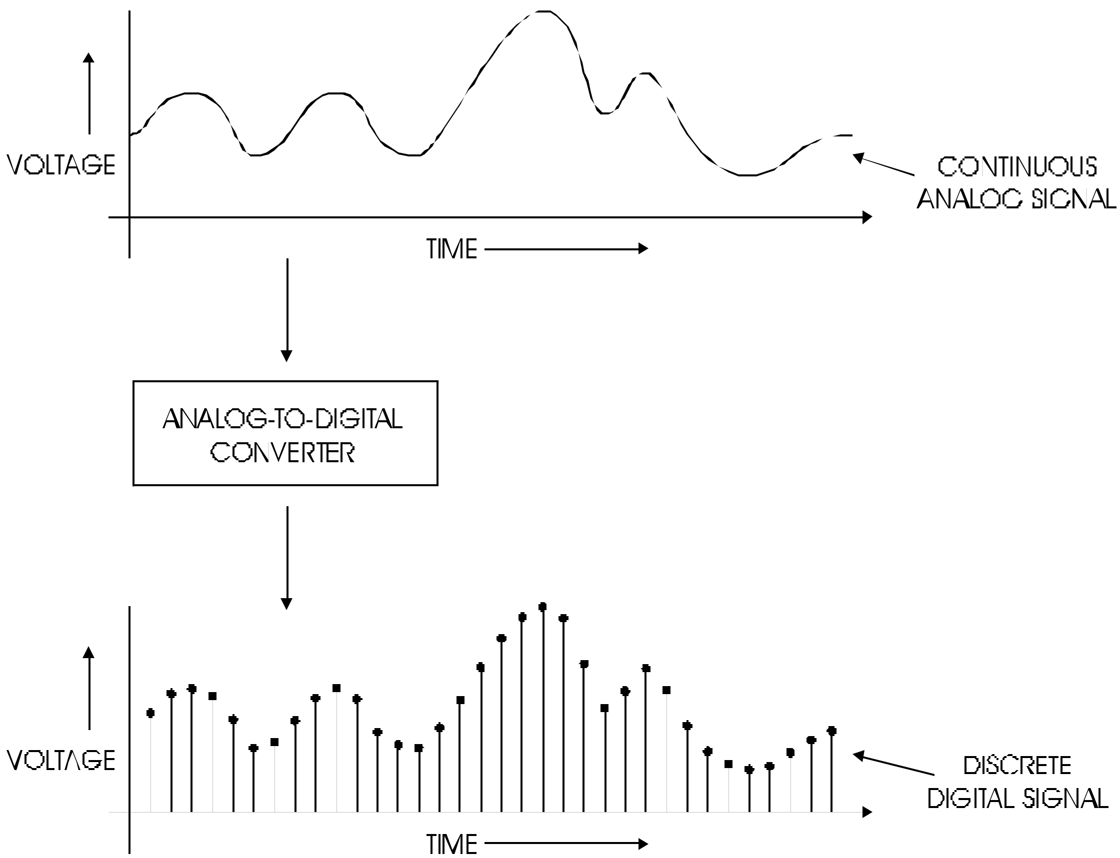

Figure Chapter 4 - -1: Analog-to-Digital Conversion of Hydrophone Data

All of the time slices that contain the echoes of a single sonar ping are called a *ping* of data. Each ping of data is processed by the SEA BEAM 2100 to produce usable output in three forms:

- *Bathymetry*. This is "traditional" sonar data—depth measurements and their positions on the sea floor. A single ping of the SEA BEAM 2100 produces up to 151 of these depth measurements (or *beams*) arranged in a *swath* as described in Chapter 2. The beams can be described also in terms of their angles and ranges from the survey ship. They are spaced 1 degree apart, and have a resolution of 2 degrees. They are stabilized for ship motions.
- *Selected Beam*. This measurement displays the amplitude of echoes received from the axis of 1 of the 151 stabilized beams as a function of time. This will show not only the echo used to find the range for the beam, but also other echoes that occurred before and after it. The angle of the beam is chosen by the SEA BEAM 2100 operator.
- *Sidescan*. This data shows the amplitude of the echoes returned from the bottom. The echoes are co-located with bathymetry. The processing of sidescan data is described in Chapter 5.

Some of the data processing, particularly in the early stages, is done on a *per-time-slice* basis. For instance, the FFT process is applied to each time slice, yielding the amplitudes of echoes received from all steered beams in a single time instant. Later processing, and the ultimate end products, are on a *per-ping* basis—the bathymetry and sidescan data that are reported apply to the echoes generated during a single ping. The selected beam reports a time sequence, in effect showing the echoes seen by a beam in every time slice during a ping.

The major processing steps used by the SEA BEAM 2100 are outlined schematically in Figure Chapter 4 - -2. Raw digital hydrophone data, which is composed of signal measurements and phase information, is processed on a per-time-slice basis by the beam steering FFT to produce steered beam data. A *dynamic threshold* value, which is used in noise discrimination, is then computed for each time slice. This value is used in later processing steps. Two distinct processing schemes are then used to convert the per-time-slice angles and amplitudes to a set of beam angles or direction of arrivals (DOAs) and time of arrivals (TOAs) of bottom echoes. Both of these processes employ ship motion data to convert direction angles from the hydrophone-centered coordinate system in which they are measured into the Earth-centered coordinate system. The two processes are known as *Bearing Direction Indicator* (BDI) and *Weighted Mean Time* (WMT). They run in parallel—the SEA BEAM 2100 does both of them at the same time—and they calculate independent measurements of angles and times. To some degree they are redundant, because each generates valid data on its own. However, the BDI process simultaneously does many of the calculations required for sidescan output (see Chapter 5), and the WMT process also generates the selected beam data. In addition, the two processes each have bottom configurations and beam angle regimes in which they perform best, so they can be used together to select final "best" DOA and TOA measurements, increasing the overall accuracy of the system. The final stage of processing uses the sound velocity profile to do "ray tracing," converting DOAs and TOAs to bathymetry data—depths and locations.

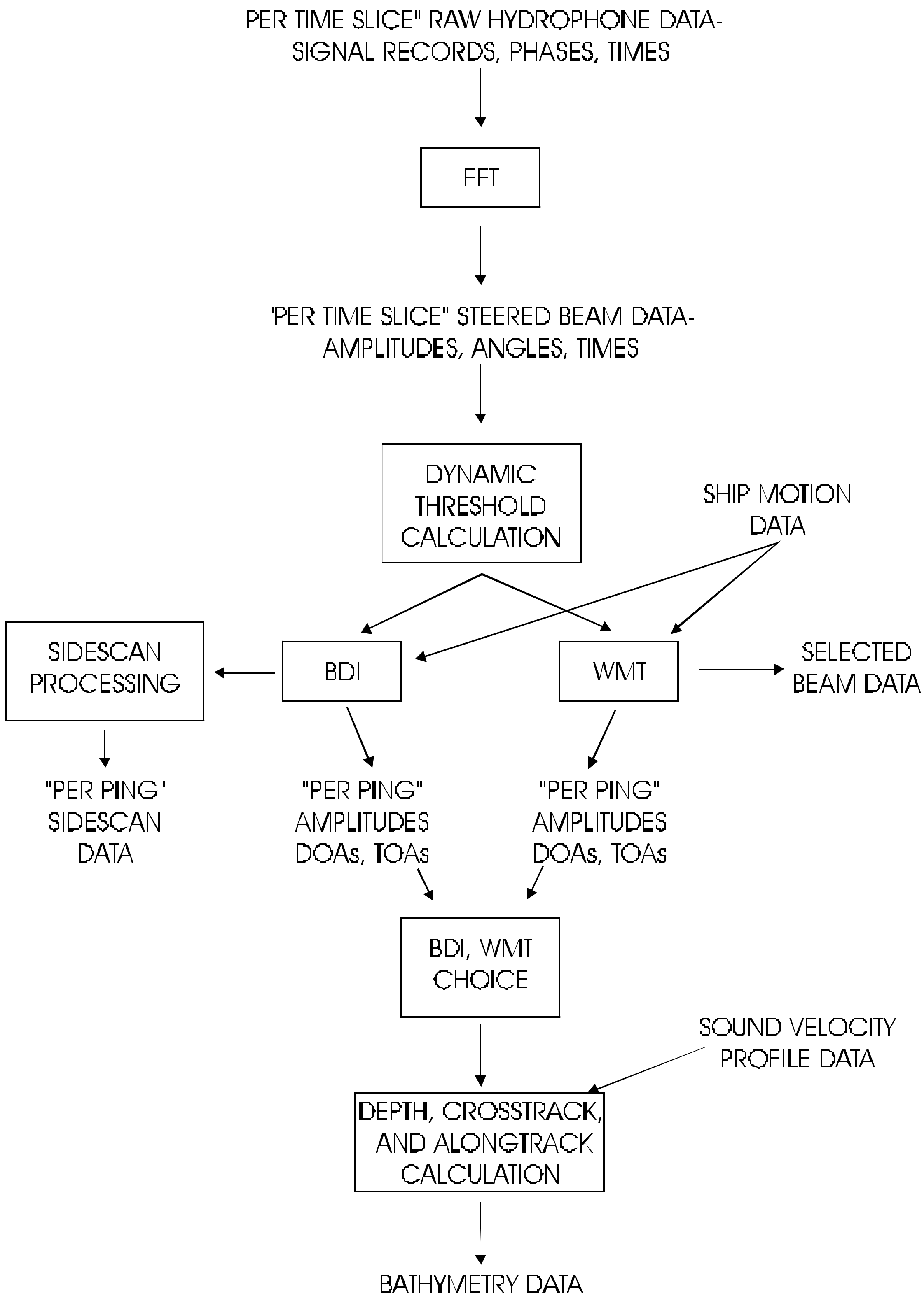

Figure Chapter 4 - -2: SEA BEAM 2100 Processing Steps – Raw Hydrophone Data to Bathymetry, Sidescan and Selected Beam

This chapter follows these processing steps in order, describing each in detail. First, however, the chapter describes the steered beam data emerging from the FFT, which forms the raw material for the SEA BEAM 2100 processing.

The Steered Beam Data

The beam forming/beam steering process described in Chapter 3 uses an FFT to convert the measurements from the hydrophone arrays into steered beam amplitudes. This is done for each time slice individually. Recall from the “Beam Steering” section in Chapter 3, that the angles of steered beams are determined by the equation (3.10):

$$\theta_k = \sin^{-1}\left(\frac{\lambda}{d} \cdot \frac{k}{N}\right) \tag{4.1}$$

where d is the spacing between hydrophones, λ is the wavelength of the signal used, and k ranges between $-N/2$ and $N/2 - 1$, N being the number of hydrophones (including “virtual” hydrophones) in the array. After the FFT, each time slice contains N amplitude measurements $A_1, A_2, ...A_N$, each associated with a steered beam angle $\theta_1, \theta_2, ...\theta_N$. Steered beam angles given by Equation 4.1 are measured with respect to the hydrophone array. The angles $\theta_1, \theta_2, ...\theta_N$ do not change between time slices.

All of the data for a single ping cycle that emerges from the FFT processing is represented as a matrix (see Figure Chapter 4 - -3). The ping cycle contains *M* time slices, represented by columns in the figure, each with an associated time t_1, t_2, ... t_M, measured relative to the ping time t_0 (often called "t-zero"). Each time slice contains *N* amplitude measurements associated with the angles θ_1, θ_2, ...θ_N (which are in the left-most column). An individual amplitude measurement A_{mn} can be identified in the matrix by its subscripts: *m* for the time slice (between 1 and *M*); *n* for the steered beam angle (from 1 to *N*).

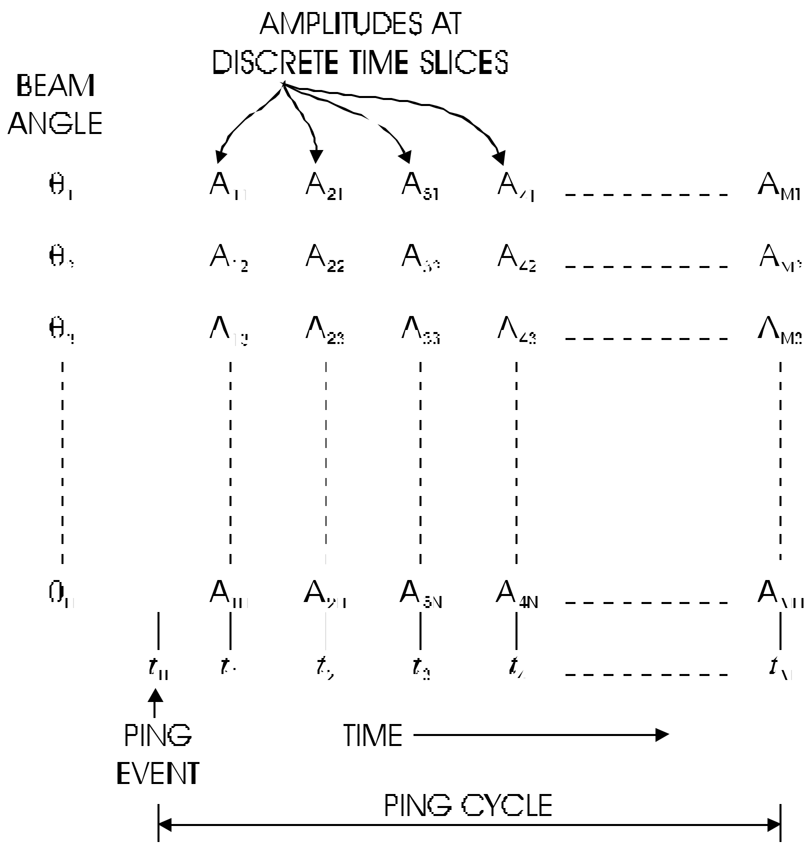

Figure Chapter 4 - -3: Matrix of Steered Beam Data from a Single Ping Containing M Time Slices

Dynamic Threshold Calculation

A single time slice of data represents the echoes received by the hydrophone array in terms of their direction (θ) and amplitude in an instant of time. Depending on the range and configuration of the bottom and the time slice, these echoes can be very different. Figure Chapter 4 - -4 through Figure Chapter 4 - -9 consider a hydrophone array receiving echoes from a single ping ensonifying a complex sea floor and the echoes that occur in different time slices. For pictorial simplicity, the system has only 12 steered beams, although the principles discussed apply to a larger number of beams.

In Figure Chapter 4 - -4, a time t_1 has passed since the sonar system has transmitted a ping. As yet, the ping has not reached the bottom, so there are no bottom echoes produced at time t_1. The time slice at time $2 \times t_1$, which is when any echoes produced at time t_1 would be received (remember, any echoes must travel *back* to the hydrophone array, and to do so requires the same amount of time it took the ping to propagate outward) will contain no echoes from the sea floor. However, it will have measurable amplitudes, as pictured in Figure Chapter 4 - -5. These amplitudes are due to background noise (discussed in "The Principles of Sonar" in Chapter 2).

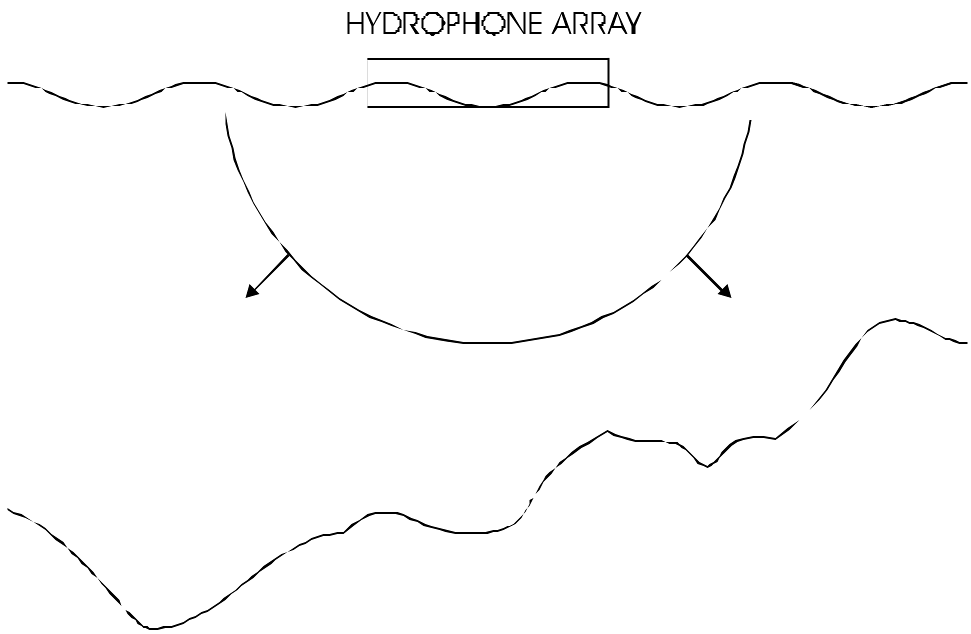

Figure Chapter 4 - -4: Hydrophone Array at Time t_1

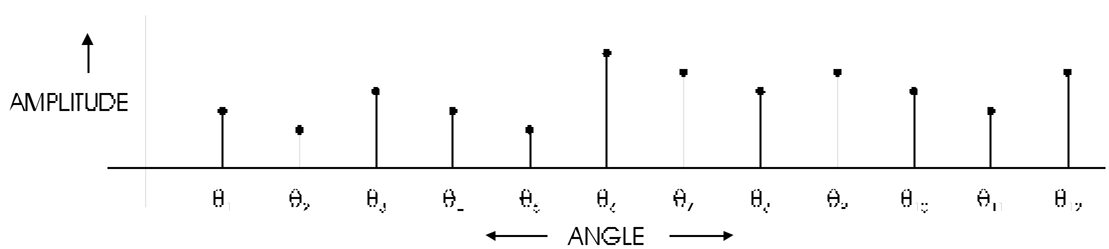

Figure Chapter 4 - -5: Time Slice at Time 2 ´ t_1

Figure Chapter 4 - -6 considers the same hydrophone array at a later time t_2. The ping has propagated to the point where it is intersecting the bottom at a single point, at angle θ_A to the hydrophone array. The time slice at time $2 \times t_2$ contains the echo from this point (see Figure Chapter 4 - -7). Note that θ_A does not necessarily occur at one of the axes of the steered beams—in general it will occur at angles between two beams. The echo will cause high amplitudes in several surrounding beams—strongest in those closest, but measurable in others. This is because each steered beam has a beamwidth (as discussed in the section, “Projector Arrays and Beam Forming,” in Chapter 3). For instance, the beam with axis at θ_7 in Figure Chapter 4 - -7, receives the echo at θ_A close to its axis—near the peak response of the beam—so it generates a strong amplitude. The beam with axis θ_9 receives the same echo farther away from its axis, generating a weaker amplitude. Far away beams, such as those at θ_2 and θ_{12}, do not see the echo at all.

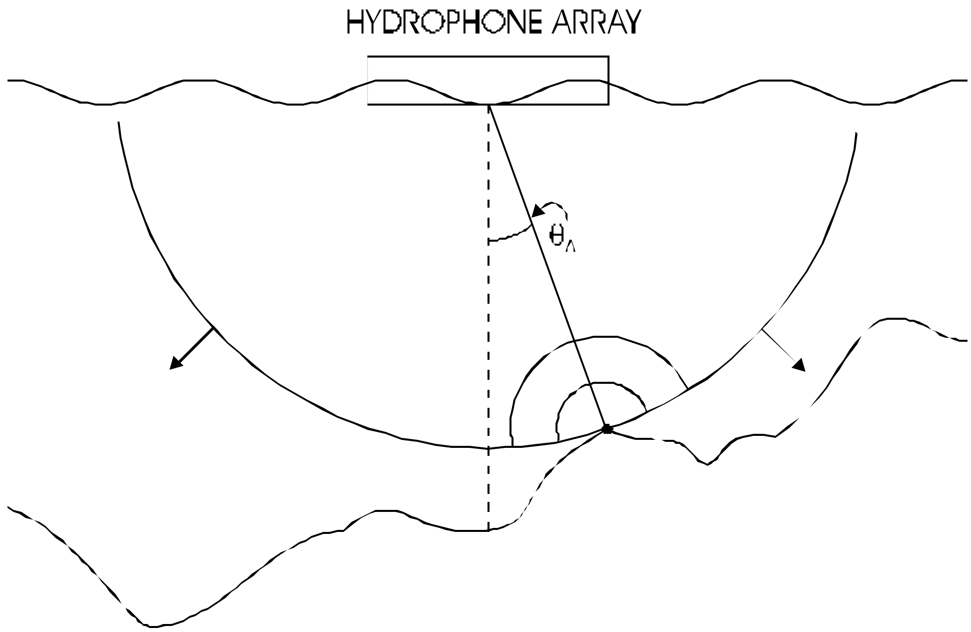

Figure Chapter 4 - -6: Hydrophone Array at Time t_2

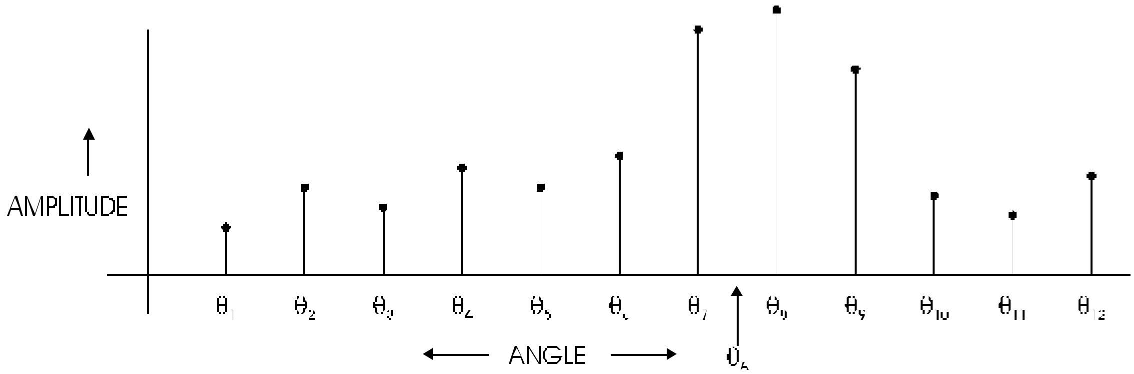

Figure Chapter 4 - -7: Time Slice at Time 2 ´ t_2

Figure Chapter 4 - -8 shows a third situation at time t_3. The ping front is intersecting the sea floor at two points, creating echoes from angles θ_B and θ_C. These echoes will cause two sets of beams to record high amplitudes, as pictured in Figure Chapter 4 - -9.

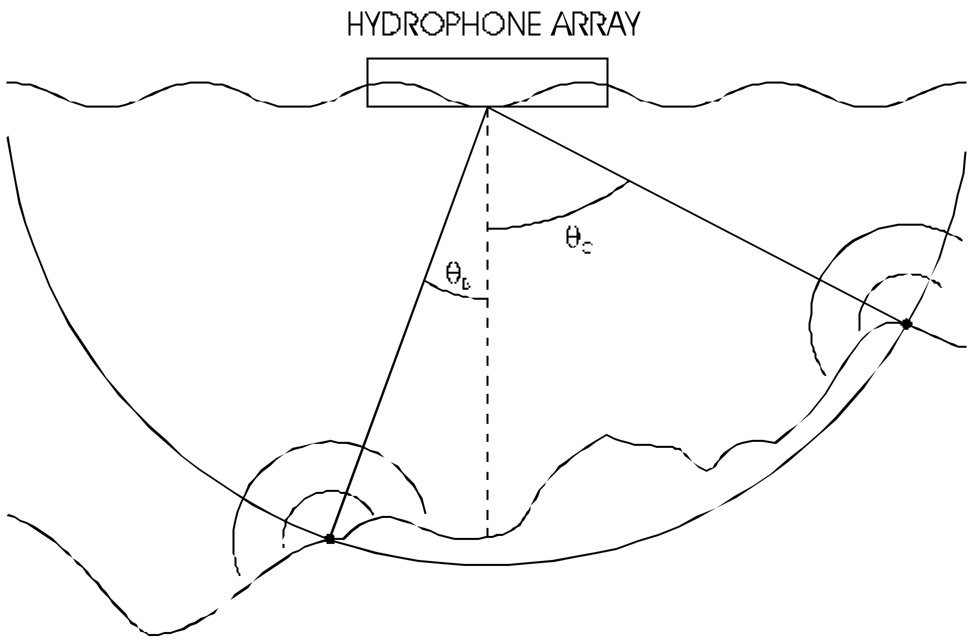

Figure Chapter 4 - -8: Hydrophone Array at Time t_3

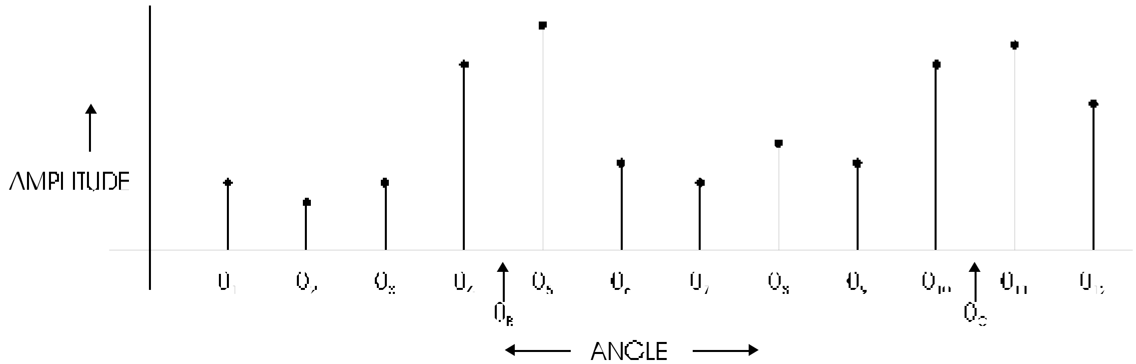

Figure Chapter 4 - -9: Time Slice at Time 2 ´ t_3

Each time slice the SEA BEAM 2100 records has some variation of the situations presented in the examples above. Time slices always record amplitudes due to noise. In addition, they can have one, many, or no echoes at all from the sea floor. Echoes from the sea floor cause amplitudes in several beams, both due to intersection of the beams' main lobes and to side lobes with the echo. Within a time slice, the true signals need to be separated from the noise and signals due to side lobes so that the former can be analyzed and the latter ignored. This process, called *noise discrimination*, is accomplished by applying a detection threshold to the time slice. A detection threshold is simply a level above which amplitudes are assumed to be parts of signals, and below which amplitudes are ignored. The level is computed based on the relative strengths of side lobes and the estimated noise levels in the steered beams and it is unique to each time slice. Figure Chapter 4 - -10 shows a detection threshold applied to the time slice pictured in Figure Chapter 4 - -9. Amplitude levels above the threshold are processed as signals, while those below the threshold are ignored (although values below the threshold can be used for sidescan). BDI and WMT have different ways of using the threshold value, as described in the sections that follow.

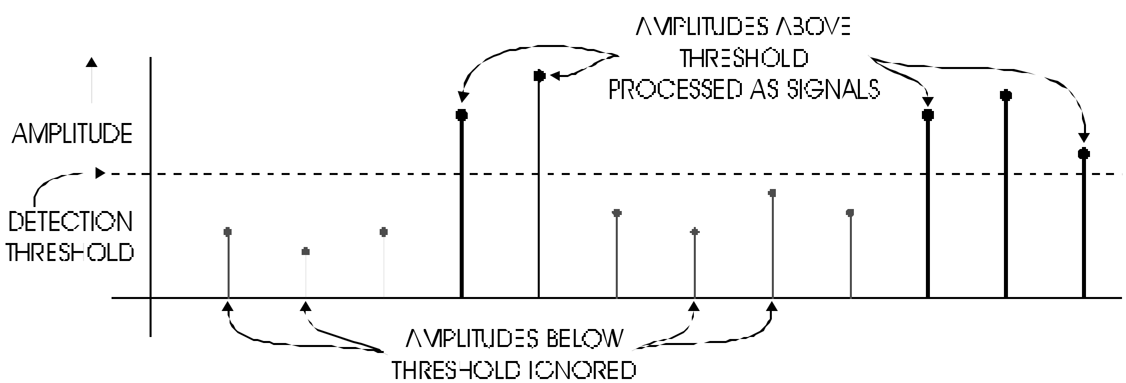

Figure Chapter 4 - -10: Dynamic Threshold Applied to a Time Slice

Time of Arrival (TOA) and Direction of Arrival (DOA) Calculations: BDI and WMT Processing

The complex matrix of data pictured in Figure Chapter 4 - -3 must be reduced from amplitude measurements on a per-time-slice basis where angles are measured relative to the hydrophone array to a smaller number of per-ping measurements from which bathymetry data can be derived. The SEA BEAM 2100 reduces the matrix to a set of echo measurements for a maximum of 151 stabilized beams for each ping. The beams are spaced 1 degree apart in the athwartship direction, and have beam widths of 2 degrees. For each beam, two pieces of information are derived:

- Echo *direction of arrival* (DOA): the true angle from which the bottom echo detected within each beam was received, in Earth-centered coordinates.
- Echo *time of arrival* (TOA): the time, relative to the time of ping transmission, at which the echo within a beam was received.

The SEA BEAM 2100 uses two independent algorithms to accomplish this—*Bearing Direction Indicator* (BDI) and *Weighted Mean Time* (WMT). BDI and WMT have different approaches to analyzing the data—BDI processing tries to accurately locate the DOA of an echo within each beam and then computes the TOA of that echo, while WMT fixes the DOA at the center of each beam and attempts to precisely calculate the time of arrival. Each of these approaches has its advantages, as explained in the sections that follow.

BDI Processing

BDI processing computes precise directions of arrival (DOAs) and times of arrival (TOAs) for echoes within each beam. The primary steps involved in this procedure are the following:

1. *High-resolution Angle Estimation*: The measurements from all steered beams in each time slice are combined to determine from which precise angles echoes are being received by the hydrophone array in that slice.
2. *Motion Compensation*: Measurements of the complex hydrophone array motions due to sea conditions are used to convert angles measured with respect to the hydrophone array into angles measured with respect to the Earth. This processing is performed on time slices individually.
3. *Application of Start and Stop Gates*: Each angle within a time slice is checked against the operator-specified (manual mode) or system-specified (auto mode) start and stop gates. Those that are not within the gates are eliminated.
4. *DOA and TOA Calculation*: All time slices for a ping are combined, and the angles and times of the echoes from each are used to compute mean DOAs and TOAs within each beam.

High-Resolution Angle Estimation

Within a time slice, the angles at which echoes strike the hydrophones do not necessarily correspond to the axis angles of the steered beams. In fact, because the beams are wide enough to overlap to some degree, an echo event is actually measured by more than one neighboring beam. Beams that have axes aimed near the true angle to an echo source measure higher amplitudes than those aimed farther away. The relative levels of these amplitude measurements can be used to find the true angle to the source with precision. This process is called *High-Resolution Angle Estimation*.

An individual time slice may contain zero, one, or many echoes. These three situations are depicted in Figure Chapter 4 - -5, Figure Chapter 4 - -7, and Figure Chapter 4 - -9. Figure Chapter 4 - -5 shows a time slice that contains no genuine echoes; Figure Chapter 4 - -7 has a single echo from direction θ_A; and Figure Chapter 4 - -9 has multiple echoes from θ_B and θ_C. Using the amplitudes measured at the steered beam angles, you can determine the true angles at which the echoes are originating—the θ_A, θ_B, and θ_C from the examples above, and amplitudes that measure the strength of the echoes corresponding to those angles.

The first stage in this process is applying the detection threshold that has been computed for this time slice. All amplitudes below the detection threshold are not considered parts of true echoes. The result of a detection threshold application to the time slice from Figure Chapter 4 - -9 is pictured in Figure Chapter 4 - -10. In the figure, all amplitudes below the detection threshold, which is represented by the dashed line, are ignored (ignored values are shaded gray). Remaining are two groups of high amplitudes (shaded black).

The amplitudes that emerge from the detection threshold are then processed to determine the true angles of the echoes that caused them. Individual echoes cause high amplitudes in several neighboring beams, so they occur in groups. Using the strength of the amplitudes in each beam, and knowing what the beam patterns of the formed beams look like, you can make a fairly accurate estimate of the true angle to the source causing the echo.

Recall that the beam pattern of a hydrophone array can be computed knowing the frequency of the sonar and the characteristics of the array (number of elements, element spacing, and so forth). An approximation of the main lobe of the beam pattern is fitted to each group of high amplitudes using a least squares fit process. The location of the peak of the best fit is taken as the angle to the true source causing the group of high amplitudes. Figure Chapter 4 - -11 shows the fitting process to the two groups of high amplitudes in this example.

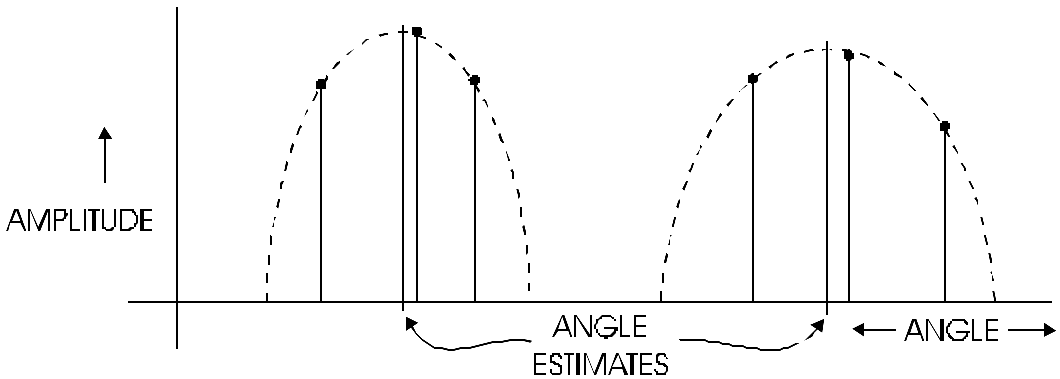

Figure Chapter 4 - -11: Parabola Fitting for High-Resolution Angle Estimation

A time slice with no strong echoes might produce no angle estimates, if all measured amplitudes are below the detection threshold. In these cases, however, the strongest amplitude value and its associated beam angle are saved for use in the sidescan data processing.

Each angle/amplitude pair that emerges from the angle estimation process is called a *hit*. A hit is composed of three pieces of data: its angle, its amplitude, and the time it occurred (equal to the time associated with the time slice).

Motion Compensation

The Angle Estimation process produces a list of hits including their amplitudes and angles for each time slice. However, the angles have been measured with respect to the hydrophone array, and the hydrophone array is mounted on a moving platform, a vessel at sea. Before the reported echoes can be translated into measurements of the sea floor, and before they can be compared between time slices (the hydrophone array will be in different positions and at different angles in different time slices), the motions of the hydrophone array must be measured and taken into account. This process is called *motion compensation*, or *beam stabilization*.

The motions of a ship at sea and the hydrophone mounted to it are highly complex and somewhat unpredictable. Some of these motions are deliberate, such as the ship’ s forward progress, or turns. However, most are due to the effects of waves.

All motion of a ship can be described by using a point called the *center of mass*. The center of mass of a ship is exactly that—it is an imaginary point in space that represents the center of the weight distribution of the ship. It is also the point about which a ship will rotate if any external force is applied to it. Around the center of mass a three dimensional coordinate system is constructed (see Figure Chapter 4 - -12). The three coordinates are:

- The x, or *acrosstrack* direction – This is the direction perpendicular to the ships track and parallel to the surface of the sea.
- The y, or *alongtrack* direction – This is the direction parallel to the ships direction of travel, or track.
- The z, or *vertical* direction – This is the direction perpendicular to the surface of the sea.

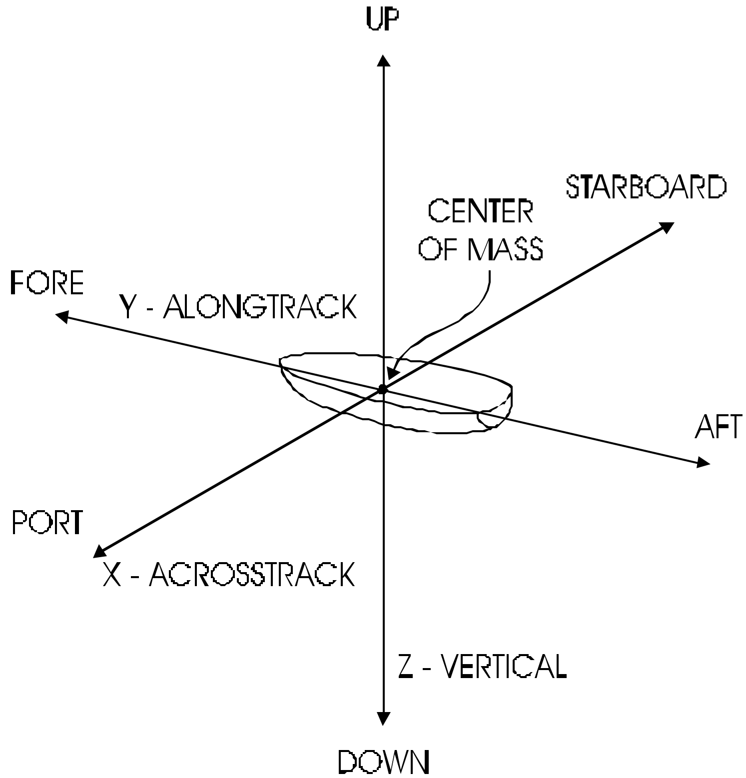

Figure Chapter 4 - -12: Ship-Motion Coordinate System

A ship at sea experiences *translational* motion in each of these three directions. Fore and aft motion in the alongtrack direction is called *surge*. Port and starboard motion in the acrosstrack direction is called *sway*. Up and down motion in the vertical direction is called *heave*.

There are also *rotational* motions around the axis of each of these coordinates (see Figure Chapter 4 - -13):

- Rotation about the x-direction is called *pitch*.
- Rotation about the y-direction is called *roll*.
- Rotation about the z-direction is called *yaw*.

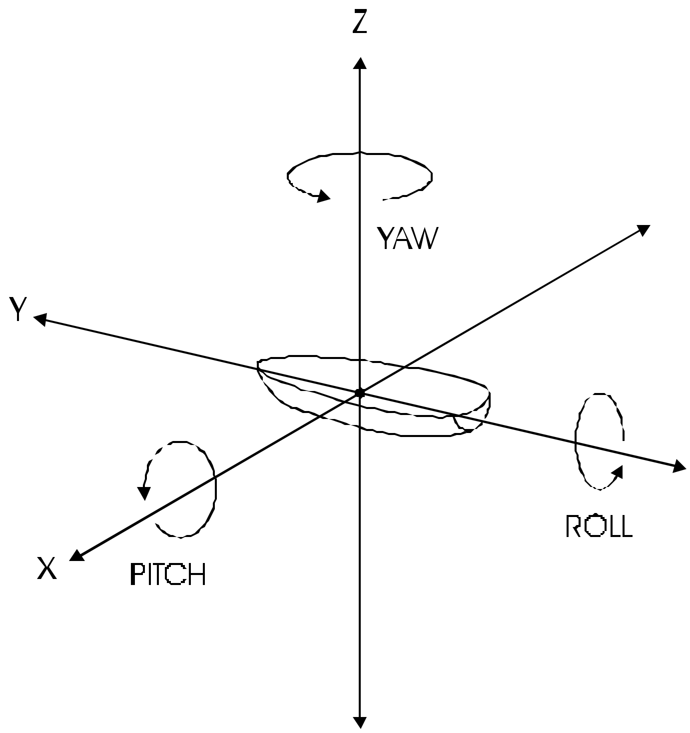

Figure Chapter 4 - -13: Rotations about the Ship Center of Mass

The effect of rotation about each of these directions is illustrated in Figure Chapter 4 - -14. The degree of rotation is measured as an angle.

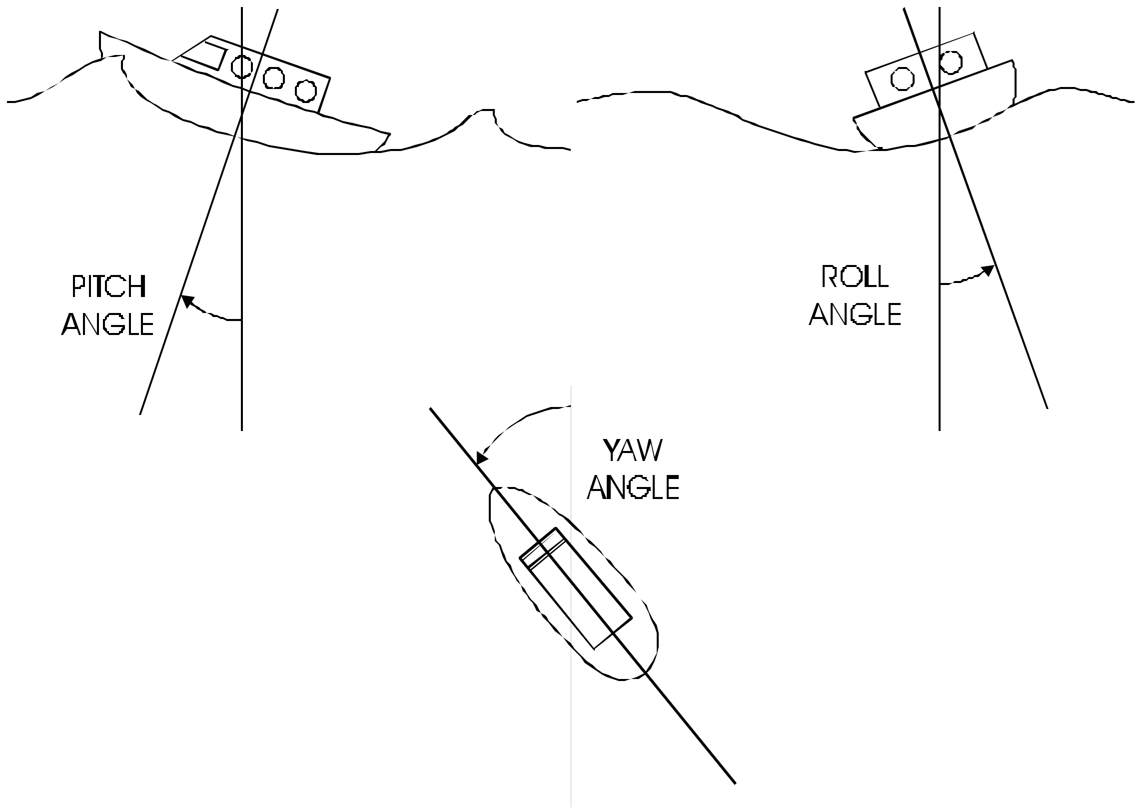

Figure Chapter 4 - -14: Roll, Pitch, and Yaw Angles

Between time slices, the ship moves in each of these six different ways: surge, sway, and heave of its center of mass, and roll, pitch, and yaw about its center of mass. In other words, the ship has six *degrees of freedom* to its motion. The SEA BEAM 2100 accepts input from two measurement systems that constantly monitor all six degrees of freedom:

- The *Navigation* instrument records the position of the ship (latitude, longitude, and heading at time of ping) associated with surge, sway, and yaw motions.
- The *Vertical Reference Unit* (VRU) records roll, pitch, and heave information.

Of these instrument readings, the roll and pitch values from the VRU are necessary for per-time-slice processing. The VRU, however, does not make measurements with the frequency of the time slices. Obtaining unique and accurate values that correspond to the times of the time slices requires linear interpolations from the two nearest VRU measurements.

BDI processing adjusts the hits in each time slice for the appropriate roll value (compensation for other motions is done elsewhere in the processing). It also takes into account two additional angles in the same direction as roll—the *mounting angle* of the hydrophone array (measured such that horizontal is zero) and the *roll bias* of the sonar installation. The roll bias angle is found through a calibration process that should be performed periodically on the SEA BEAM 2100 (see Chapter 8 in the *SEA BEAM 2100 Operator's Manual*). Together, these three values form a *roll offset angle*, θ_R. Each hit in a time slice can be converted from the coordinate system of the hydrophone array to the Earth-centered coordinate system by adding θ_R to its measured angle. This process is illustrated in Figure Chapter 4 - -15.

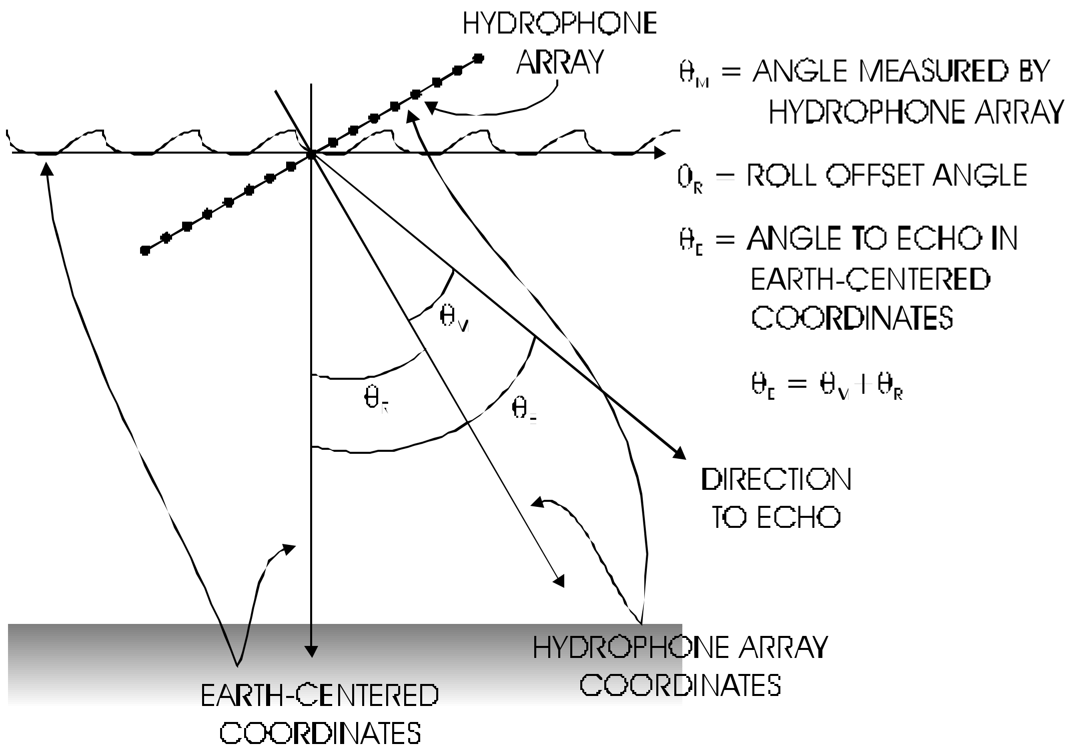

Figure Chapter 4 - -15: Adjusting Measured Angles for Roll

Application of the Start and Stop Gates

The SEA BEAM 2100 allows the operator (either manually or automatically) to choose a set of *start gates* and *stop gates*. While the system operator sees the start and stop gates as a tracker of depth on screen, internally they are specified in terms of beam angle and time. For a particular angle, the start gate tells the SEA BEAM 2100 that all hits which occur before it at that angle should be ignored. The stop gate specifies that all hits which occur after it should be ignored. Only hits that occur in the time between the start and stop gates are retained.

Within a single time slice, there will be ranges of angles at which a hit should be retained, and at which a hit should be ignored. The gates are applied to all time slices, and all hits that fall outside the start and stop gates for their respective angles are discarded.

Direction of Arrival (DOA) and Time of Arrival (TOA) Calculations

All remaining hits from a ping cycle are then compiled. Recall that each hit has three pieces of information associated with it—its amplitude, its angle in the Earth-centered coordinate system, and the time at which it occurred. In Figure Chapter 4 - -16 dots are plotted to represent each of the hits in a ping cycle. Each hit is located on the plot based on its angle θ_H and time t_H (the amplitude of each hit is not represented in the figure). The bulk of the hits are located in the same area, forming a "cloud," which represents the profile of the sea floor.

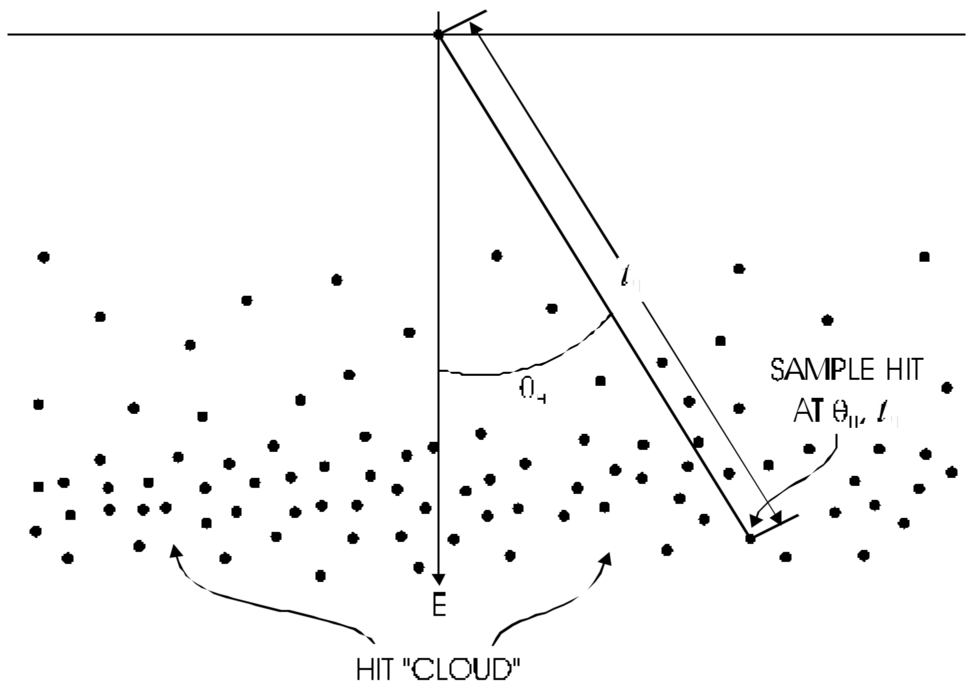

Figure Chapter 4 - -16: Hits Plotted Based on Angle and Time

This plot can be divided up into areas that correspond to the predefined beams of the SEA BEAM 2100. Each beam is centered on an integer degree and has a width of 2 degrees. There are up to 151 beams. In Figure Chapter 4 - -17, a sample beam is plotted with axis angle θ_B. Within its 2-degree beamwidth, this sample beam contains a number of hits (drawn as black dots) that is a subset of all of the hits (drawn as gray dots). The SEA BEAM 2100 uses the enclosed subset of hits within each beam to calculate a mean DOA, TOA, and amplitude corresponding to that beam.

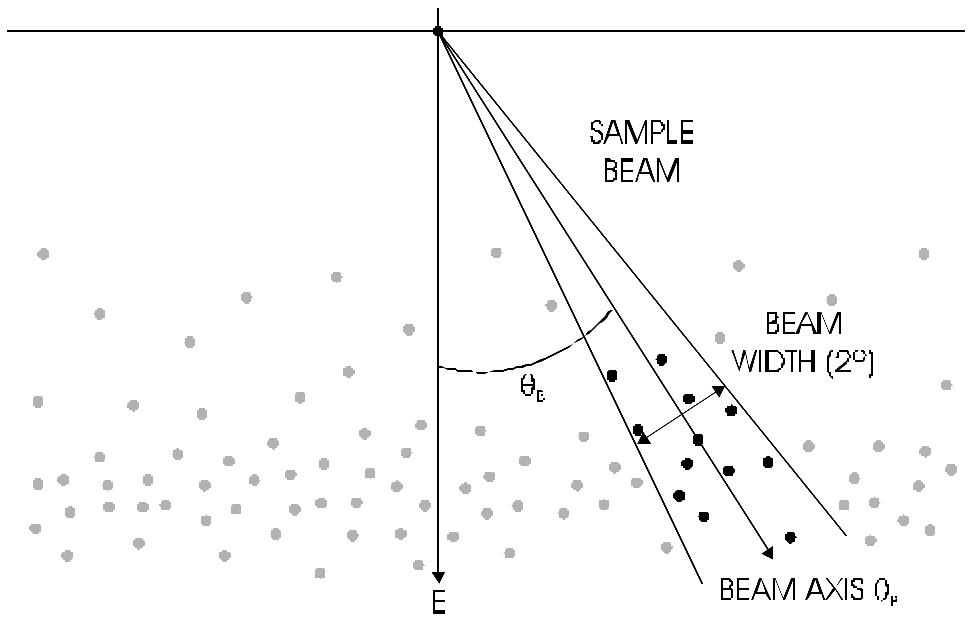

Figure Chapter 4 - -17: Sample Predefined Beam Encompassing a Subset of Hits

This process has two steps:

1. A mean and standard deviation of the TOAs of all enclosed hits is computed. These are used to compute a statistical "envelope" in time, centered at the mean time t_{MEAN} with a width twice that of the standard deviation t_σ (see Figure Chapter 4 - -18). Hits within the beam that fall outside this envelope are discarded.

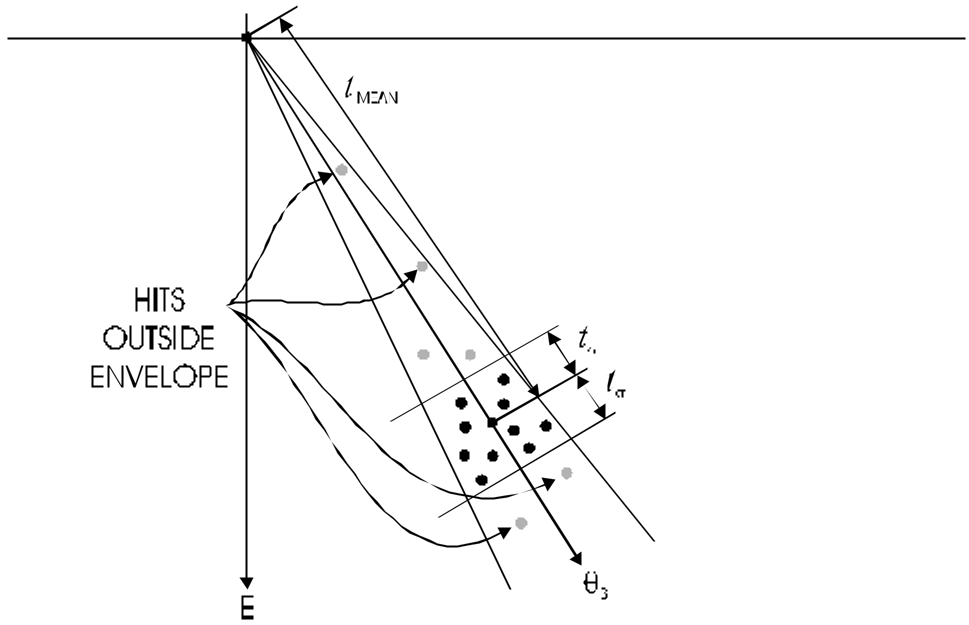

Figure Chapter 4 - -18: Hit Envelope Calculation Within a Beam

2. The amplitude-weighted mean TOA and DOA are computed from the times and angles of all remaining hits. These values are then used as the TOA and DOA for the beam (see Figure Chapter 4 - -19). The amplitude of the beam is computed by a simple mean.

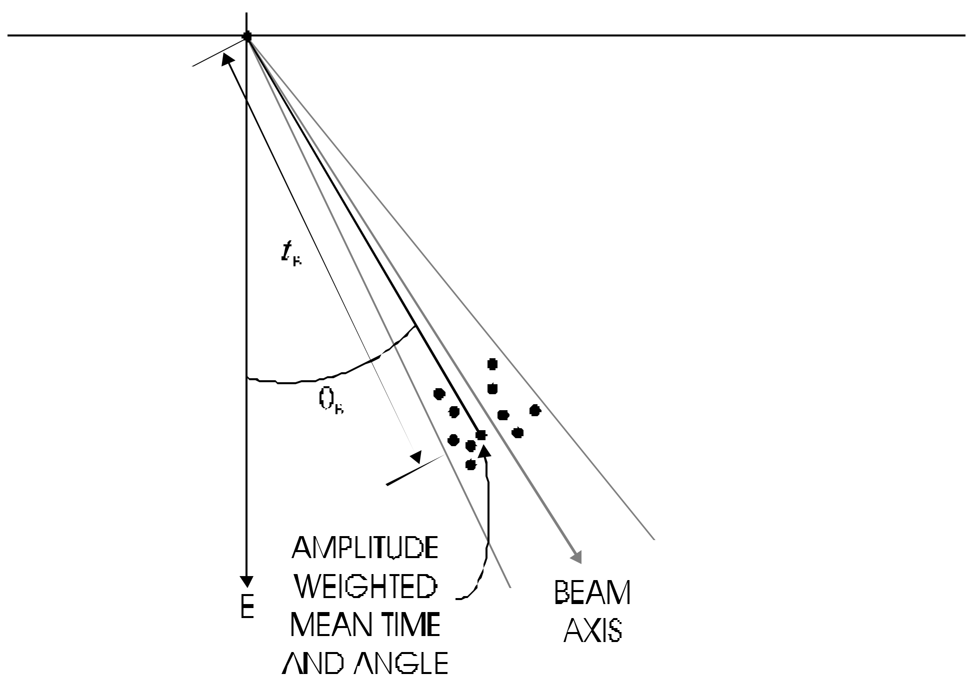

Figure Chapter 4 - -19: Amplitude-Weighted TOA and DOA

For each of up to 151 beams, TOA, DOA, and beam amplitude values are calculated. Note that the final DOA need not coincide with beam axis.

WMT Processing

In contrast to BDI, Weighted Mean Time (WMT) processing begins by defining a set of beam angles (or DOAs) in the Earth-centered coordinate system and then computes the precise TOA of the echoes from those angles. In the case of the SEA BEAM 2100, up to 151 such angles are defined, positioned one degree apart at integer degree values -75°, -74°,...-1°, 0°, 1°, ...74°, 75° (that is, at the axis of the beams used in BDI processing). Each defined DOA angle is called a beam.

The processing required for each beam is identical and independent of all of the other beams. WMT can be described by following the processing of only a single beam, which is called θ_B. It should be remembered that this procedure is repeated for each of the other beams as well.

Interpolating Amplitudes for Each Time Slice

The first stages of WMT processing are done on each time slice of raw steered beam data individually. Recall that a time slice of steered beam data has N measurements of amplitude A_1 - A_N at angles θ_1 - θ_N. There is also a threshold value T_s, which was computed using the processes described in the section on Dynamic Thresholding. Beginning with a defined beam angle θ_B, each of the angles can be adjusted in the time slice for roll θ_R (where θ_R contains all roll factors: roll bias, mounting angle, and time-dependent roll – see *Motion Compensation*), and find the two closest, θ_n and θ_{n+1} on either side of θ_B (see Figure Chapter 4 - -20). Note that the values of n and $n + 1$ will be different for each time slice, because there will be different roll values θ_R for each time slice.

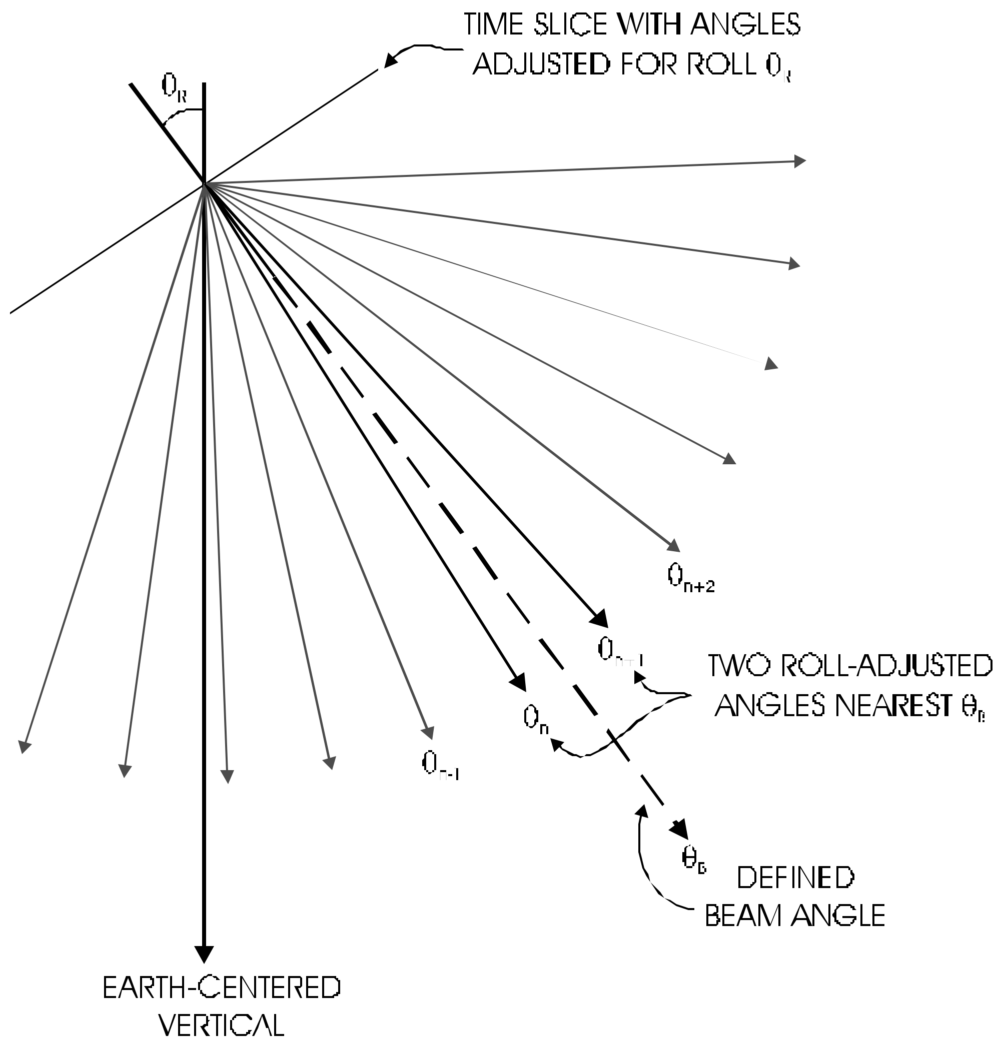

Figure Chapter 4 - -20: Finding the Roll-Adjusted Angles Nearest the Beam Angle

Both θ_n and θ_{n+1} have amplitude values associated with them, A_n and A_{n+1}. They will also have complex beam patterns, which tell you their response to echoes as a function of angle from their axis (see Figure Chapter 4 - -21). For each of these two beams, you can calculate a relative "weight" based on the response level of their beam pattern at the angle between them and θ_B (θ_B - θ_n, or θ_{n+1} - θ_B). From their amplitudes A_n and A_{n+1} and these computed weights, you can interpolate a new amplitude A_B, which is the amplitude of the echo received from direction θ_B. Thus, you are obtaining the echo returns in a beam whose axis is always fixed with reference to earth. This processing is repeated for each time slice.

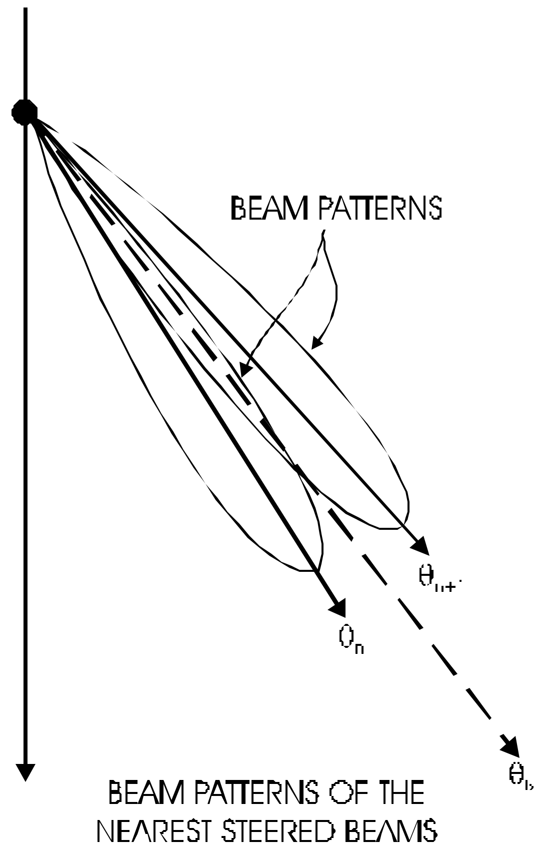

Figure Chapter 4 - -21: Beam Patterns of the Nearest Steered Beams

Amplitude-Weighted Time of Arrival (TOA) Computation

The amplitudes of the echoes A_B associated with each time slice are collected and ordered sequentially in time. Since there are many time slices per ping, the collection can be quite large. The sequence of amplitudes represents a record of the echoes received from θ_B during the ping cycle, including noise events, true bottom echoes, and reverberation events. A collection of amplitudes A_B for beam angle θ_B is represented schematically in Figure Chapter 4 - -22.

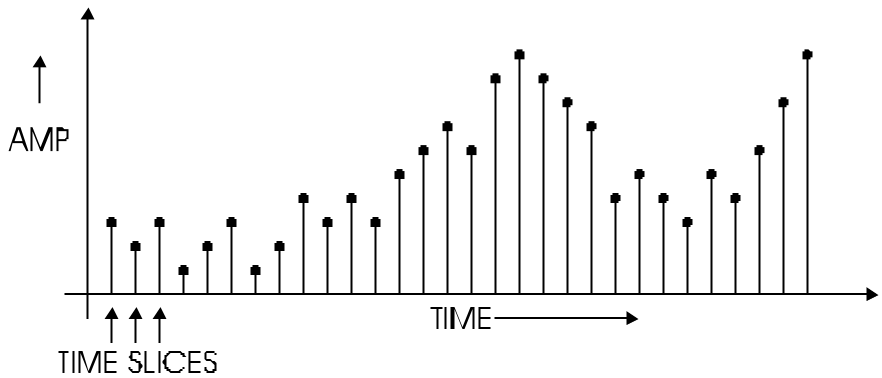

Figure Chapter 4 - -22: Interpolated Amplitudes for a Single Beam in All Time Slices

Time sequences such as this can be examined by the operator if the beam with angle θ_B is the *selected beam.* The selected beam, which is chosen from the SEA BEAM 2100 menu (see Chapter 9 of the *SEA BEAM 2100 Operator's Manual*), corresponds to one of the beam angles used in WMT processing. The sequence of amplitudes of the selected beam is represented on a logarithmic scale. It allows the operator to examine the "cleanliness" of acoustic returns—if beams contain well-defined bottom echoes, if there is much noise present, if there is are secondary echoes, and so forth.

For each beam, an associated *start gate* and *stop gate* are specified as times (either by the SEA BEAM 2100 operator or computed automatically). Essentially, the start gate tells the SEA BEAM 2100 to only process time slices that occur after it, and the stop gate tells it to only process time slices that occur before it. All other time slices are ignored when computing WMT TOAs. In Figure Chapter 4 - -23 start and stop gates are applied to the sequence of echo events for the beam angle θ_B.

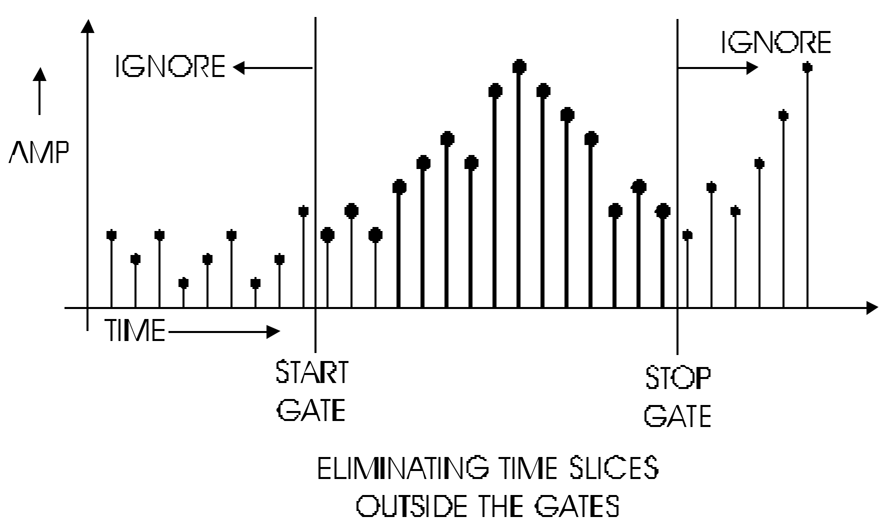

Figure Chapter 4 - -23: Eliminating Time Slices Outside the Gates

Recall that for each time slice, there was a threshold value T_S computed in the Dynamic Threshold Processing. In Figure Chapter 4 - -24, the values of T_S associated with each time slice are plotted. For some time slices, the amplitude A_B falls below the threshold. In these cases the time slice is ignored.

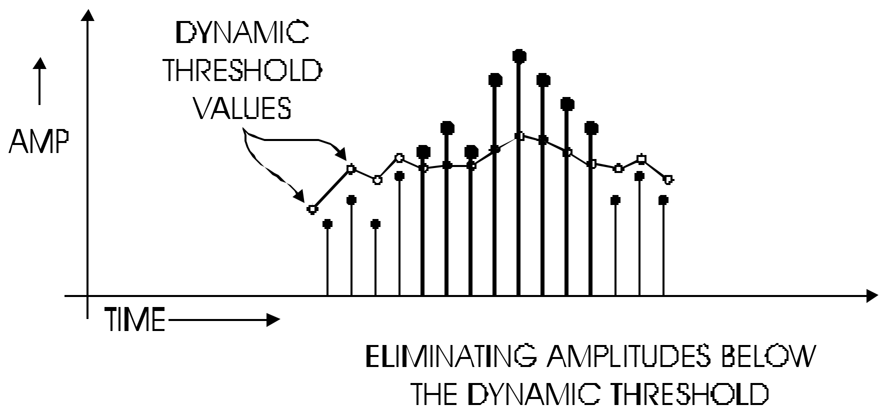

Figure Chapter 4 - -24: Eliminating Amplitudes Below the Dynamic Threshold

The remaining sequence of amplitudes contains only those time slices between the start and stop gates that have amplitudes above their associated thresholds. From this, a TOA is computed for the echo in each beam. The TOA is found using an amplitude-weighted average of the times of time slices that are between the gates and that have amplitudes above the thresholds. TOAs are computed for up to 151 beams in WMT processing.

Choosing between BDI and WMT Data

The BDI and WMT processes both produce DOA and TOA calculations for each of up to 151 beams in the swath for each ping. The final stage of processing is to convert these records into true bathymetry data—depth measurements and corresponding positions in terms of longitudes and latitudes. Before doing so, the SEA BEAM 2100 must determine which of the results from the two processes to use for producing the final product.

Both BDI and WMT have regimes in which they are likely to produce better estimations of echoes. Figure Chapter 4 - -25 and Figure Chapter 4 - -26 consider two situations. Figure Chapter 4 - -25 shows what is called the *specular* regime, where a sonar is looking in a direction perpendicular to the sea floor.
Figure Chapter 4 - -26 shows the *non-specular* regime, where a sonar is looking at a shallow grazing angle to the sea floor. Both situations consider a single beam of a multibeam sonar, which has some beam width such that it is sensitive to echoes from an area on the sea floor.

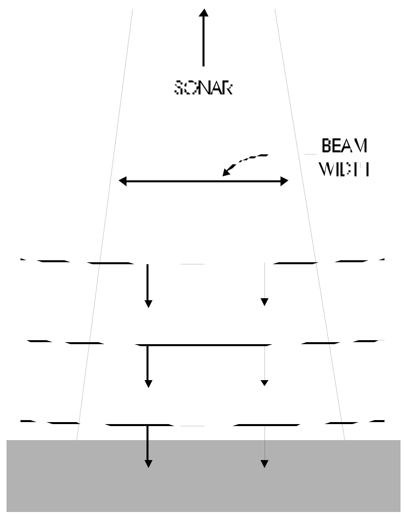

Figure Chapter 4 - -25: Specular Regime: Sonar Perpendicular to the Sea Floor

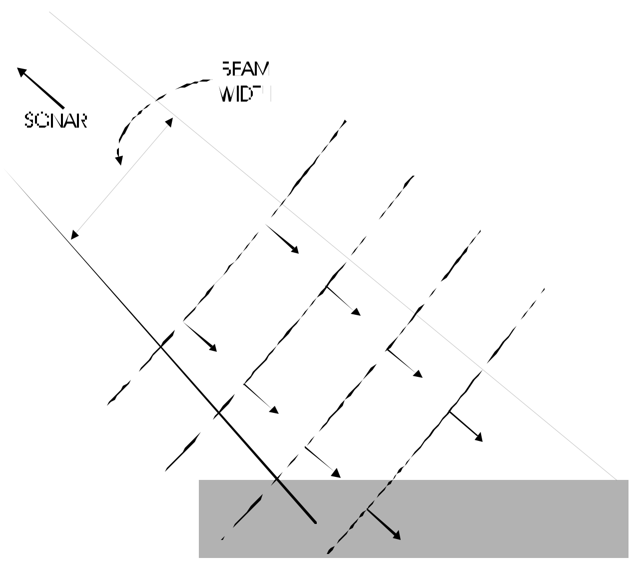

Figure Chapter 4 - -26: Non-Specular Regime: Sonar at an Angle to the Sea Floor

In the specular situation depicted in Figure Chapter 4 - -25, the spherical ping front from a sonar is almost parallel to the bottom and will simultaneously strike the bottom along a wide area. Within a sonar beam, the ping will produce a strong echo with a very short duration. An amplitude versus time plot of this event is pictured in Figure Chapter 4 - -27. On the other hand, a ping front in the non-specular situation depicted in Figure Chapter 4 - -26 will strike a small portion of the sea floor at a time and be in contact with the bottom for a long time as it propagates. Its echo will be weak in amplitude but long in duration as depicted in Figure Chapter 4 - -28.

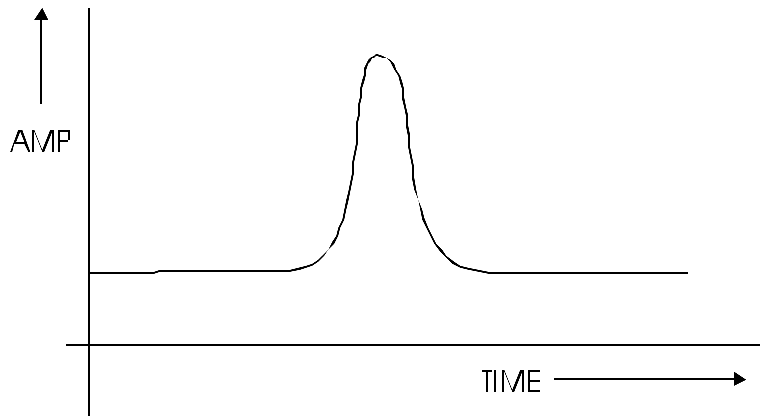

Figure Chapter 4 - -27: Amplitude versus Time Plot of the Echo Event in the Specular Regime

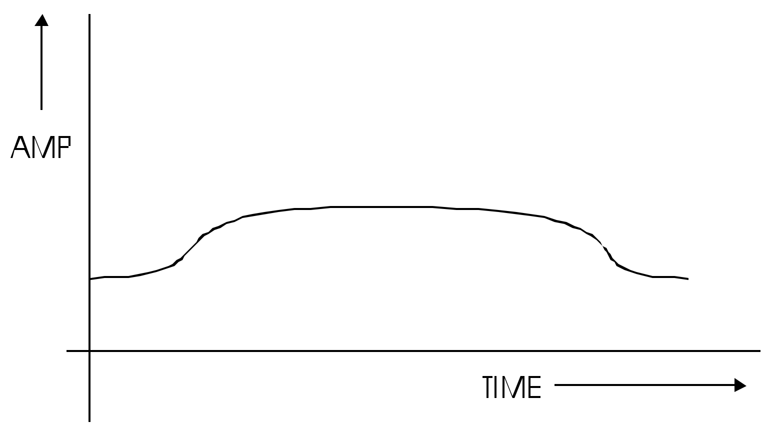

Figure Chapter 4 - -28: Amplitude versus Time Plot of the Echo Event in the Non-specular Regime

Recall that WMT processing holds fixed the angle of an echo within a beam (at the axis of the beam) and computes its TOA by amplitude weighted average. BDI, on the other hand, attempts to accurately fix the angle of an echo within the beam and calculate the TOA for it. You can see by looking at Figure Chapter 4 - -25 that finding an accurate angle in the specular case is not an easy task. Because the echo from all angles within the entire area observed by a beam arrive at the same time, there is little angle-specific information to work with. In this case, BDI computations would be unreliable. However, because the echo has such a short duration (see Figure Chapter 4 - -27), a precise calculation of its arrival time can be made using WMT processing. In the non-specular situation, accurate angle calculations can be made because the echoes from different angles within a beam are spread out over time. BDI processing produces good results in this situation. WMT processing, in contrast, would have difficulty accurately locating the time of an echo by amplitude-weighted mean, because the echo would have such a long duration with a poorly-defined amplitude peak (see Figure Chapter 4 - -28).

Because BDI results generate more accurate DOA information, the SEA BEAM 2100 system attempts to use them where possible. This is mostly in the non-specular regions, generally in the "outer" beams that are at large angles from the vertical (although you could imagine situations where the non-specular region would be directly below the survey ship, depending on the bottom configuration – see Figure Chapter 4 - -29). Where BDI calculations produce no results, WMT processing is used.

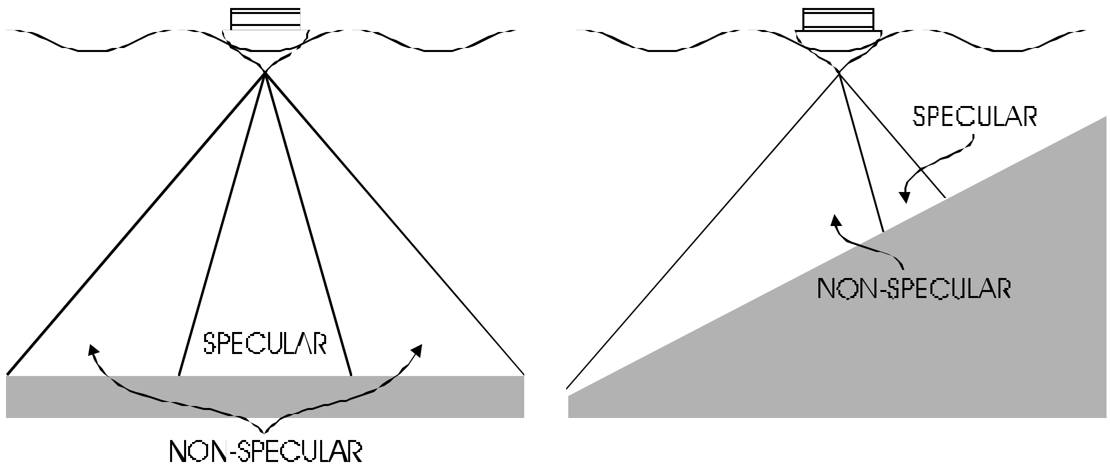

Figure Chapter 4 - -29: Specular and Non-specular Regimes with Different Sea Floors

Range Calculation and Bottom Location

The final stage in bathymetry processing is to convert echo DOA and TOA measurements into depths and positions. In doing so, the complications introduced by the pitch of the survey vessel at the time of the ping and changes in the velocity of sound at different ocean depths must be taken into account.

Consider a survey ship transmitting a single ping. At the time of transmission, the ship will have a pitch angle, which is recorded by the VRU system (see the "Motion Compensation" section above). Recall from the section, "Beam Formation," in Chapter 2, that the SEA BEAM 2100 transmits a fan-shaped beam, narrow in the alongtrack direction, but wide in the acrosstrack direction. This beam illuminates a strip of the ocean floor, ideally directly below the survey ship in a dead calm sea. However, because the ship will have a pitch angle at the time a ping is transmitted, the area ensonified by the ping will be offset in the alongtrack direction by the pitch angle (see Figure Chapter 4 - -30).

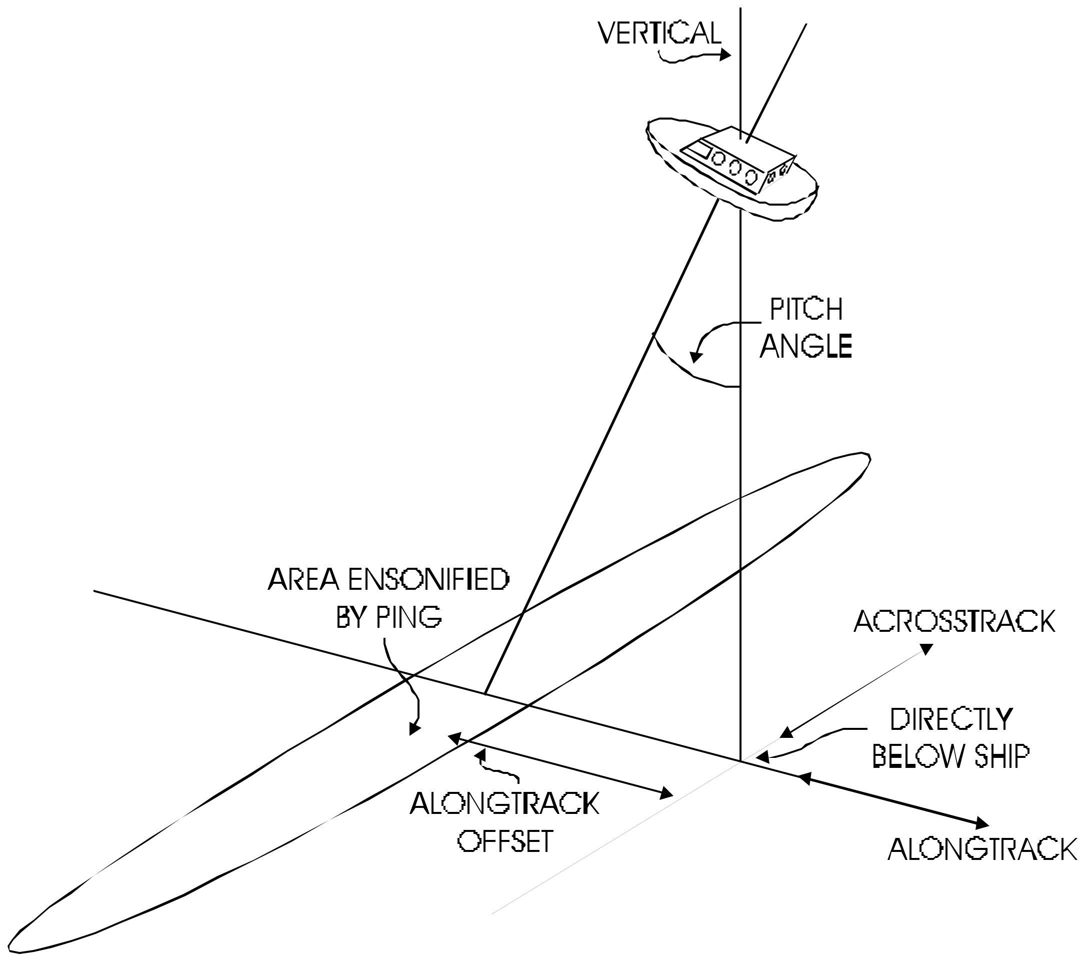

Figure Chapter 4 - -30: Offset of Ping Illumination Due to Pitch

Next, look at the echo from a single beam, which has an angle and TOA measurement from the WMT and BDI calculations. Recall from the “Beam Steering” section in Chapter 2 that the SEA BEAM 2100 beam is fan-shaped, narrow in the acrosstrack direction, but wide in the alongtrack direction. It observes echoes from a long, narrow strip of the ocean floor, but only sees echoes from transmitted pings in the small area where this strip intersects the area illuminated by the ping (see Figure Chapter 4 - -31). This position will have an offset in the along-track direction given by the pitch angle, and an offset in the across-track direction given by the beam DOAs. The angle between the across-track direction and the direction to the position of the echo is called the *bearing angle*. The angle between the vertical and the echo position (as seen by the ship) is called the *launch angle*. Both the bearing angle and the launch angle can be determined from the pitch and beam angles.

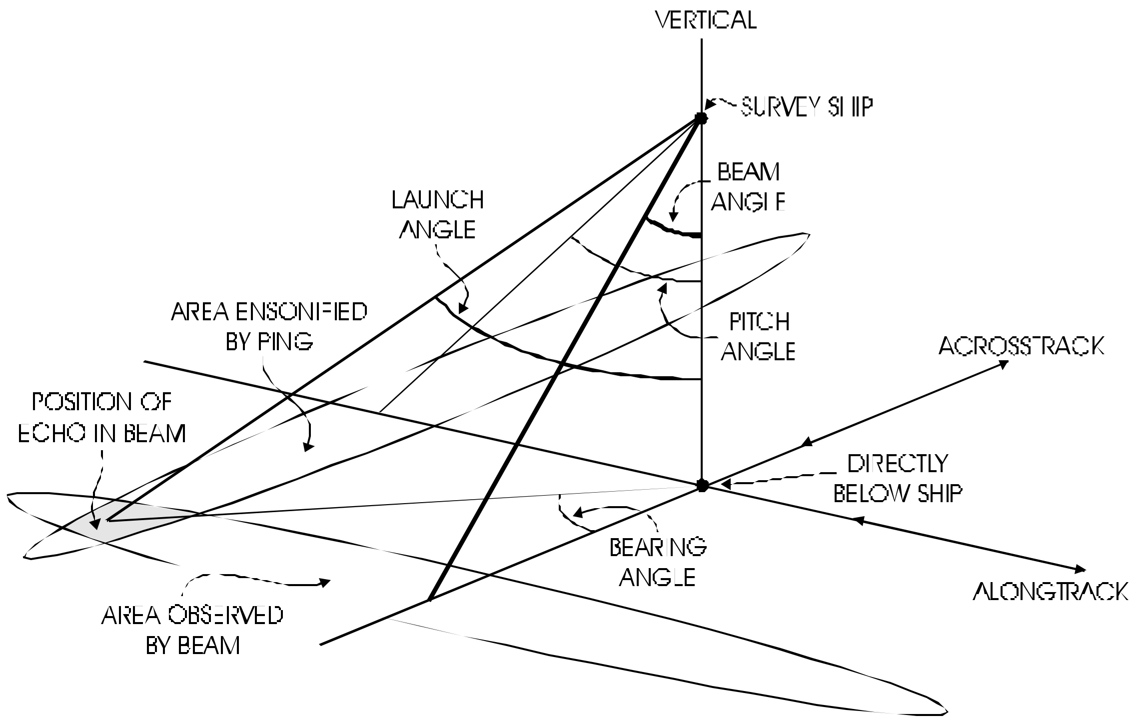

Figure Chapter 4 - -31: Position of the Echo in a Single Beam

The launch angle represents the angle at which an echo was received by the survey ship. The TOA of the echo represents the time it took the ping to travel to the position of the echo and back to the ship. Using these two values, you can compute the exact location of the echo in latitude and longitude and depth if you know the sound velocity characteristics of the ocean between the surface and the bottom.

Sound Velocity and Ray Tracing

The sound velocity characteristics of a typical ocean environment are very complex. Sound velocity in water depends on the salt content (or *salinity*) of the water, its pressure, and temperature. While salinity is a fairly stable quantity throughout the oceans, and changes in water pressure with depth follow well-understood laws, the temperature of ocean water can change from place to place, between different depths in the same place, and even vary from day to day. The most accurate bathymetry results only from a sonar system which has up-to-date information about the changes of the sound velocity as a function of depth (called the *sound velocity profile*) for the area in which it is operating.

The sound velocity profile of an area of ocean can be approximated by a set of layers, each with a different sound velocity. Sound traveling through different layers moves at different speeds. In addition, when changing from one layer to another, the direction of the sound changes. When traveling from a region of high sound velocity to one of lower sound velocity, a sound wave bends toward the vertical. When traveling from low to high speed regions, it bends away from the vertical. If you start with the launch angle and TOA of an echo, you can follow the path an the echo must have taken from the bottom, changing its angle based on the sound velocity profile (see Figure Chapter 4 - -32). Within each layer, you subtract the amount of time it would take the echo to travel through the layer at the appropriate angle (twice—once down, once back) from the TOA. Eventually, you are going to run out of time, yielding the location of the true echo. This process is called *ray tracing*. Using the location of the true echo, you can get the true depth to the echo, and the *bearing offset*—the distance between it and the position directly below the sonar. Combining the bearing angle (see Figure Chapter 4 - -31) and the navigation information of the survey ship with the bearing offset will give the exact longitude and latitude of the echo position.

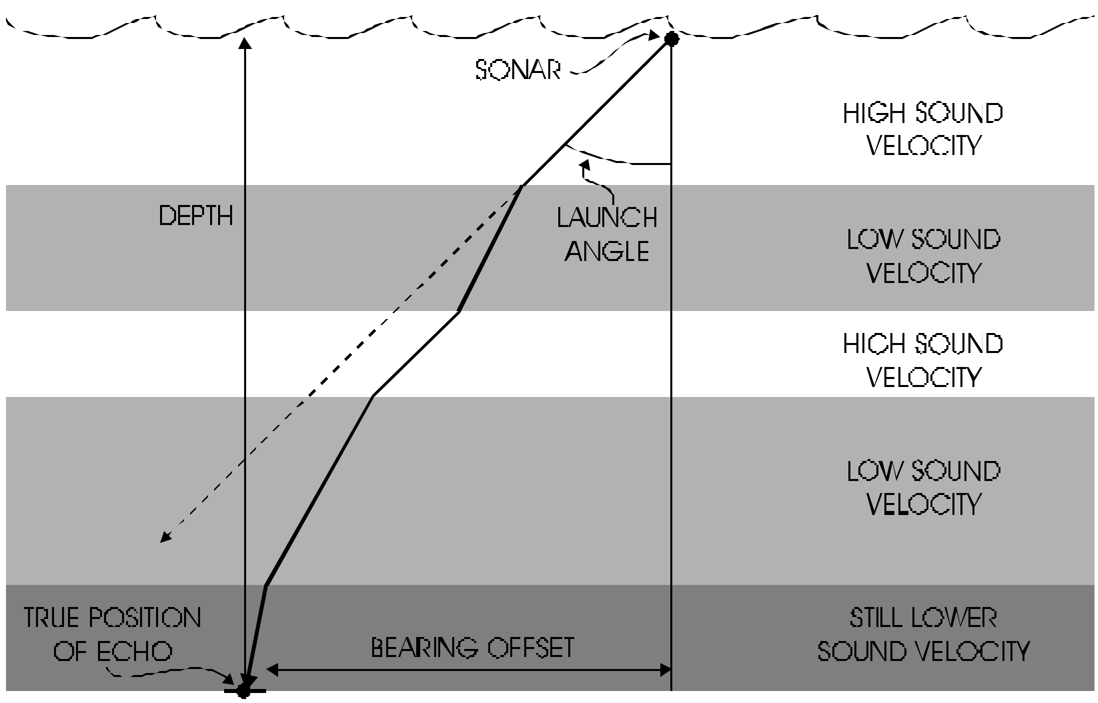

Figure Chapter 4 - -32: Ray Tracing to Find the Bottom

The SEA BEAM 2100 system uses a sound velocity profile with up to 29 layers of different sound velocity, which are described by 30 depth/sound velocity value pairs entered by the operator. Ray tracing is performed for each of the echoes reported by the BDI and/or WMT processing, yielding up the 151 echo depths and locations for each ping. This process makes the assumption that the velocity gradient is linear. Interested readers can refer to *Acoustical Oceanography* by Clarence S. Clay and Herman Medwin: John Wiley & Sons, 1977.

Chapter 5 - Sidescan Sonar

Previous chapters in this document presented sonar as a tool for finding water depths using the time delays of acoustic echoes. Yet this is only one function of sonar and only one of the two ways sonar is employed in the SEA BEAM 2100 system. The other way in which the SEA BEAM 2100 may be used is as a *sidescan* sonar. This section provides a description of sidescan sonar—how it works and what it is used for. It includes a detailed description of the SEA BEAM 2100 sidescan sonar system including an examination of the methods used for collecting and processing data.

Understanding Sidescan Sonar

Instead of measuring the depth to the ocean bottom, a sidescan sonar reveals information about sea floor composition by taking advantage of the different sound absorbing and reflecting characteristics of different materials. Some types of material, such as metals or recently extruded volcanic rock, are very efficient at reflecting acoustic pulses. Clay and silt, on the other hand, do not reflect sound well. Strong reflectors create strong echoes, while weak reflectors create weaker echoes. Knowing these characteristics, you can use the strength of acoustic returns to examine the composition of the sea floor. Reporting the strength of echoes is essentially what a sidescan sonar is designed to do.

Combining bottom-composition information provided by a sidescan sonar with the depth information from a range-finding sonar can be a powerful tool for examining the characteristics of an ocean bottom. Figure Chapter 5 - -1 shows an example of such a combination of data types. The seafloor canyon that was mapped in bathymetry in Figure 1-1 is shown mapped in sidescan. The bathymetry map clearly shows the shape of the canyon, while the sidescan indicates that the material forming the floor of the canyon, which is highly reflective, is different from that of the canyon walls and from the surrounding sea floor.

Figure Chapter 5 - -1: Example of Sidescan Mapping

How Sidescan Sonar Works

Sidescan sonar employs much of the same hardware and processes as a conventional depth-sounding sonar. Pulses are transmitted by a transmitter using a projector (or array of projectors), and hydrophones receive echoes of those pulses from the ocean floor and pass them to a receiver system. Where sidescan sonar differs from a depth-sounding system is in the way it processes these returns.

To explain the processing of a sidescan sonar, recall the description of a simple, single-beam echo sounding system in Chapter 2, “Sonar Concepts“ (see Figure Chapter 5 - -2). To briefly review, the transmitter of the single-beam echo sounder produces an acoustic pulse, or ping, which is transferred into the water by the projector. The ping expands as a spherical wave from its source, striking the sea floor at the point closest to the projector source. The ping is then reflected in a return spherical wave, part of which is detected by the hydrophone. The receiver records the returned echo, which can be illustrated by a plot of amplitude as a function of time (see Figure Chapter 5 - -3). The time between the transmission of the ping and the reception of its echo is used to compute the range to the sea floor.

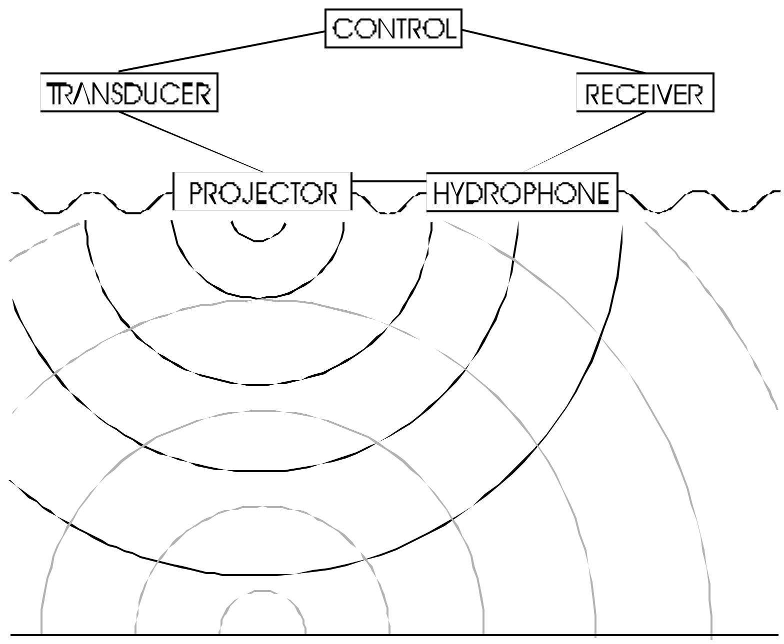

Figure Chapter 5 - -2: Single-Beam Echo Sounding System

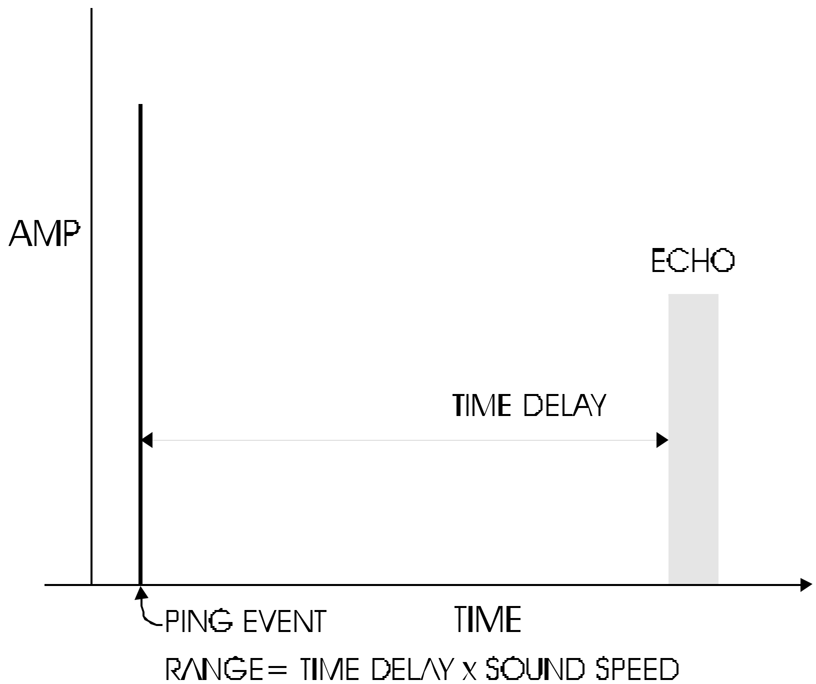

Figure Chapter 5 - -3: Plot of Amplitude as a Function of Time

This simplified picture does not consider what happens to the transmitted pulse *after* it first strikes the bottom, because a single-beam echo sounder is only interested in the time between transmission and the earliest return echo. Yet to a sidescan sonar, the first returned echo only marks when things start to get interesting. Look at what happens to the transmitted pulse as it continues its spherical propagation.

Figure Chapter 5 - -4 shows the single-beam echo sounder schematic at a time shortly after the ping first intersected with the bottom. At this time, the first return echo is on its way back to the hydrophones. But the ping is still expanding, and in our schematic is intersecting the bottom at two points. These points also create echoes. They are weaker than the first return (remember, as the spherical pulse expands and propagates, it loses power), and they occur after it does (because it took the ping longer to get to them). It is easy to see that as the pulse front continues to propagate, it will produce a continuous series of weakening echoes in time. If the receiver continues to collect these echoes, it will see a amplitude versus time sequence similar to the one pictured in Figure Chapter 5 - -5, with a strong first bottom echo followed by a declining slope of continuous returns.

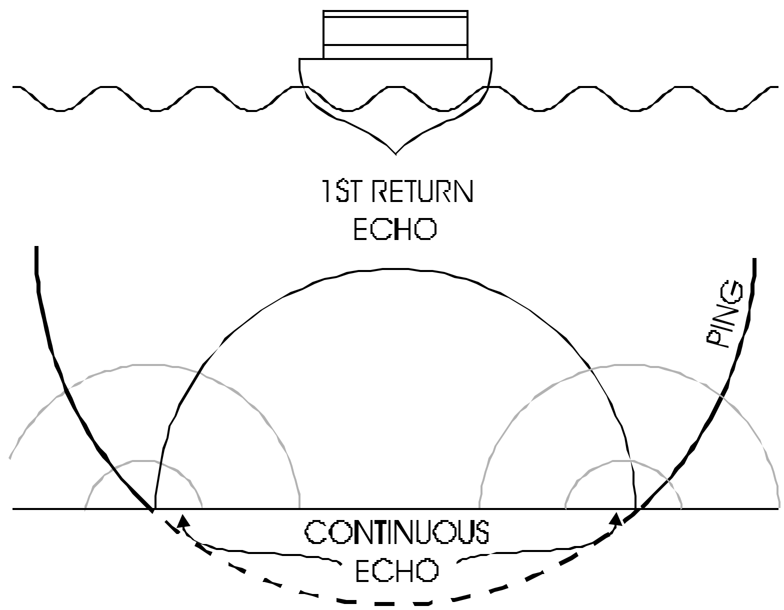

Figure Chapter 5 - -4: Single-Beam Echo Sounder Schematic

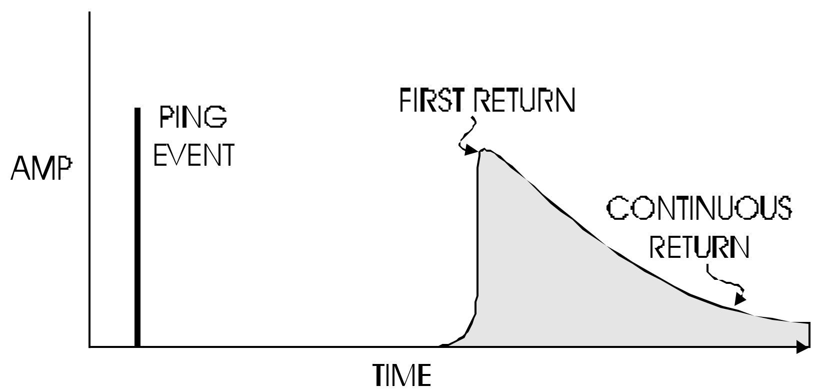

Figure Chapter 5 - -5: Amplitude Versus Time Sequence

Thus far, this discussion has ignored the characteristics of the ocean bottom. Although unstated, the assumption to this point has been that the bottom is perfectly flat and perfectly uniform. Consider now what happens when some detail is added to the ocean bottom. Figure Chapter 5 - -6 redraws the schematic (shown in Figure Chapter 5 - -4) with a spherical pulse front some time after the first bottom echo. In this case, however, a box represents detail on the bottom. This box is more efficient at reflecting acoustic energy than the surrounding uniform bottom. Because of this, the energy of its echo is slightly higher than that of the surrounding bottom, which causes a small jump in the amplitude measured by the receiver at the time of its return. An observer looking at the amplitude versus time sequence in Figure Chapter 5 - -7 would be able to discern from this jump that some discrete feature exists on the bottom.

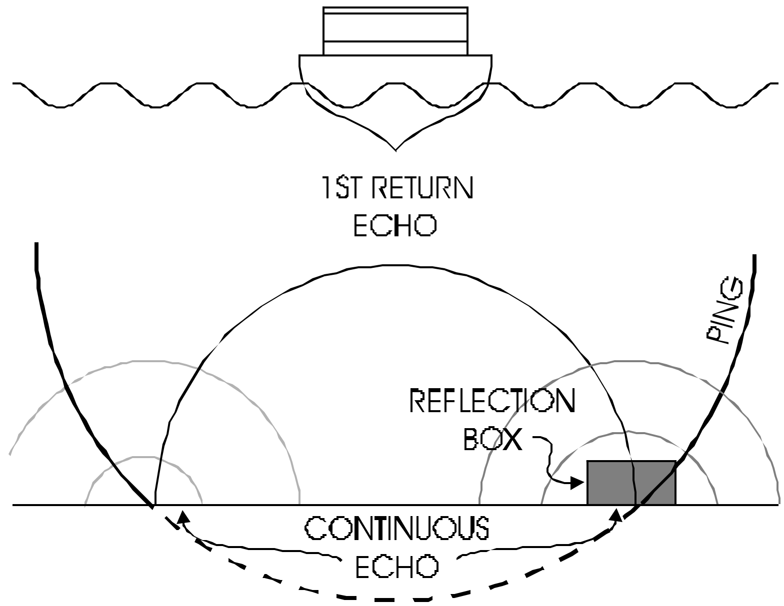

Figure Chapter 5 - -6: Schematic with a Spherical Pulse Front with a Detailed Bottom

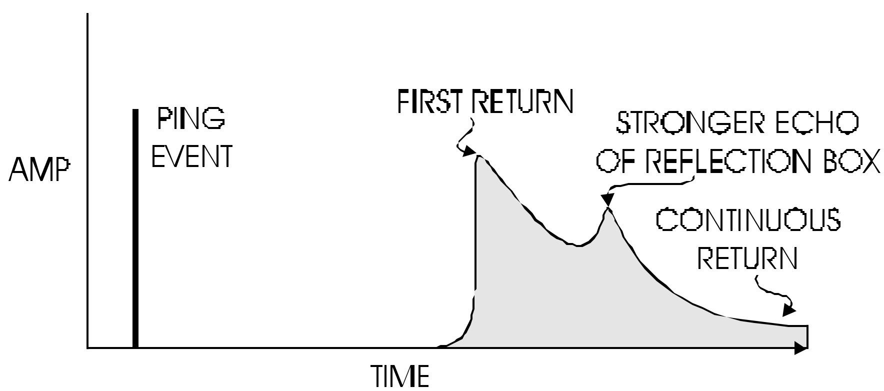

Figure Chapter 5 - -7: Amplitude Versus Time Sequence

In reality, of course, ocean bottoms can be very complex. They may be composed of many different components, all with different acoustic reflection characteristics. True amplitude versus time sequences observed by receivers are similarly complex.

A Basic Sidescan Sonar

As a practical instrument, the simplistic sidescan sonar described above is not very useful. While it provides the *times* of echoes, it does not provide their *direction*. Returning to the example presented in Figure Chapter 5 - -6 and Figure Chapter 5 - -7, the sidescan sonar detects a bottom feature (the box). From the amplitude versus time plot in Figure Chapter 5 - -7, an observer can tell there is a highly reflective feature on the bottom. From the time difference between the first echo (which is presumed to be due to the bottom directly below the sonar system) and the echo of the reflective feature, the observer can compute the range to the feature from the sonar. But remember, this is all the information the observer has.

Figure Chapter 5 - -8 shows the bottom in this example redrawn from an overhead view. The “X” marks the point on the sea floor where the ping strikes first, creating the first return echo. After striking at the “X,” the spherical pulse front continues to propagate, intersecting the bottom in an expanding circle, eventually striking the bottom feature represented by the box. The observer can compute the range R between the “X” and the box, but otherwise does not know where on the ring of the expanding wave front the box is. In the real world, where sidescan sonars are used to locate objects such as rock formations or sunken vessels on the bottom, it is easy to see that this simple depth sounder amplitude information is too limited to be useful.

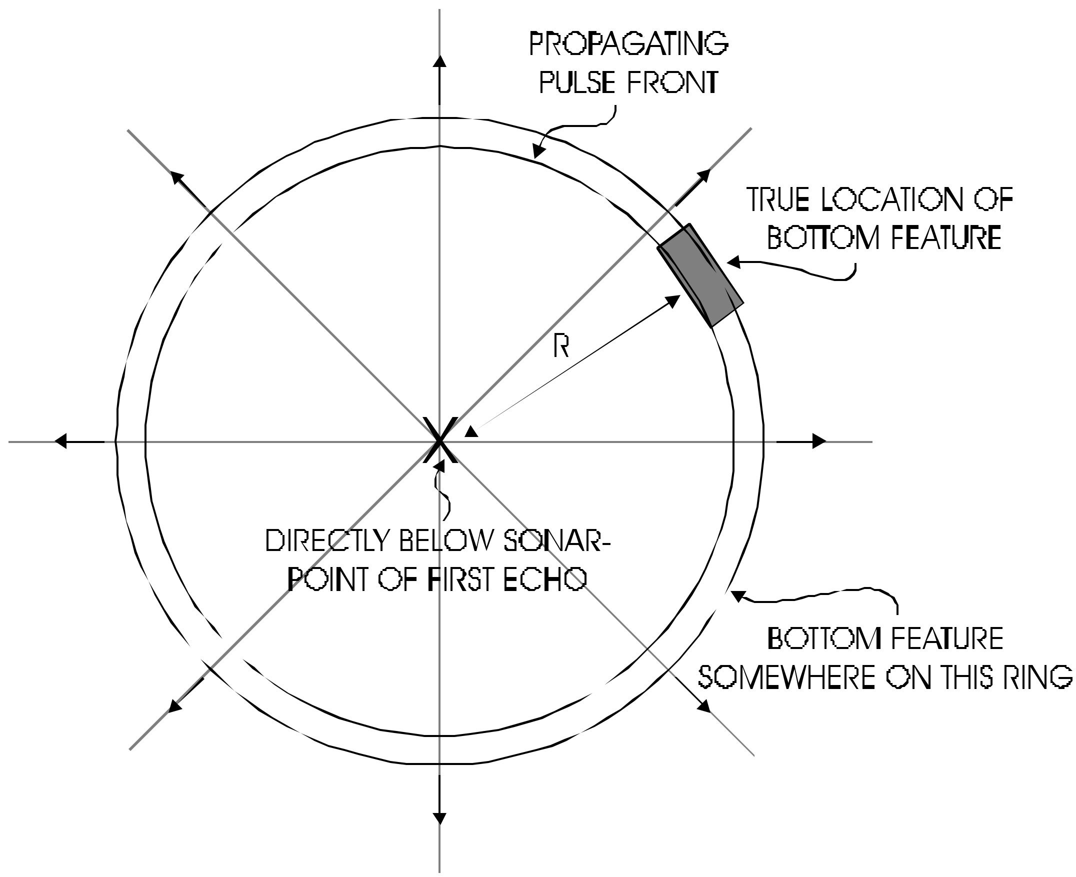

Figure Chapter 5 - -8: An Overhead View of the Bottom

Most sidescan sonars deal with this problem by introducing some *directivity* to their projected pulses, and, to some degree, their receivers. This is done by using a *line array* of projectors to send pulses. The long axis of the line array is oriented parallel to the direction of travel of the sonar survey vessel (often the arrays are towed behind the ship). Recall from the discussion of Beam Forming in Chapter 3 that a line array of projectors sends a circular pulse that expands in a plane perpendicular to the long axis of the array. Figure Chapter 5 - -9 shows a survey vessel towing a line array, and the propagation of circular pulses from that array. These pulses first strike the bottom directly below the sonar system, and then their intersection with the sea floor travels away from the array in either direction. Echoes are returned first from the bottom directly below the array, followed by echoes from points farther and farther away along a line perpendicular to the array axis and the survey ship' s track.

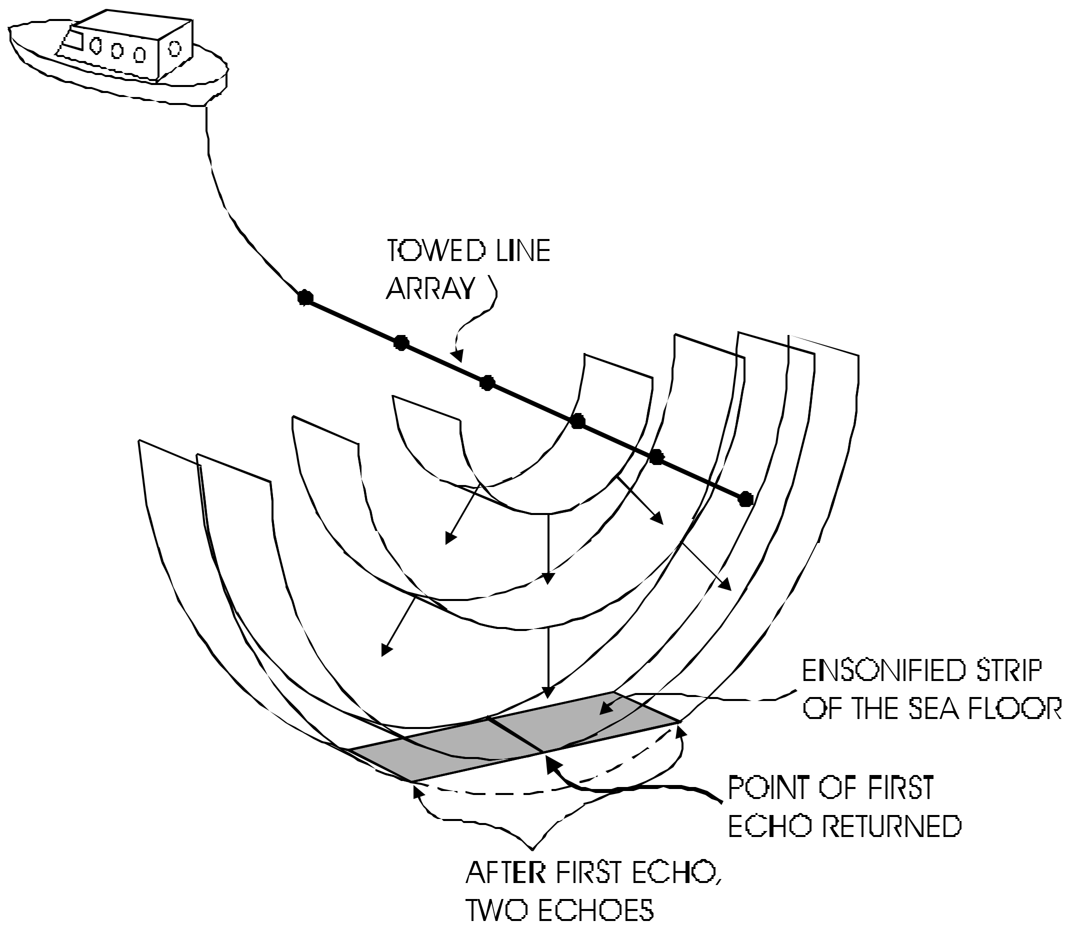

Figure Chapter 5 - -9: Survey Vessel Towing a Line Array

Sidescan sonars can receive the echoes from the bottom using two hydrophones, each set up to receive the returns from one side of the ship’ s survey track. In reality, instead of one projector and two hydrophone arrays, two line arrays are used as transducers. One transmits a fan beam towards the port side and then listens to its returns, and the other does the same on the starboard side. To understand the reason for this arrangement refer again to Figure Chapter 5 - -9. When a pulse front first strikes the bottom below the survey vessel, an echo returns from only the one point of intersection. Later, however, the pulse front intersects the bottom at two points, one on each side of the ship. The echoes from these two points would occur simultaneously, and a single hydrophone system would have no way of distinguishing between them. If, however, two separate hydrophones each record the echoes from only one side of the ship, there would be no such confusion. The name *sidescan* is used for historical reasons—because these sonars were originally built to be sensitive to echo returns from bottom locations on either *side* of a survey ship, instead of directly below as was the case for a traditional single-beam depth-sounder. With the advent of multibeam sonars such as the SEA BEAM 2100, which map both depth and sidescan across a swath of the bottom, the distinction inherent in this name has become less meaningful.

In practice, sidescan sonars tend to mount both the line array and hydrophones on a *towfish*, a device that is towed in the water somewhat below the surface behind a survey vessel. As the survey vessel travels, the towfish transmits and listens to the echoes of a series of pulses (see Figure Chapter 5 - -10). The echoes of each pulse are used to build up an amplitude versus time plot (or *trace*) for each side of the vessel (see Figure Chapter 5 - -11). To adjust for the decline in the strength of echoes due to attenuation, a time-varying gain is applied to the amplitude values so that sea floor features with similar reflectivities have similar amplitudes. Eventually the noise inherent in the system (which remains constant) becomes comparable to the amplitude of the echo, and the amplified trace becomes dominated by noise. Recording of each trace is usually cut off before this occurs so that the next ping can be transmitted.

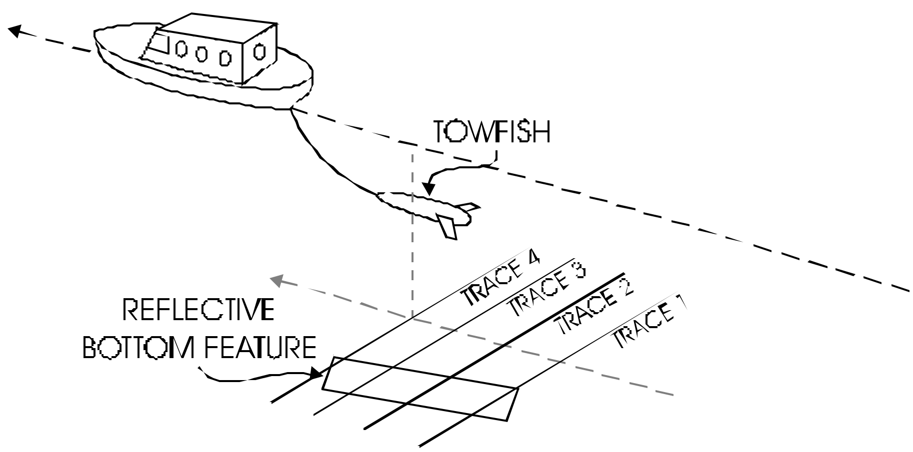

Figure Chapter 5 - -10: A Sidescan Sonar Measuring a Featured Ocean Floor with Four Pings

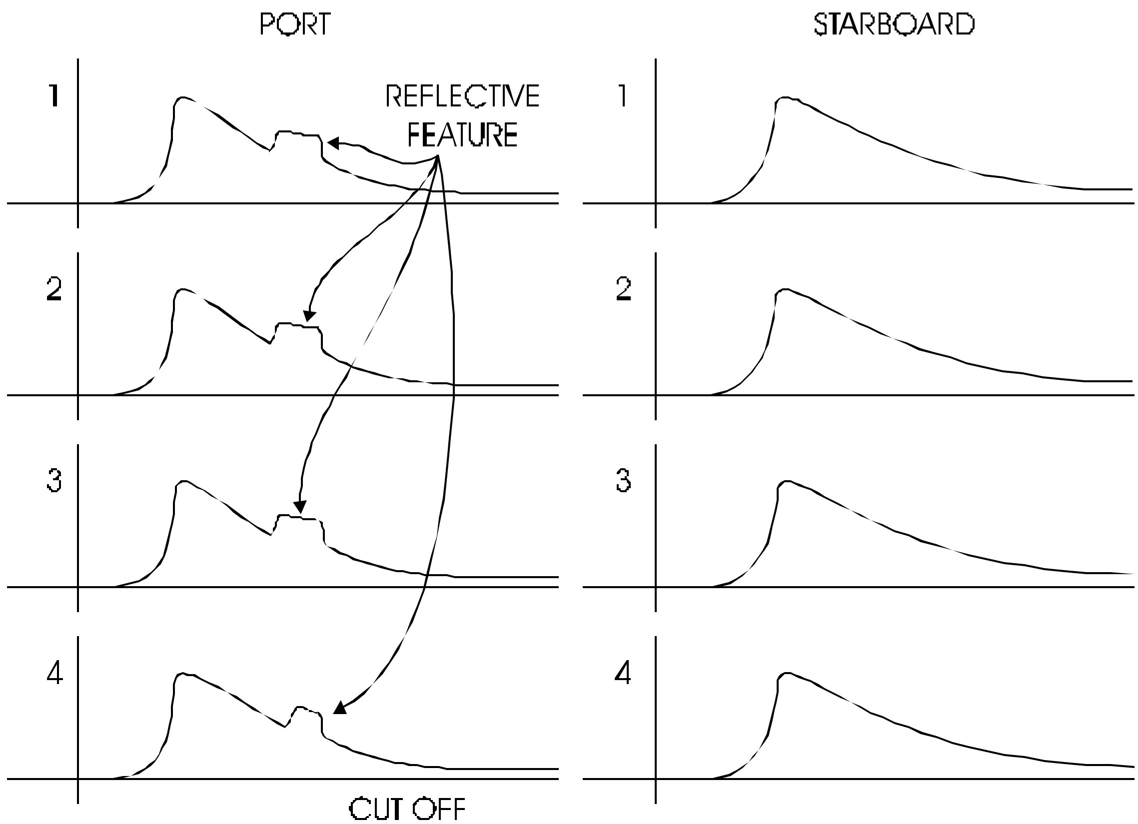

Figure Chapter 5 - -11: Amplitude Versus Time Plot for the Four Pings in Figure Chapter 5 - -10

Each trace is converted into a series of gray shades on a plotting device. The shade of gray is determined by the amplitude (white corresponding to high amplitude, black to low amplitude, or vice-versa). The port and starboard traces are plotted next to and facing each other so that the ship' s track is at the center of the picture, and subsequent pairs of traces are plotted in series to build up a "picture" of the bottom (see Figure Chapter 5 - -12).

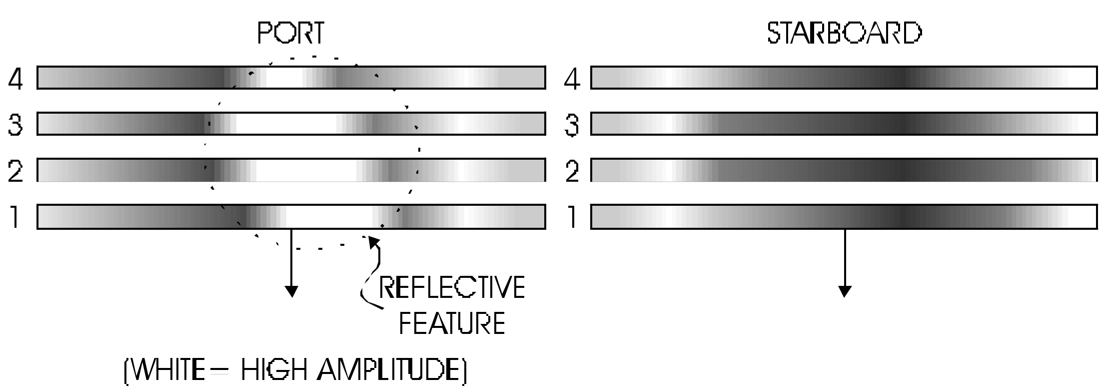

Figure Chapter 5 - -12: Port and Starboard Traces Plotted in Series

Figure Chapter 5 - -13 shows a sample of sidescan data from a SEA BEAM 2100 survey. In the figure, the survey vessel has traveled from the upper left to the lower right, and dark gray shades represent higher amplitude echoes.

Several hundred sidescan swaths, showing both port and starboard, are represented by the many parallel gray lines that cross the ship' s track. The noisy dark area across the middle is directly below the ship' s track. Clearly visible on the starboard (lower) side of the ship' s track are two dark lines, which are the sidescan echoes of undersea pipelines.

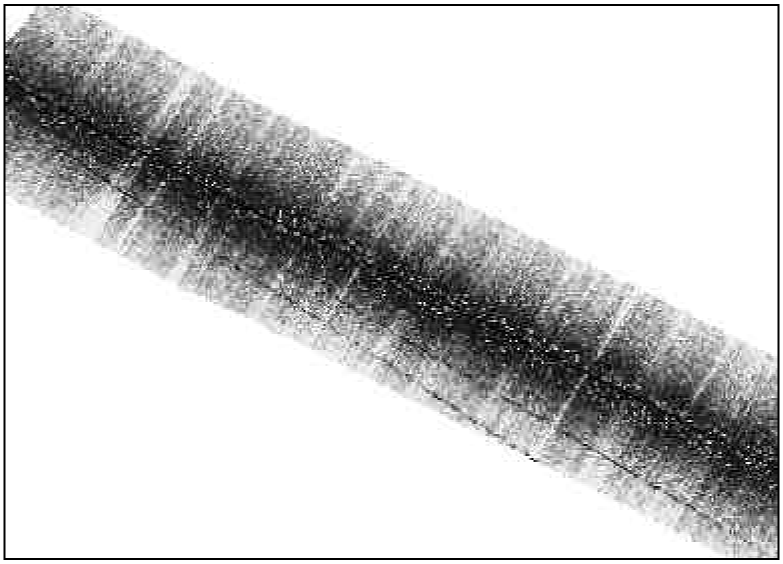

Figure Chapter 5 - -13: Undersea Pipelines Detected Using Sidescan Sonar

Limitations of Traditional Sidescan Sonar

In the above treatment of sidescan sonar, note that all of the examples deal with a flat ocean floor. In reality the ocean floor is far from flat, which introduces uncertainties in the interpretation of sidescan data. Recall that the only information a traditional sidescan sonar provides is a series of echo amplitudes as a function of time. The directivity of the sonar indicates which direction these echoes were coming from. But an observer cannot really be sure of the exact location of the sources of these echoes.

This problem is illustrated in Figure Chapter 5 - -14, which shows only one half of a traditional two-hydrophone sidescan sonar. In this case, the sonar is surveying over an area that has a sharply sloped bottom. The first place the circular pulse fronts strike the bottom is not directly below the survey vessel, but at a point on the sloped bottom well off to the side. This is the point that will cause the earliest amplitude on the amplitude versus time trace (see Figure Chapter 5 - -15). The point directly below the sonar will cause an echo at a slightly later time. At this same time, two points on the slope will be causing an echo. Because they occur at the same time, the echoes of these three widely separated points will be confused on the trace. It is clear that by looking at only the amplitude versus time trace in this example, an observer would not have an accurate picture of the sea floor. Because of this problem, traditional sidescan sonars are really only useful for flat or near-flat bottoms, or when used in combination with bathymetry information.

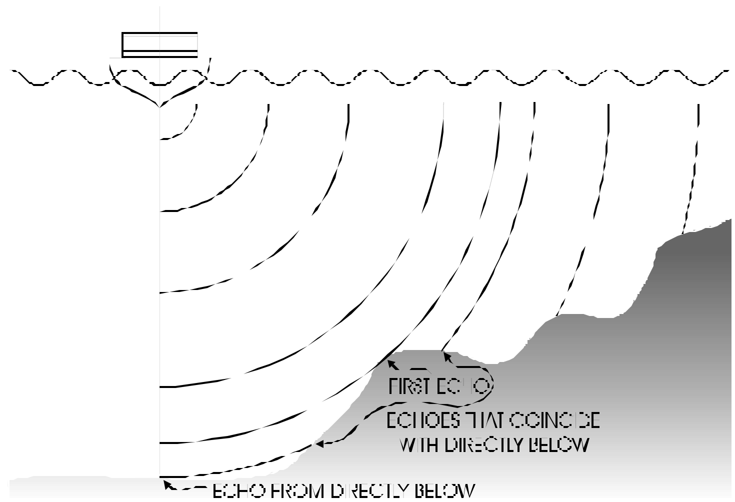

Figure Chapter 5 - -14: Half of a Two-Hydrophone Sidescan Sonar

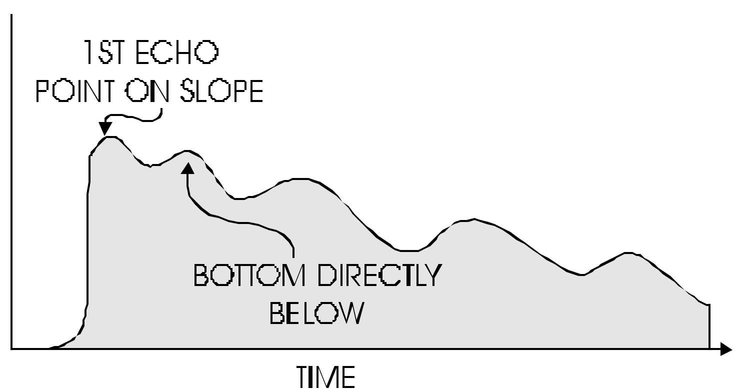

Figure Chapter 5 - -15: Amplitude versus Time Plot for the Situation Depicted in Figure Chapter 5 - -14

The SEA BEAM 2100 Sidescan Sonar

While primarily designed as a depth-sounding instrument, the SEA BEAM 2100 simultaneously provides sidescan data of the ocean bottom. This sidescan data measures roughly the same swath area covered by the depth information, but with considerably better resolution. Where the depth measurements are limited in their resolution to 151 beams of roughly 1°-widths, the sidescan divides the swath width into 2000 pixels of data. Unlike traditional sidescan sonars that use a flat-bottom assumption to find the location of objects on the ocean floor, the SEA BEAM 2100 sidescan information is *co-located* with the measured depths, so an observer can tell not only the amplitude of a return as in conventional sidescan but also *where it is* on the bottom. This co-located data allows bottom features to be examined in terms of their geometry, shown by the depth information and their composition as indicated by their sidescan returns.

To maximize the sidescan capabilities of the SEA BEAM 2100, you need to understand the processes used to collect it. This section gives a brief overview of the steps of sidescan data collection performed by the sonar, with particular emphasis on where and when sidescan returns can be influenced by user intervention.

Producing Sidescan Data With the SEA BEAM 2100

The SEA BEAM 2100 sidescan sonar uses the same hardware as the depth-sounding sonar. In fact, it uses the same pings and much of the same processing. Only fairly late in the data processing do the procedures for measuring bathymetry and generating sidescan imagery diverge. This arrangement allows the SEA BEAM 2100 to produce both types of data without much more computation than would be required for each individually.

As described in previous chapters, the projectors in the SEA BEAM 2100 system are arranged in a line array, similar to a traditional sidescan sonar. The projector array is aligned with the direction of travel of the survey vessel, although rather than being towed, it is mounted on the ship’ s hull. This array ensonifies a strip of the bottom perpendicular to the survey vessel’ s track. Instead of using line arrays for both transmission and reception in traditional sidescan sonar, the SEA BEAM 2100 has an array of hydrophones (between 48 and 80, depending on the installation), mounted athwartship—at right angles to the projector array. The data from the hydrophones is processed to extract both amplitude and angle information. While this processing is a complex procedure, it can be understood as a series of fairly straight-forward steps.

Many of the steps in the procedure are the same as those required for bathymetry measurement. Specifically, the processing required for Beam Forming and Beam Steering, High-Resolution Angle Estimation and Adjusting Final Angles for Roll is identical for both types of measurements. These processes are all described in detail in earlier chapters (Beam Forming and Beam Steering in Chapter 3, and Angle Estimation and Roll Compensation in Chapter 4). To briefly review:

- Beam Forming and Beam Steering – The amplitude and phase information from all of the elements in the hydrophone array are passed through an FFT to obtain amplitudes detected by several steered beams (the number of beams depends on the installation).
- High-Resolution Angle Estimation – The measurements of all beams in each time interval are collected into a time slice. Within each time slice, the response pattern of the beam is used to precisely determine the angle to specific echo events that occur in that time slice.
- Adjusting Final Angle for Roll – The angles measured in the above item are adjusted to the changing angle of the hydrophone array, yielding the true angles to echoes on the sea floor.

BDI bathymetry and sidescan processing essentially share the result of these three procedures. Emerging from them is a list of time slices, each with amplitudes and direction angles for a number of echo events (called hits). At this point, the Bathymetry and Sidescan processing diverge.

Mapping Sidescan Values for 2000 Pixel Resolution

The final stage of sidescan data processing is mapping the detected echoes to build an image of the sea floor. In detecting the echoes of a specific ping, the SEA BEAM 2100 monitors the particular set of sequential time slices that generally range between when the first (nearest) and last (farthest) bottom echoes are expected. This range is controlled by the SEA BEAM 2100 operator through the Start and Stop Gates settings (see Chapter 9 of the *SEA BEAM 2100 Operator's Manual* for information about the theory and operation of the Start and Stop Gates settings).

Recall that the sidescan process collects the echoes from a swath of the sea floor that is oriented perpendicular to the path of a survey vessel. For each bottom swath, the SEA BEAM 2100 sidescan data is mapped into an array of 2000 pixel locations. This array contains the amplitudes of echoes from the sea floor. The physical size represented by these 2000 pixels is determined by the value of *sidescan pixel size*, which is set by the SEA BEAM 2100 operator (see Chapter 10 of the *SEA BEAM 2100 Operator's Manual* for information on setting sidescan pixel size). For instance, if the sidescan pixel size is set to 2 meters per pixel, the 2000-pixel sidescan swath is 4000 meters wide. In all cases the mapped swath is centered directly below the path of the survey vessel.

The echoes from all relevant time slices are added to the sidescan swath array. The echo angles are converted to physical locations on the bottom based on sound velocity. These are then mapped into the pixels in the sidescan swath array (see Figure Chapter 5 - -16). Amplitudes of echoes that fall within the physical limits of the 2000 pixel swath are retained; all others are discarded. At the conclusion of the process, some pixels will have no echoes recorded in them, some will have one, and others will have many. Pixels that have one echo are assigned the amplitude of that echo. If a pixel has more than one echo, the average of the amplitudes is used. Pixels with no reported echoes are assigned a value interpolated from neighboring pixels.

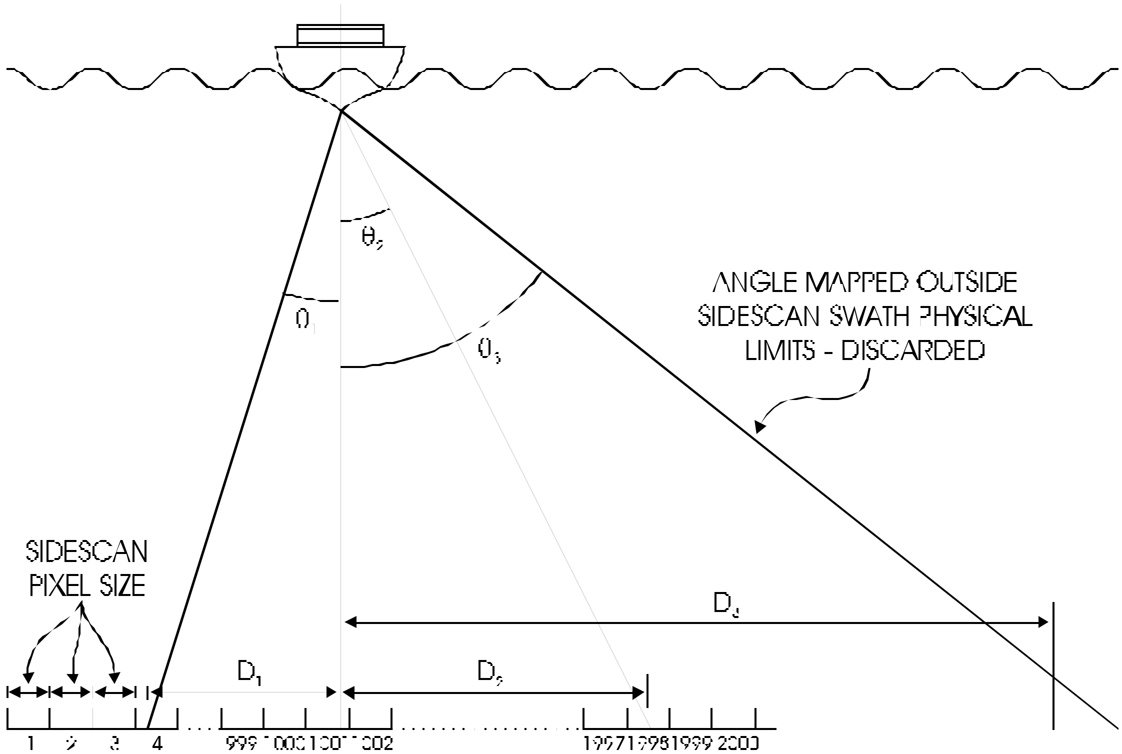

Figure Chapter 5 - -16: Mapping Hits in the Sidescan Array

The 2000 amplitude values that result from this process are recorded in the sidescan sonar record.

Display of Sidescan Data

The SEA BEAM 2100 displays the 2000 pixels of sidescan data as gray scales on both the operator control station screen and a thermal graphic recorder. To accomplish this, the amplitude values of the sidescan data are converted to gray scales.

The amplitude values are first converted to dB power units using the following conversion formula:

Power (dB) = 20.0 x log10 (Amplitude)

The conversion of power to gray scale is governed by the SEA BEAM 2100 operator through the values of *gray scale minimum* and *gray scale maximum*. See Chapter 10 of the *SEA BEAM 2100 Operator's Manual* for information on setting these values.

Glossary of Terms

absorption loss	The energy lost by a propagating wave to the medium in which it is traveling.
acoustic energy	The energy carried by a sound wave.
acrosstrack	See athwartship.
active sonar	A device that makes remote measurements in a water medium by transmitting sounds and processing their echoes off remote targets.
alongtrack	Dorection parallel to a ship's keel and its direction of motion.
amplitude	The measured size of the oscillations of a wave.
analog signal	A measurement that is continuous in time.
angle of incidence	The angle at which a sound pulse strikes a medium, usually measured with respect to the perpendicular.
athwartship or **acrosstrack**	The direction that is perpendicular to a ship's keel.
attenuation	Any loss in energy of a propagating wave.
backscattering strength	The fraction of incident energy per unit area that is directed back from the ocean bottom in the direction of the projector.
bathymetry measurement	See echo sounding.
beam	Used to describe focusing of acoustic energy by a hydrophone system or of sensitivity to received acoustic energy within a narrow solid angle.
beam forming	The process of using projector arrays and hydrophone arrays to produce narrow transmit beams and receive beams.
beam pattern	A description of the focusing of transmitted or received acoustic energy within a beam as a function of angle. Also called a power pattern or directivity pattern.
beam stabilization	See motion compensation.
beam steering	The process of using time delays or phase delays to direct the beams of a hydrophone array at specific angles.
beam width or **beam solid angle**	A measurement of the size of the main lobe of a beam pattern. Measured at the half power point.
bearing angle	The angle between the direction to a bottom echo and the athwartship direction, measured on the sea floor.

Bearing Direction Indicator (BDI)	One of two algorithms used by the SEA BEAM 2100 to convert steered beam data into Time of Arrival (TOA) and Direction of Arrival (DOA) measurements for bathymetry. See also WMT.
center of mass	A point in space within an object about which its weight is evenly distributed and about which it will rotate.
compressional wave	A wave that propagates through a medium such that oscillations occur in the direction of propagation Compare to translational wave.
constructive interference	The overlap of two or more wave patterns in phase, such that their peaks and troughs coincide creating new, higher peaks and new, deeper troughs, respectively.
degrees of freedom	The number of different ways in which an object may move, including both translational and rotational motion.
destructive interference	The overlap of two or more wave patterns out of phase, such that the peaks of one wave line up with the troughs of another, effectively canceling them.
detection threshold	A predicted amplitude value applied to the values in a time slice to eliminate the noise from the true echoes of the sea floor.
digital signal or **discrete signal**	A representation of an analog signal by periodic measurements of its amplitude with a frequency sufficient to uniquely identify the signal's analog qualities.
direction angle	The angle at which the axis of a beam is directed, and where it has peak sensitivity (in the case of a hydrophone array) or where it transmits peak energy (in the case of a projector array).
directivity	A measure of the degree to which a beam pattern is focused, such that narrow beam patterns have high directivity and wide beam patterns have low directivity.
directivity patterns	See beam patterns.
discrete Fourier Transform	A Fourier Transform that is accomplished by means of a sum of discrete values, rather than by using an integral.
Dolph-Chebyshev shading	A shading technique that generates uniform, low level side lobes in a beam pattern.
dynamic threshold	The computation of detection thresholds for individual time slices based on the specific content of each time slice.
echo	The acoustic energy of a sound that has "bounced" off a remote target.
echo sounder	The instruments used to make bathymetric measurements, for example, SEA BEAM 2100.

echo sounding or **bathymetry measurement**	Remote measurement of the depth of the ocean floor.
element spacing	The distance between projectors or hydrophones in an array.
ensonify or **illuminate**	To bathe a target or area on the sea floor with transmitted sound.
far field	A regime in which the distances to objects of remote sensing is much larger than the size of the device doing the remote sensing, allowing a simplification of the mathematics involved through approximation. In a sonar, far field approximations are valid if the ocean depth is much larger that the size of the sonar.
Fast Fourier Transforms (FFT)	An algorithm used to solve a discrete Fourier Transform with minimal computation time.
first side lobes	The first and strongest side lobes outside of the main lobe of a beam pattern.
frequency	The number of oscillations of an acoustic wave that pass an individual hydrophone each second.
heave	Ship motion in the vertical direction.
hydrophone	A device that “listens” to sounds in water by converting the physical oscillations it experiences due to impinging sound waves into voltages.
illuminate	See ensonify.
isotropic expansion	The expansion of transmitted energy such as a pulse of sound, such that it is propagating equally in all directions.
isotropic source	A source of an isotropically expanding signal, such as a single small projector.
half power point	The point on the main lobe of a beam pattern at which it is transmitting or receiving at half of its peak power.
high-resolution angle estimation	The process by which the steered beam data is used to estimate the angles of echoes to a high degree of accuracy. Part of BDI processing.
hydrophone array	A group of hydrophones that collectively process incoming signals, usually with the purpose of beam formation and beam steering.
impedance	A measure of the “resistance” of a material to a wave propagating through it. For sound waves, the impedance is a product of a material’s density and the sound speed within it.
interference	The interaction of wave patterns from more than one source, which causes new wave patterns. Can be constructive, destructive, or a combination of both.

launch angle	The angle between the vertical and the direction of arrival of an echo, including offsets due to pitch.
line array	A projector or hydrophone array where the elements of the array are arranged in a line.
local speed of sound	The speed at which a sound wave will travel in a medium. In water, the sound speed is a function of the salinity, pressure, and temperature of the water, but is independent of the characteristics of the sound itself.
main lobe	The part of a beam pattern into which the bulk of energy is transmitted to or received from.
maximum response axis (MRA)	The angle of a beam pattern at which maximum power is transmittted or received.
mounting angle	The angle at which a hydrophone array is fixed to the bottom of a ship, measured such that a horizontal array has a mounting angle of zero.
motion compensation or **beam stabilization**	The process by which the motions of a survey vessel are removed from sonar data to make bathymetric measurements in the Earth-centered coordinate system.
multibeam sonar	An instrument that can map more than one location on the ocean floor with a single ping and with higher resolution than single-beam echo sounders.
noise discrimination	A process by which noise is ignored and signals are extracted from a noisy sonar input.
noise level	The magnitude of unwanted spurious signals in the sonar input.
non-specular regime	The situation where the echoes from the bottom are scatter-dominated, usually where the sonar is at an angle to the perpendicular to the sea floor.
passive sonar	Listening devices that record the sounds emitted by objects in water (seismic events, ships, submarines, and marine creatures, which all emit sounds on their own).
peaks	Maximum values of the amplitude of a wave.
phase delay or **phase difference**	The fractional number of oscillations of a wave as it propagates some distance.
phase shift	A change in the phase of a signal applied to compensate for a phase delay.
ping	A short pulse of sound generated by an active sonar for undersea measurement.

ping cycle	A continuous cycle for a depth sounder used to collect a series of depth measurements as the ship it is mounted on travels.
ping time or **ping interval**	The amount of time required for return echoes and processing between the transmission of pings.
peaks	The high pressure regions in the series of pressure oscillations that make up a sound wave.
pitch	Rotation of a ship about the acrosstrack dimension.
power	The energy of a sound wave per unit time. Computed as the square of the amplitude of the wave.
principle of reciprocity	A transducer instrument acting as a hydrophone will produce a beam pattern identical to that of it acting as a projector.
projector	A device that transmits sound into water.
projector array	A group of projectors that collectively produce sounds, usually with the purpose of beam forming and beam steering.
resolution	A characteristic of a sonar that is determined by the size of the beam solid angle.
roll	Rotation of a ship about the alongtrack dimension.
roll bias	An offset angle in the roll direction that depends on the ship configuration but is stable over short periods of time. Measured during calibration of a sonar system and applied to all measured angles.
roll offset angle	The combination of all angles about the alongtrack dimension, including time-dependent roll, roll bias, and mounting angle.
salinity	The relative salt content of the ocean, part of sound velocity profile computations, usually in parts per million (PPM).
sampling rate	The time between digital measurements of an analog signal.
scatter	Energy that bounces off a target in all directions (in other words, is not reflected).
selected beam	An operator-selected angle at which the echoes received by the sonar are reported as a function of time. This allows an examination of the quality of sonar returns.
shading	A technique whereby the signals to or from particular elements of transducer array are reduced such that side lobes in the resultant beam pattern are reduced.
shading value	A factor applied to the signal from a particular transducer element in a shading scheme.
side lobe	Smaller lobes of the beam pattern in which sensitivity rises and falls at large angles from the beam axis in an endless series.

side lobe level	The magnitude of the first side lobe in a series of side lobes, usually expressed as a fraction of the peak of the main lobe.
sidescan sonar	A sonar that measures the strength of echoes from different locations of the ocean floor, revealing information about the composition of the material there.
signal-to-noise ratio	The ratio of the received signal strength to the noise level, which gives a measure of the detectability of a signal.
signal excess (SE)	The amount by which the return signal exceeds the minimum signal level required for detection.
single-beam depth sounders	Echo sounding devices that make one-per-ping measurements of the ocean depth at many locations.
sonar	A device used to remotely detect and locate objects in the water using sound.
sonar devices	A family of instruments that use sound for remote-sensing in a water environment.
Sonar Equation	A mathematical expression that relates all the factors involved in the acoustic echoing process.
sound speed	The speed at which sounds propagate in a medium.
sound velocity profile	Description of the sound velocity as a function of the depth at a given location.
specular regime	The situation where the echoes from the bottom are reflection-dominated, usually where the sonar is near perpendicular to the sea floor.
spreading loss	Drop in energy per unit area as a propagating pulse front expands.
start and stop gates	Operator-selected values that bracket the times at which the sonar processing should pay attention to the echoes. Start and stop gates can be unique for each beam angle.
surge	Translational motion in the alongtrack direction.
swath	A contiguous area on the ocean bottom, usually a strip of points in a direction perpendicular to the path of the survey vessel.
swath width	The dimension of the swath in the athwartship direction (perpendicular to the path of the ship), which can be measured either as a fixed angle or as a physical size that changes with depth.
sway	Translational motion in the acrosstrack direction.
target strength	A term for the backscattering strength when dealing with discrete objects, such as a mine or a submarine.

time delay	The amount of time required for a wave to propagate between two locations.
time shift or **phase shift**	A translation of a signal in time used to make up for a time delay.
time slice	A discrete time interval containing all of the information received by all of the hydrophones in an array in one digital time sample.
time spacing	The interval between discrete digital time samples. See also sampling rate.
towfish	A device that is towed in the water somewhat below the surface of the water behind a survey vessel.
transducer	A general term for devices that convert energy from one form to another, including both hydrophones and projectors.
transmission loss	Combination of spreading loss and absorption loss of a sound wave.
translational wave	A wave that propagates through a medium such that oscillations occur perpendicular to the direction of propagation.
transmitted source level (SL)	A measure of the amount of acoustic energy put into a signal by the projector.
troughs	The low pressure regions in the series of pressure oscillations that make up a sound wave; minimum values of the amplitude.
unstabilized beam	A beam for which no adjustments for a ship's motion are made.
wavelength	The physical distance between peak amplitudes in a wave.
Weighted Mean Time (WMT)	One of two algorithms used by the SEA BEAM 2100 to convert steered beam data into Time of Arrival (TOA) and Direction of Arrival (DOA) measurements for bathymetry. See also BDI.
yaw	Rotation of a ship about the vertical dimension.