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.

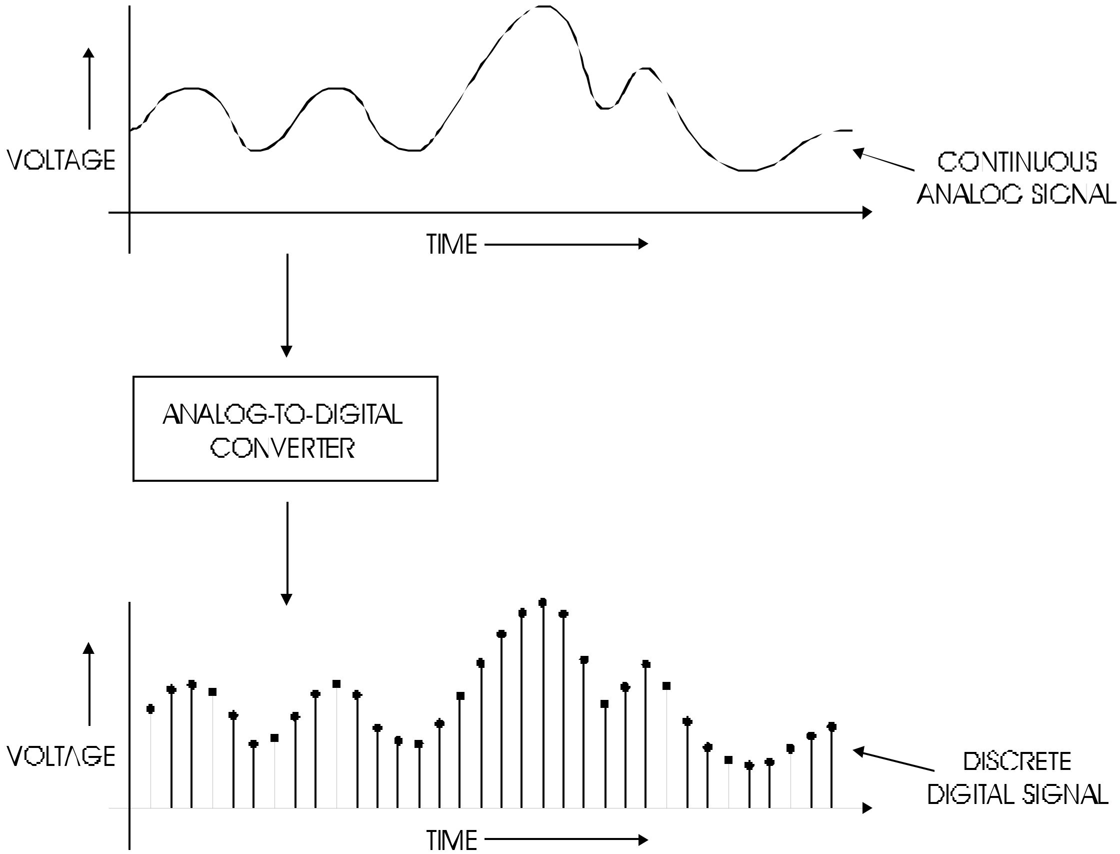

Figure Chapter 4 - -1: Analog-to-Digital Conversion of Hydrophone Data

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.

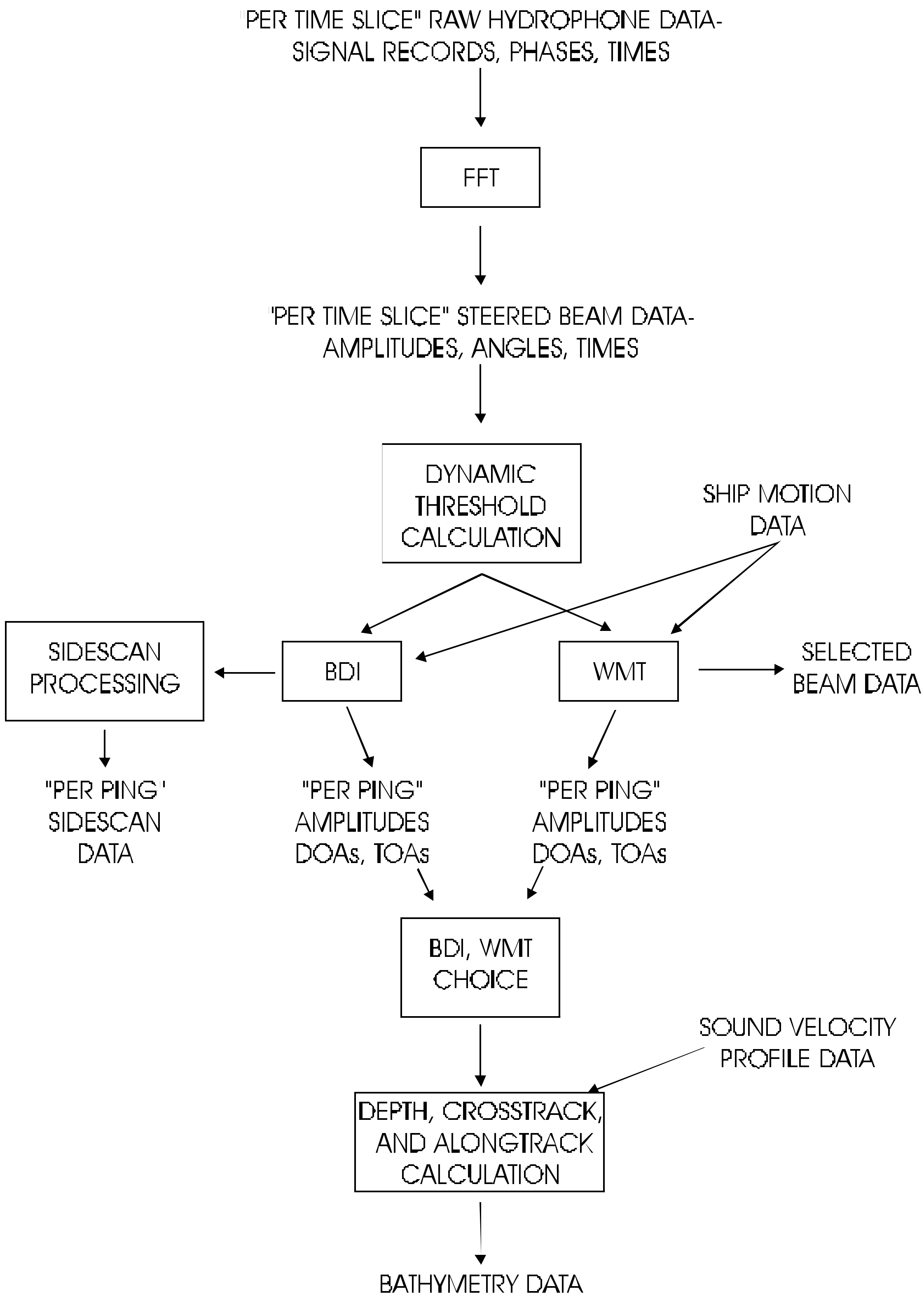

Figure Chapter 4 - -2: SEA BEAM 2100 Processing Steps – Raw Hydrophone Data to Bathymetry, Sidescan and Selected Beam

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*).

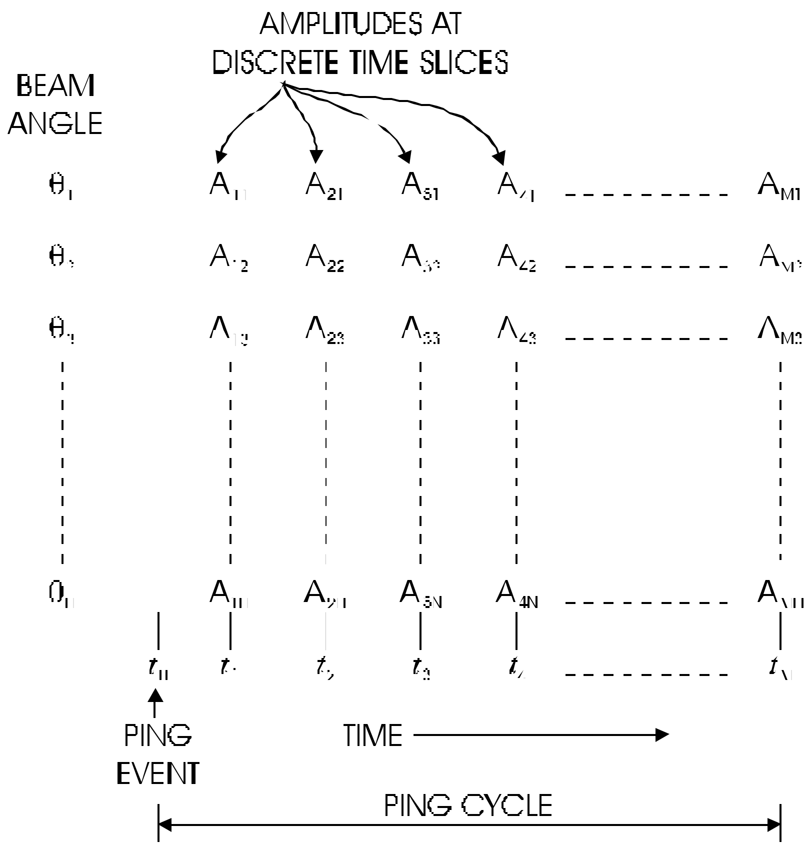

Figure Chapter 4 - -3: Matrix of Steered Beam Data from a Single Ping Containing M Time Slices

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).

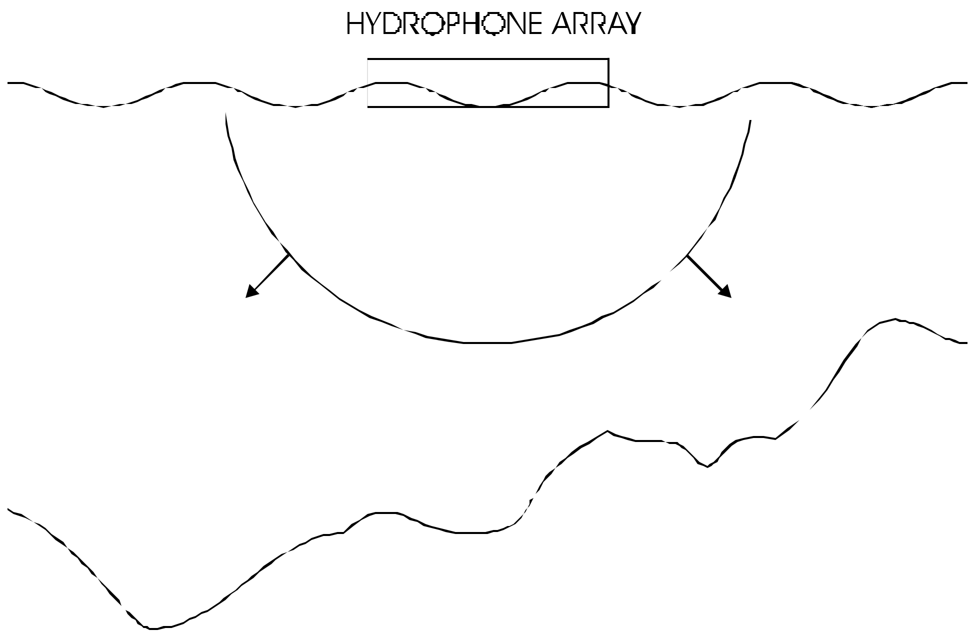

Figure Chapter 4 - -4: Hydrophone Array at Time t_1

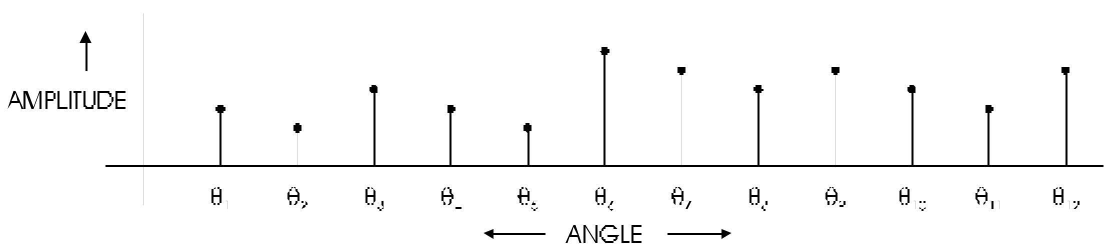

Figure Chapter 4 - -5: Time Slice at Time 2 ´ t_1

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.

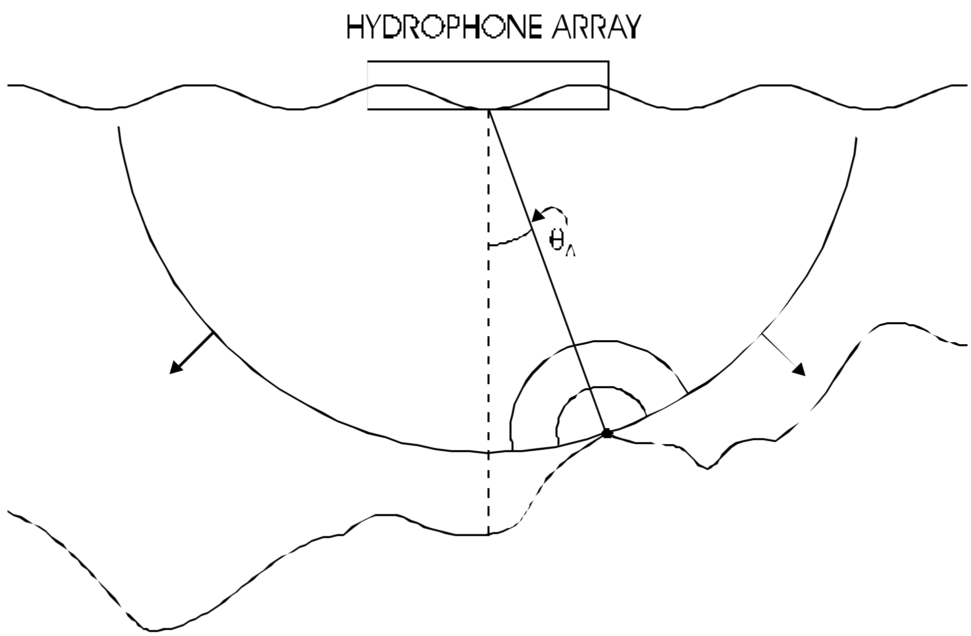

Figure Chapter 4 - -6: Hydrophone Array at Time t_2

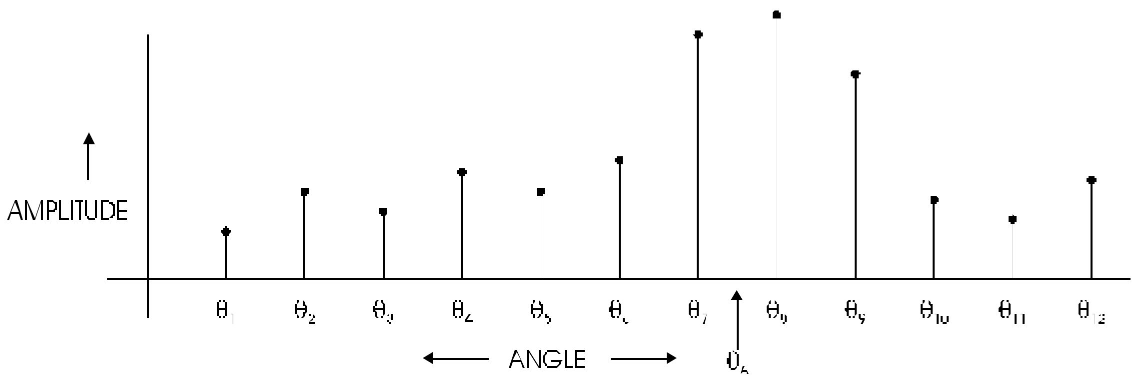

Figure Chapter 4 - -7: Time Slice at Time 2 ´ t_2

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.

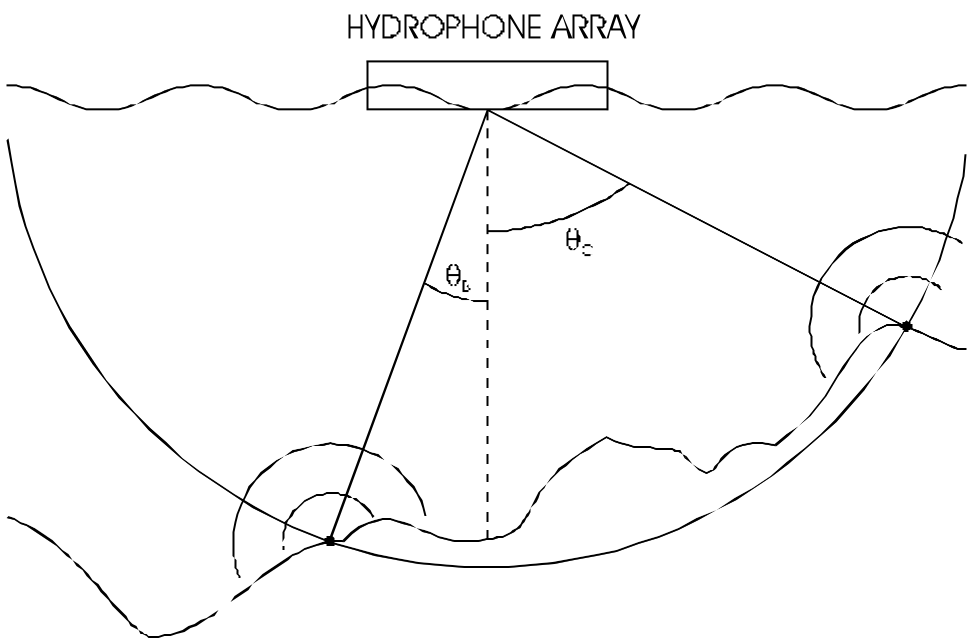

Figure Chapter 4 - -8: Hydrophone Array at Time t_3

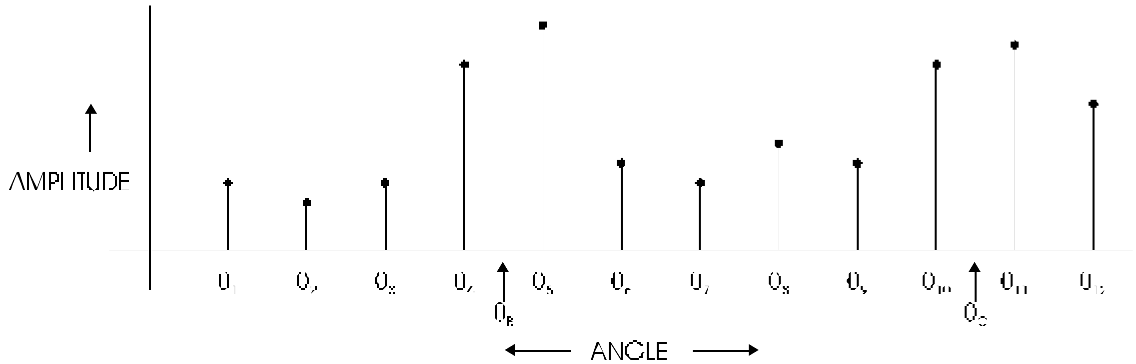

Figure Chapter 4 - -9: Time Slice at Time 2 ´ t_3

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.

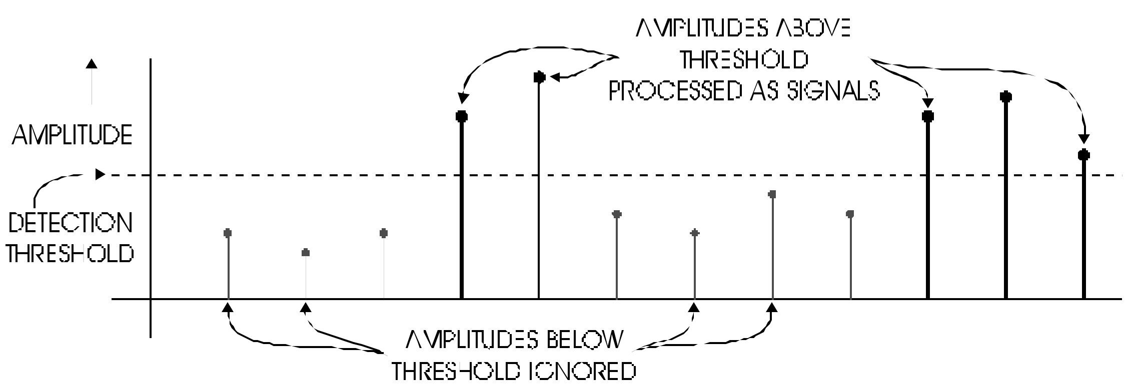

Figure Chapter 4 - -10: Dynamic Threshold Applied to a Time Slice

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.

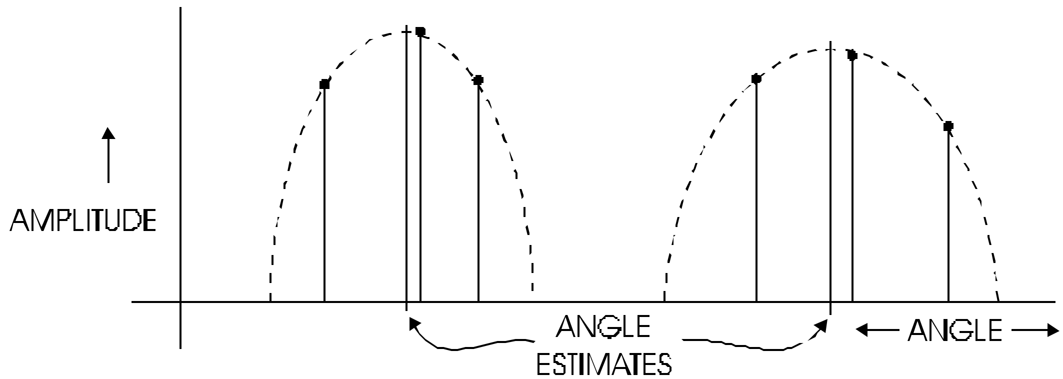

Figure Chapter 4 - -11: Parabola Fitting for High-Resolution Angle Estimation

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.

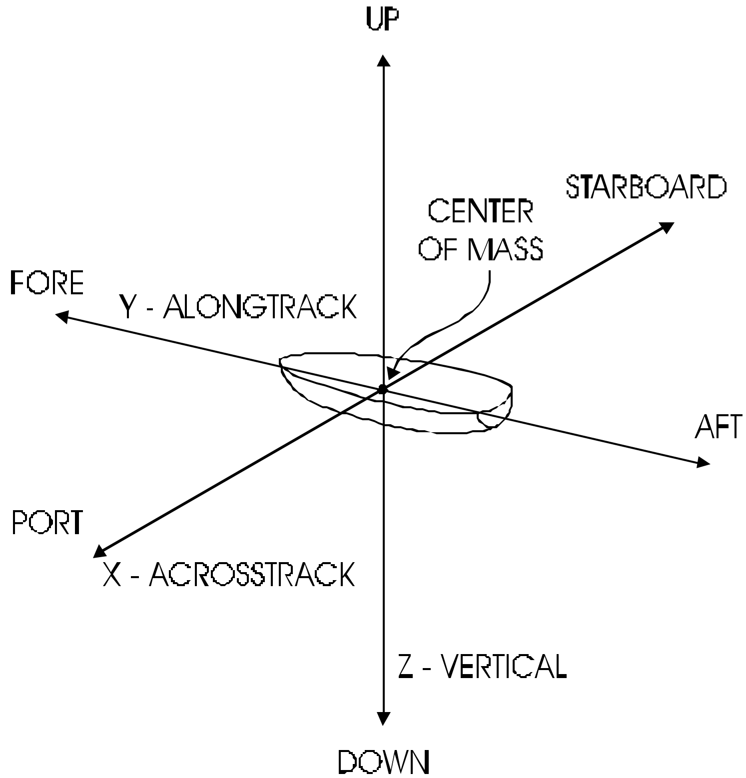

Figure Chapter 4 - -12: Ship-Motion Coordinate System

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*.

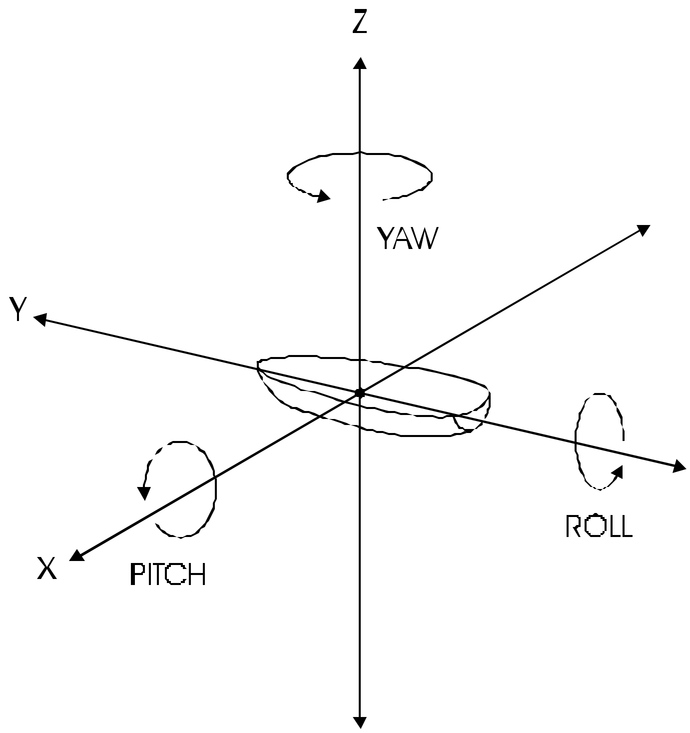

Figure Chapter 4 - -13: Rotations about the Ship Center of Mass

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.

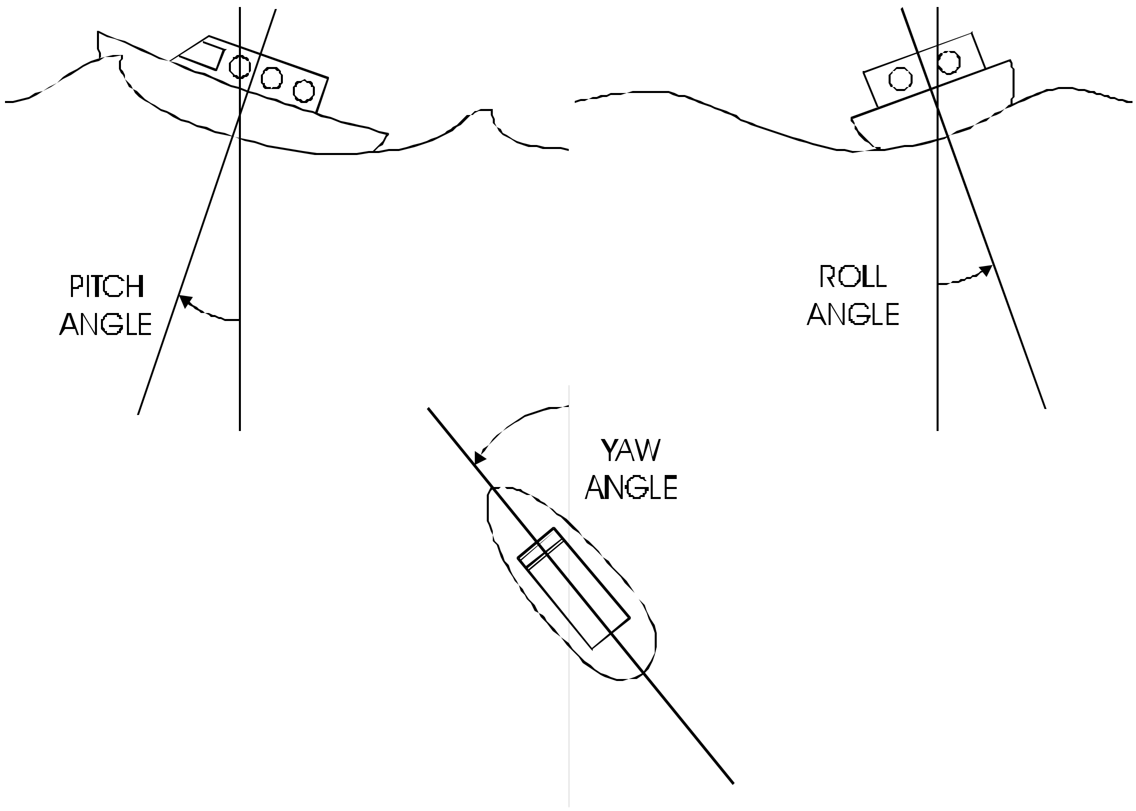

Figure Chapter 4 - -14: Roll, Pitch, and Yaw Angles

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.

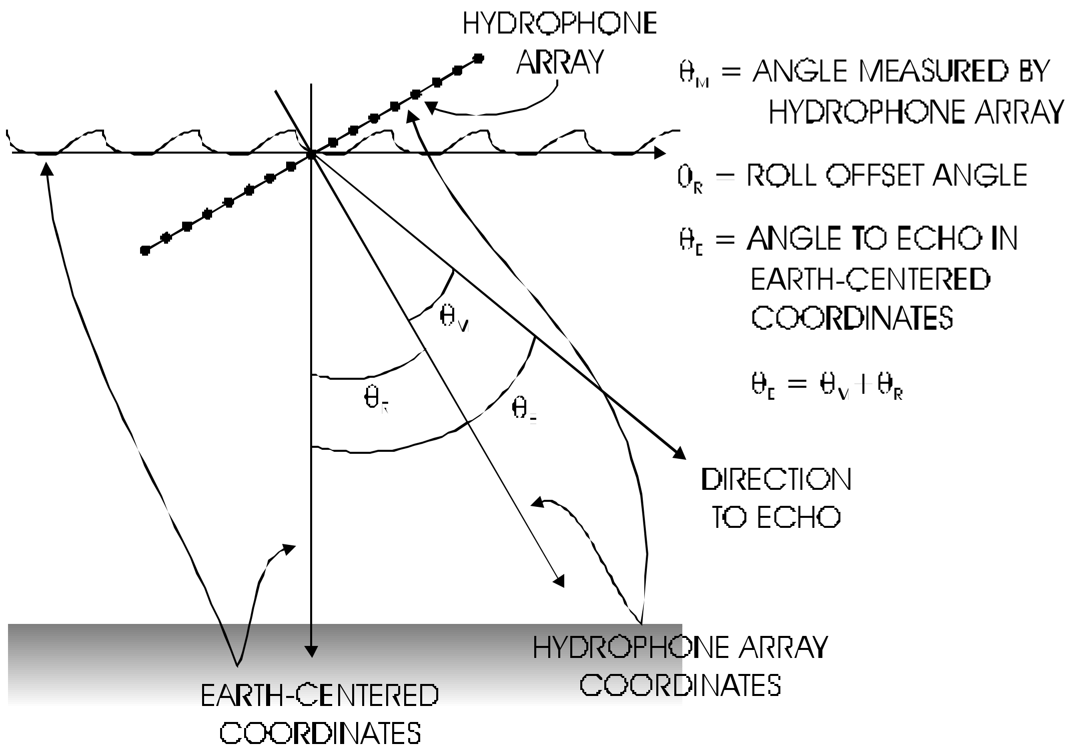

Figure Chapter 4 - -15: Adjusting Measured Angles for Roll

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.

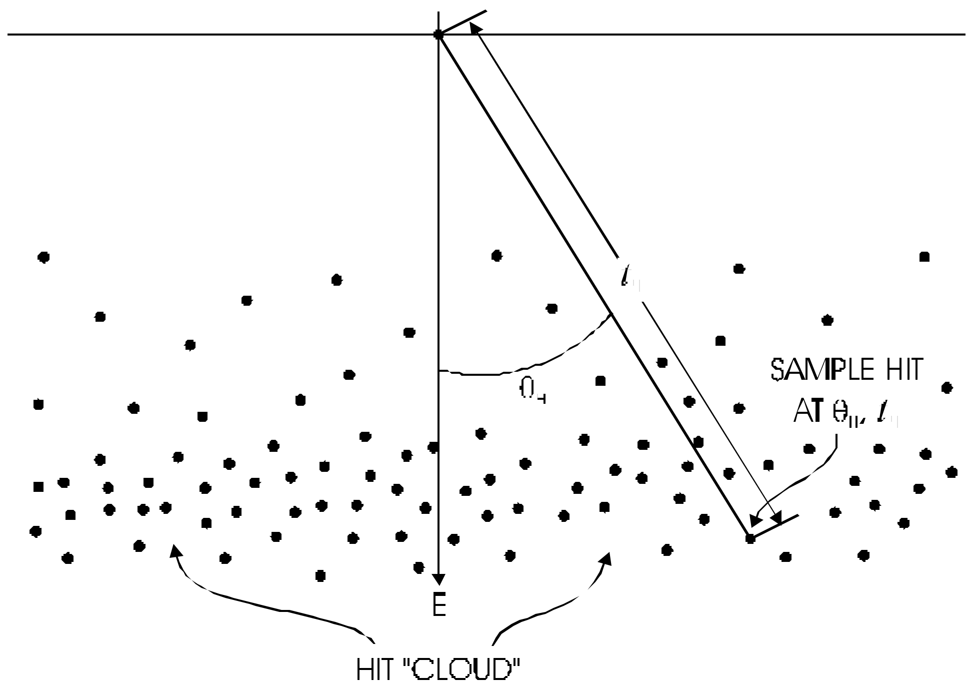

Figure Chapter 4 - -16: Hits Plotted Based on Angle and Time

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.

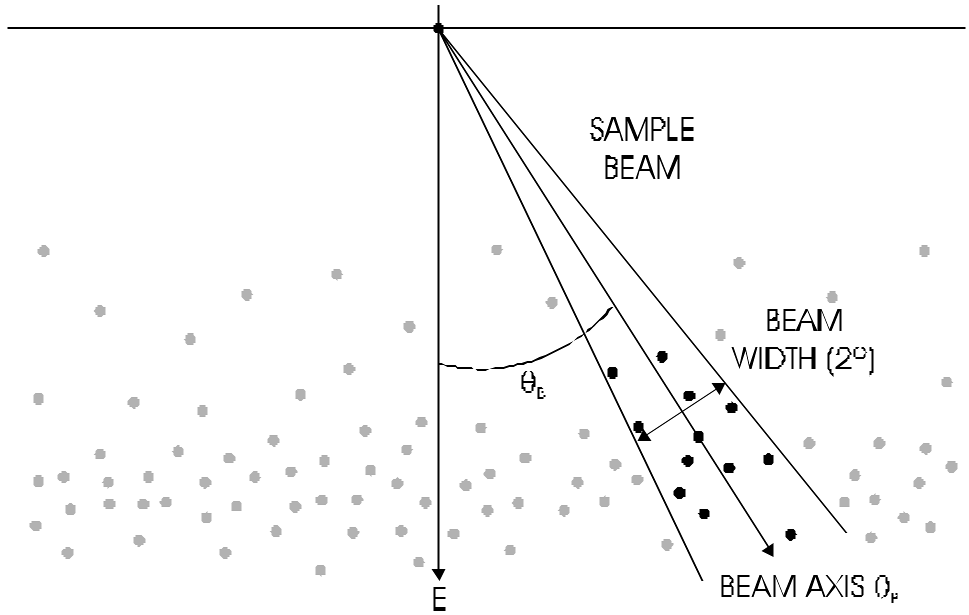

Figure Chapter 4 - -17: Sample Predefined Beam Encompassing a Subset of Hits

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.

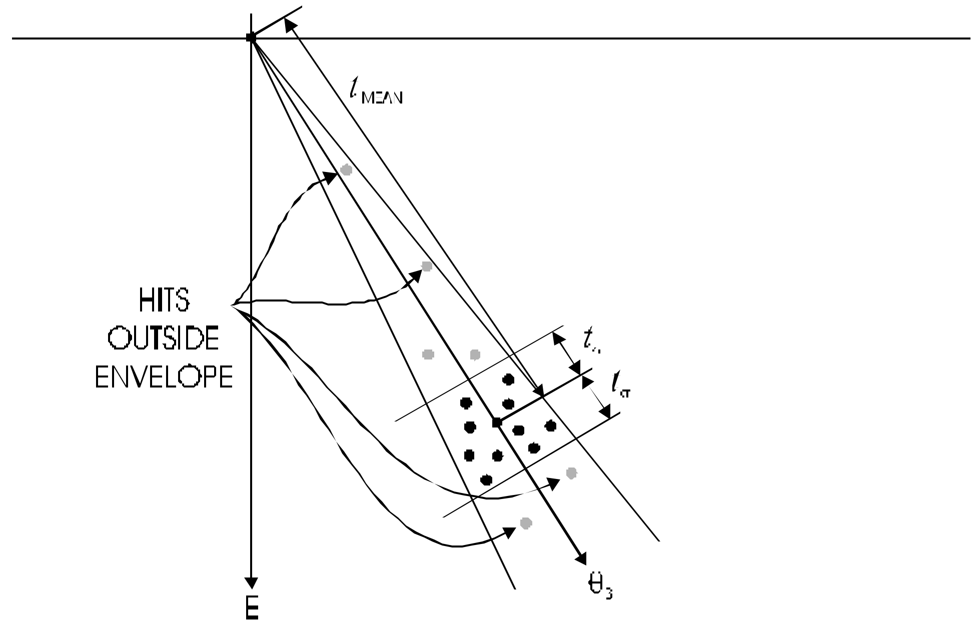

Figure Chapter 4 - -18: Hit Envelope Calculation Within a Beam

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.

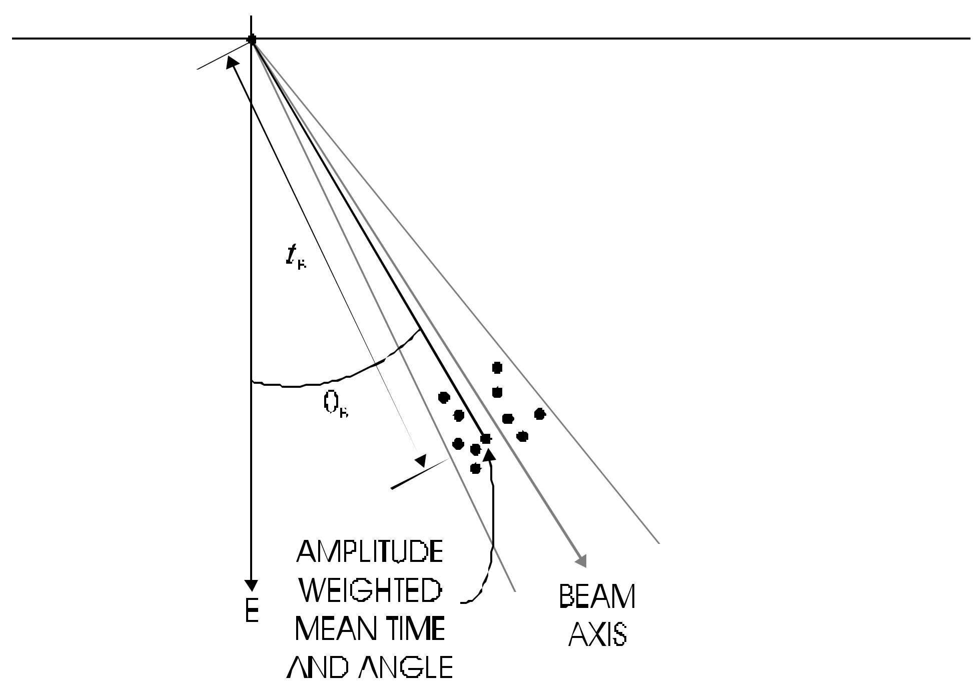

Figure Chapter 4 - -19: Amplitude-Weighted TOA and DOA

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.

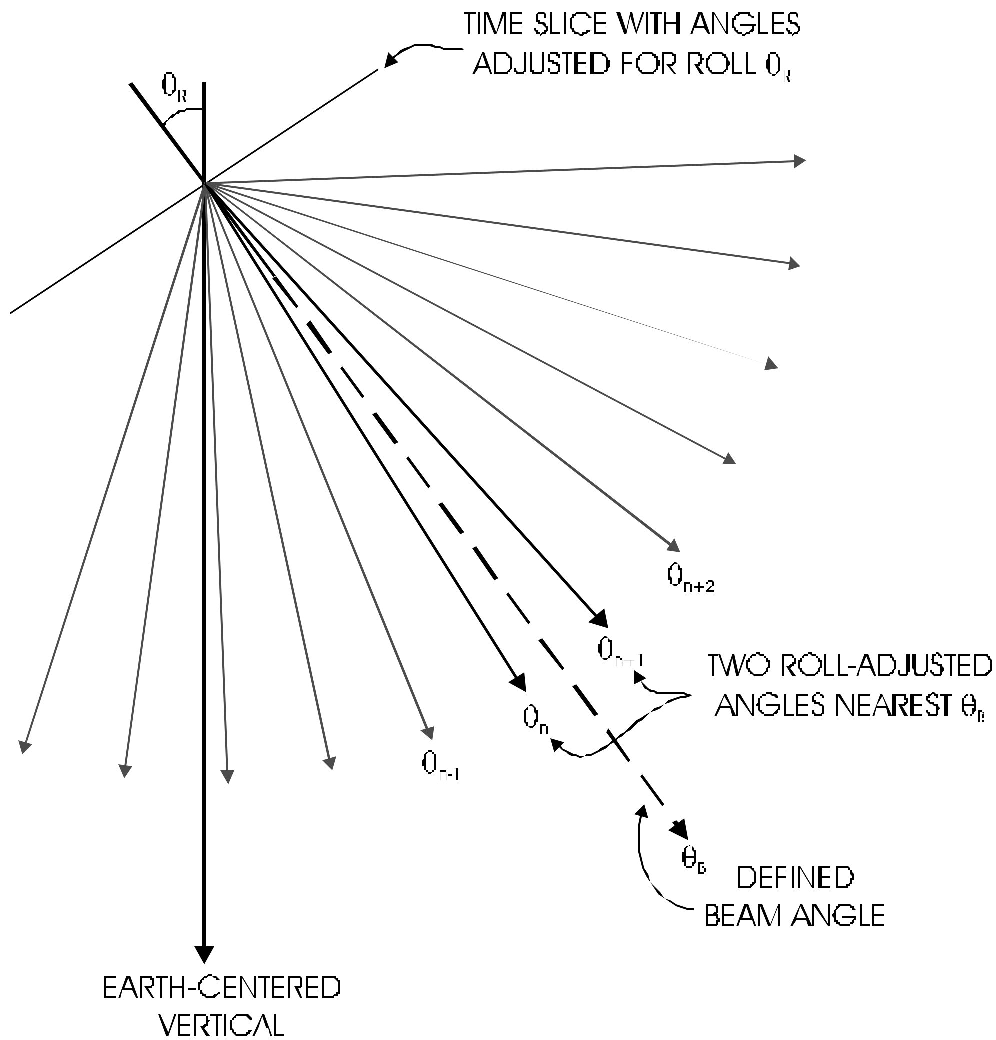

Figure Chapter 4 - -20: Finding the Roll-Adjusted Angles Nearest the Beam Angle

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.

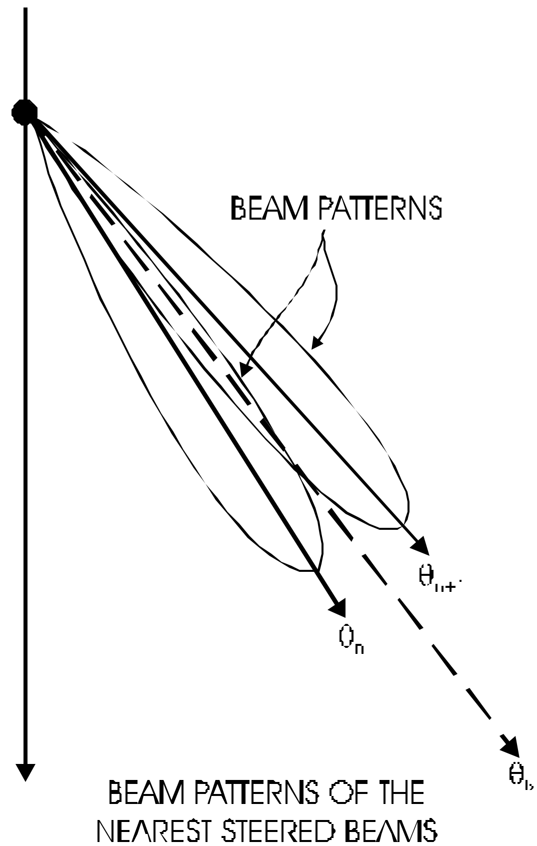

Figure Chapter 4 - -21: Beam Patterns of the Nearest Steered Beams

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.

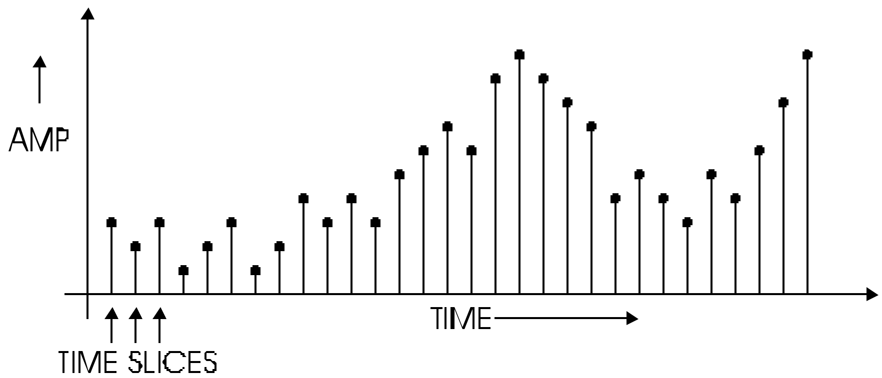

Figure Chapter 4 - -22: Interpolated Amplitudes for a Single Beam in All Time Slices

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.

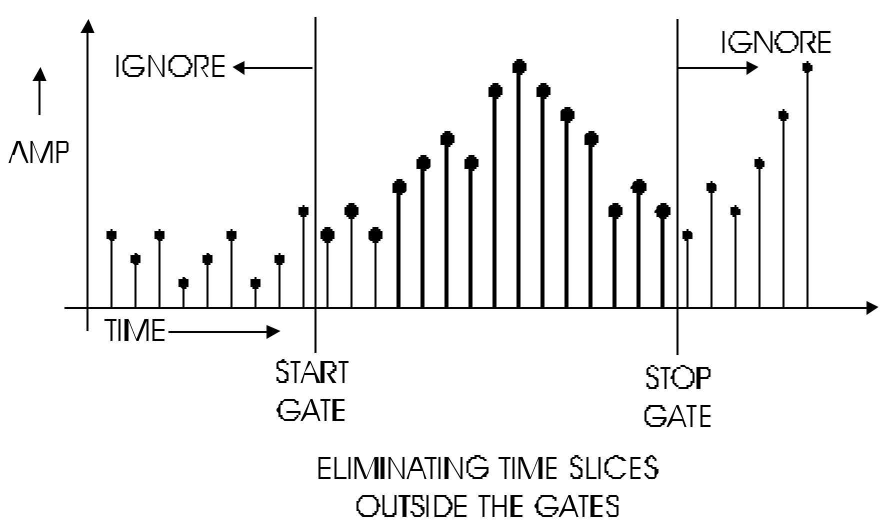

Figure Chapter 4 - -23: Eliminating Time Slices Outside the Gates

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.

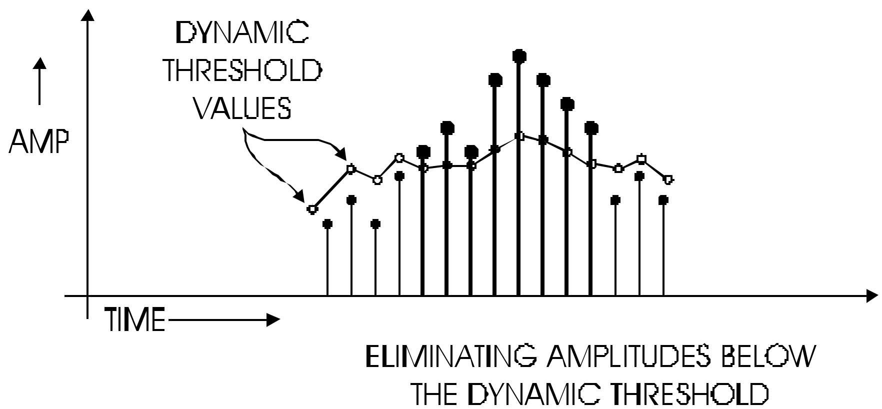

Figure Chapter 4 - -24: Eliminating Amplitudes Below the Dynamic Threshold

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.

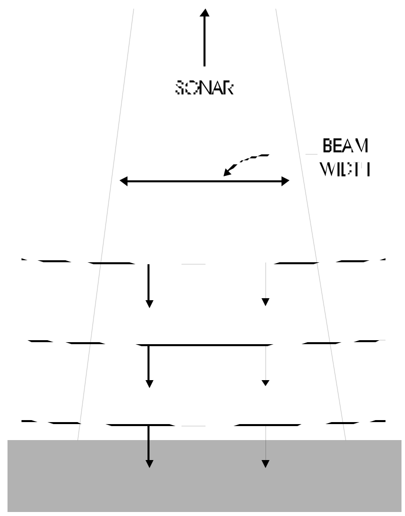

Figure Chapter 4 - -25: Specular Regime: Sonar Perpendicular to the Sea Floor

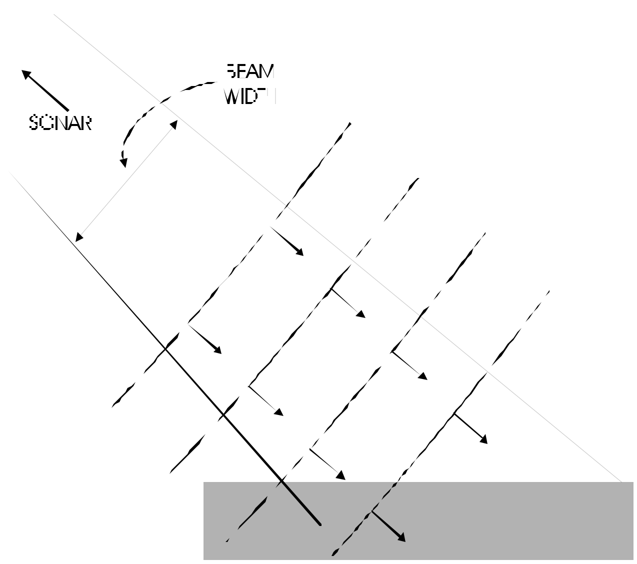

Figure Chapter 4 - -26: Non-Specular Regime: Sonar at an Angle to the Sea Floor

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.

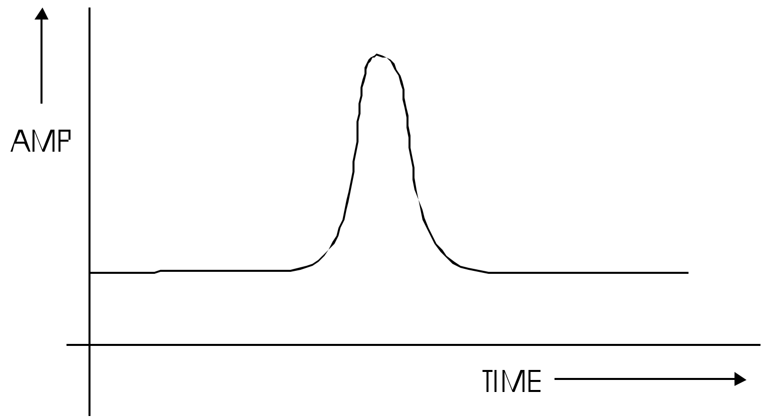

Figure Chapter 4 - -27: Amplitude versus Time Plot of the Echo Event in the Specular Regime

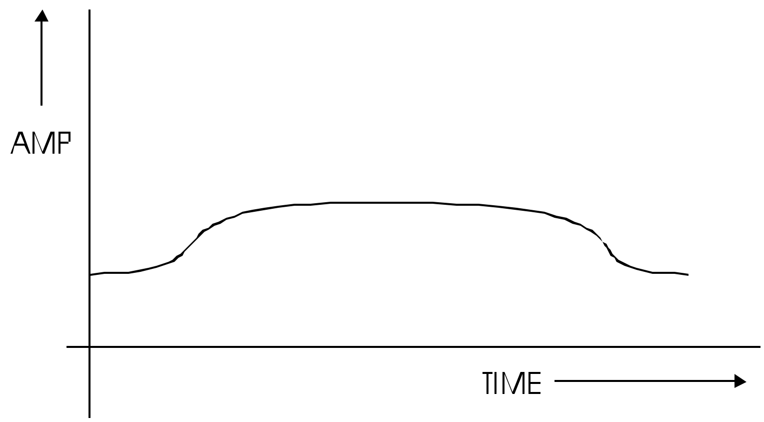

Figure Chapter 4 - -28: Amplitude versus Time Plot of the Echo Event in the Non-specular Regime

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.

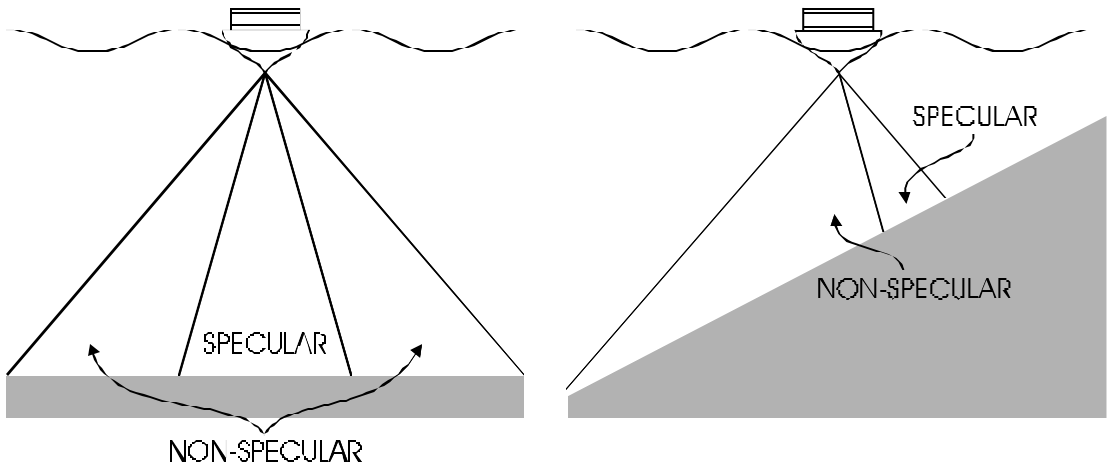

Figure Chapter 4 - -29: Specular and Non-specular Regimes with Different Sea Floors

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).

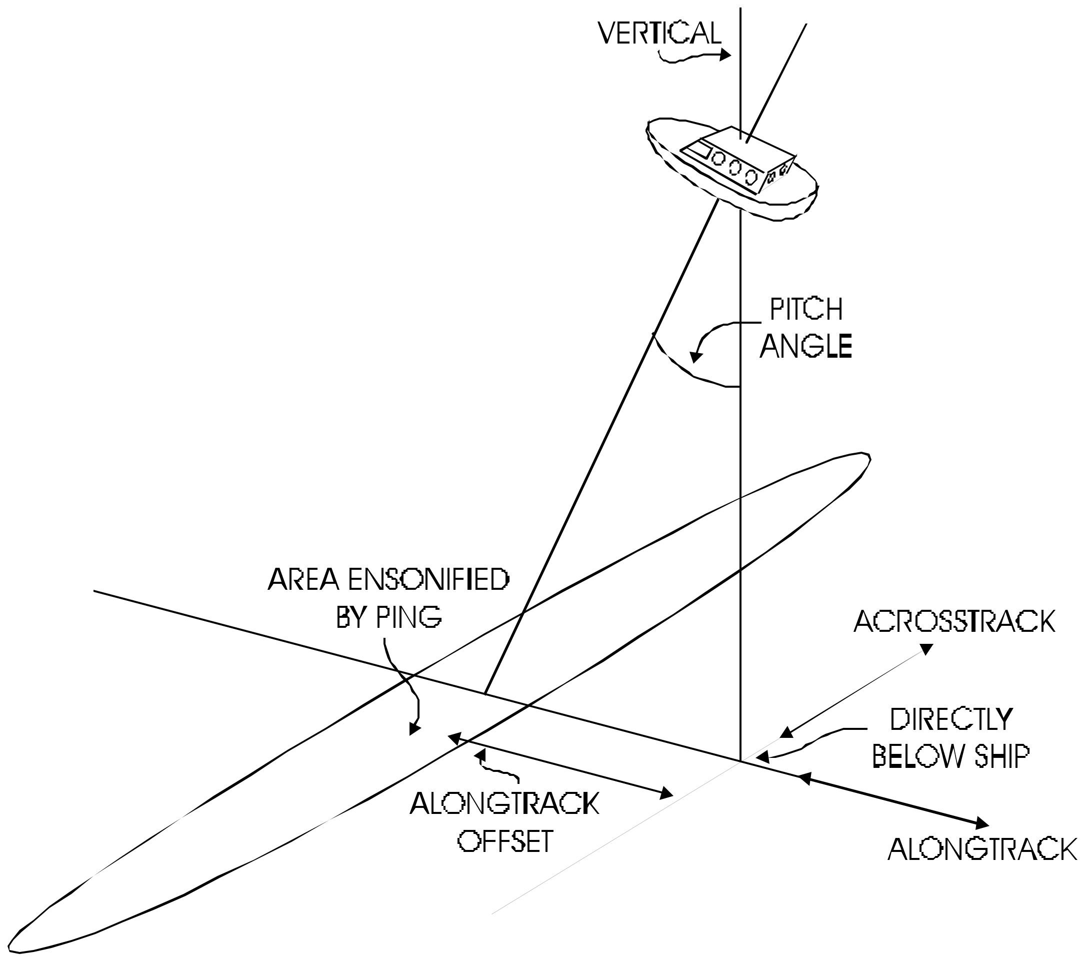

Figure Chapter 4 - -30: Offset of Ping Illumination Due to Pitch

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.

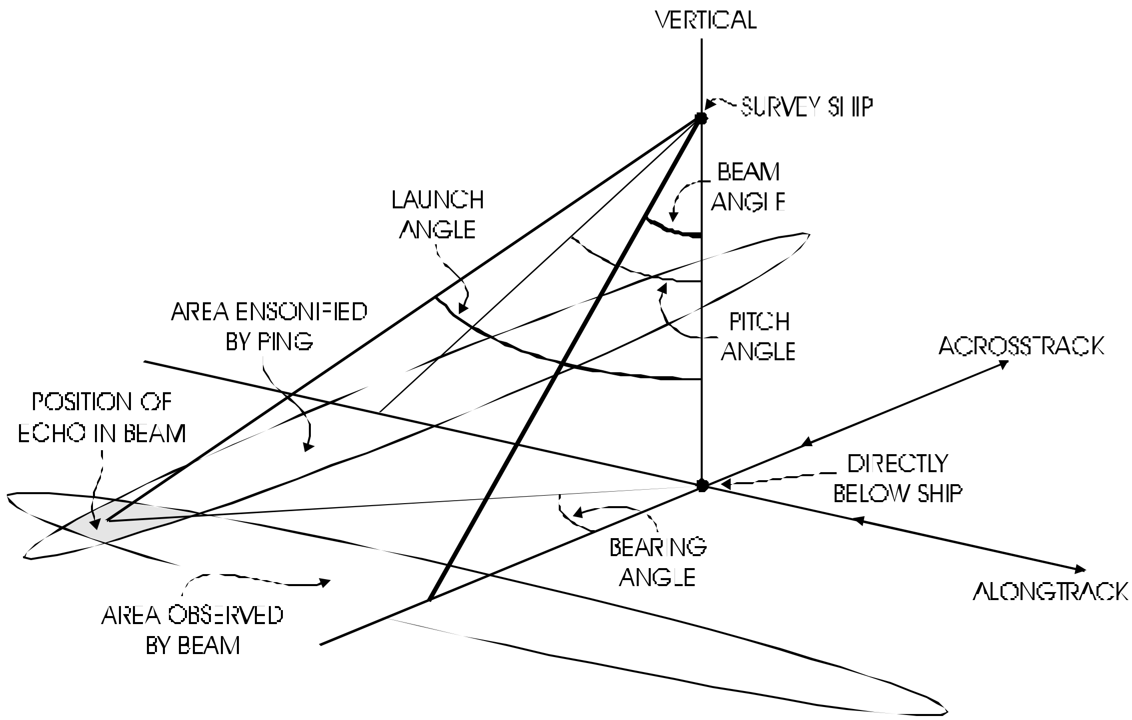

Figure Chapter 4 - -31: Position of the Echo in a Single Beam

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.

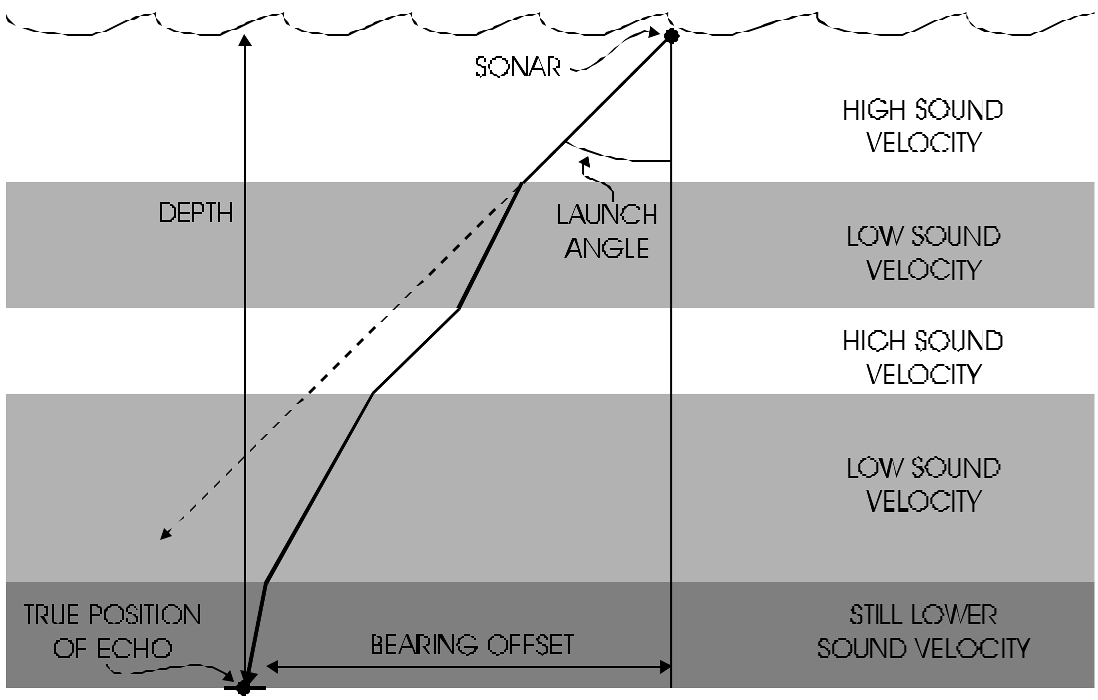

Figure Chapter 4 - -32: Ray Tracing to Find the Bottom

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.