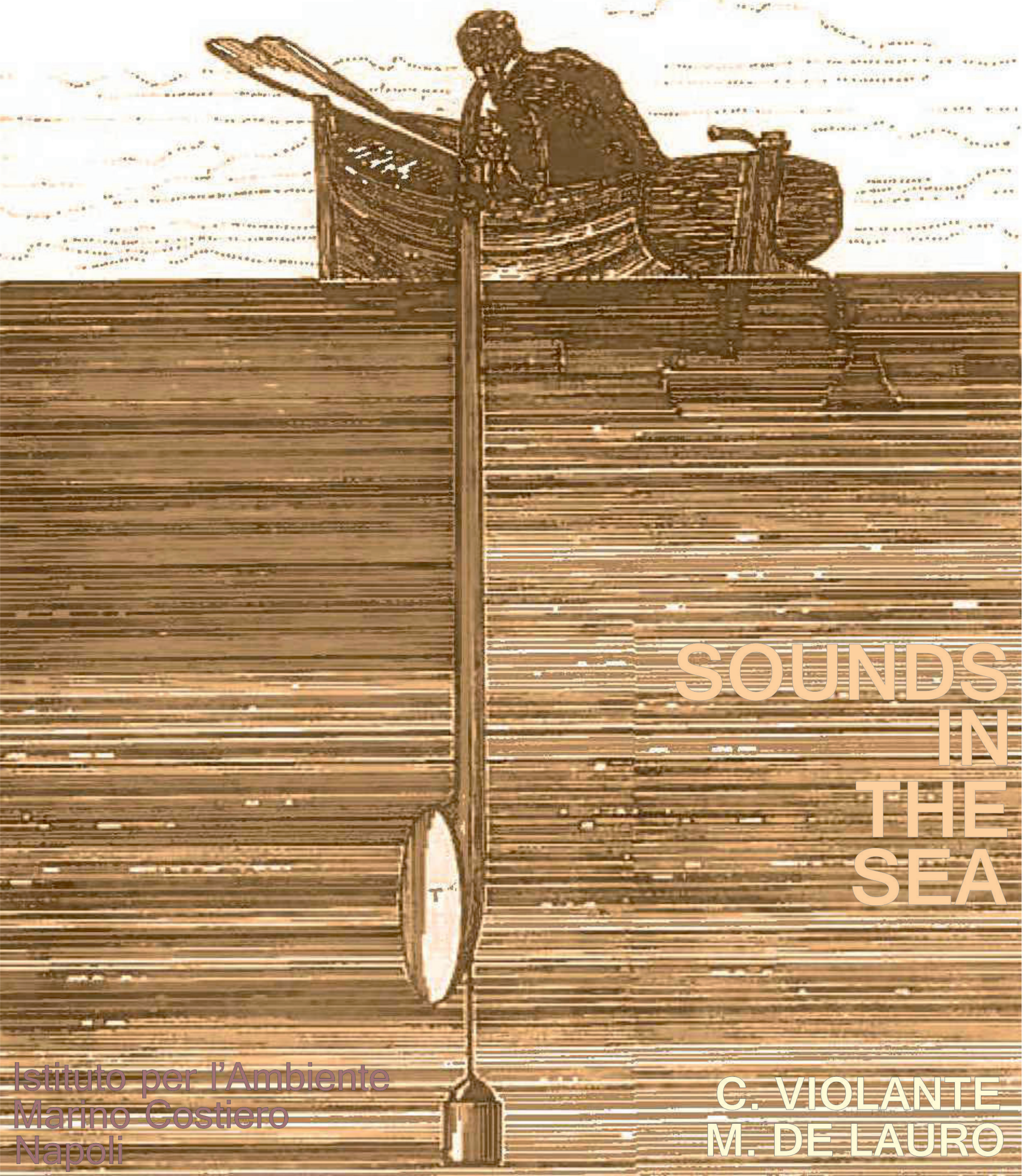
ACOUSTICS FOR MARINE SURVEYS



SOUNDS IN THE SEA

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Cover

Daniel Colladon's work to determine the speed of sound in the water. September 1826.

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ACUSTICS FOR MARINE SURVEYS

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TECHNOLOGY OVERVIEW

SONAR is an acronym for (So)und (Na)vigation and (R)anging. Sound waves have a physical character that differs from that of other types of propagating waves, i.e. light and radio waves. Sound and acoustic are terms that can be used interchangeably, although the latter is a broader term. The former is most often used to describe acoustic frequencies within the range of human hearing, which leads to terms like ultrasonic and sub-sonic for acoustic frequencies that are respectively, above and below the range of human hearing.

Acoustic waves are based on vibrations of the actual material of the medium and are manifested as periodic variations of pressure in the medium. As a result of this physical nature of acoustic waves, the exact composition of the material through which an acoustic wave travels will impact the energy that is necessarily lost as the wave propagates through the material. When a propagating acoustic wave encounters a sudden change in the properties (sound speed and/or density, but specifically the product of sound speed and density) of the actual material of the medium, a portion of the acoustic wave will change its propagation direction. That portion of the acoustic wave that reverses its propagation direction is the echo which echo sounders are designed to exploit for distance measurements. Figure 1 shows the basic principle of an acoustic wave reflecting from the ocean floor and the simple formula for reducing the time of flight to a depth value.

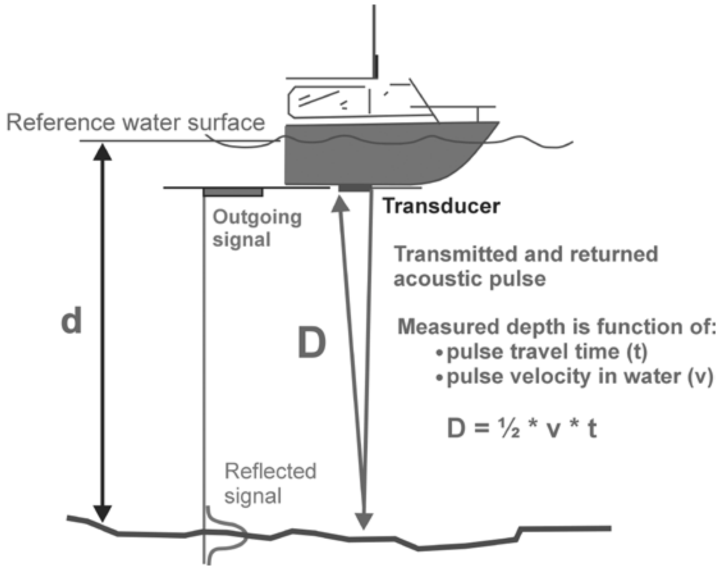


Figure 1. Echosounding Fundamentals

If the transmission/reception of acoustic energy can be confined to a singular narrow angular sector, the detection of an echo at some time after a pulse is transmitted provides both the range and bearing to the point in space where the echo was generated. Measuring the local configuration of the seabed with acoustics is that basic: transmit acoustic energy toward the bottom and detect the arrival times and directions of the acoustic energy that returns from the bottom. The measured ranges and 3-dimensional directions to points where the echoes were generated can be converted into 3-dimensional locations, relative to the transducer. Finally it is necessary to transfer the echo generation locations from the transducer frame of reference into the ship's frame of reference and finally into the appropriate reference frame for presenting the survey results.

DEVELOPMENTAL HISTORY

The earliest methods for sounding water depths were simple and direct. A weight attached to a rope served the needs of early man to measure depths that were too deep to measure with a pole. In approximately 450 BC, Herodotus, a Greek chronicler, reported a water depth of 11 fathoms, one day's sailing distance off the Egyptian coast (Harre, 1992). In the early part of the nineteenth century when the advent of oceanic submarine cables accelerated the need for soundings in deep water, the measurement tool was an extension of the weight attached to a rope. It was a lead weight attached to a wire line. Note: The action of measuring depth is that of taking a sounding, based on the old French verb sonder, meaning to probe the unknown. The use of sound to take a sounding was an invention made in the early part of the twentieth century. Nevertheless, in the twenty-first century, a graduated wire line with an attached lead weight remains an accepted means to confirm the correct operation of modern echo sounders.

In 1490, Leonardo da Vinci wrote, “If you cause your ship to stop and place the head of a long tube into the water and place the other extremity to your ear, you will hear ships at a great distance from you”. This is generally accepted as the earliest documented reference to acoustics in the sea (Bell, 1962). In 1827, documented investigations into the propagation of sound in water (Lake Geneva) were conducted. In 1877, Lord Rayleigh described the basic mathematics of acoustic waves in “The Theory of Sound”. In 1912, one month after the RMS Titanic collided with an iceberg, a patent application was filed with the British Patent Office for echo ranging with underwater sound. That device was intended to detect submerged objects, like for example, the underside of an iceberg. In 1914, the outbreak of World War I provided the impetus for developing the capability to detect submerged objects, like for example, an enemy submarine.

Echo sounders were commercially available for use in deep water by 1925 (Klein, 1968). Depths were determined by measuring the time interval required for a short sequence of sound waves (acoustic pulse) to travel from the ship to the ocean bottom (where the sound waves are reflected, producing an echo) plus the time for the subsequent echo to return to the ship. One-half of that time interval multiplied by the speed of sound gives the depth. These early echo sounding designs were limited by the technology for making precise measurements of short time intervals. Consequently, the measurement of acoustic time of flight was unsuitable for application to measuring shallow depths until a decade later. It is interesting to note, that in this same era, acoustic travel times were also employed in the determination of horizontal positions (Hawley 1931). In 1935, the U.S. Coast and Geodetic Survey began employing shallow water echo sounders for hydrographic surveys.

The development of acoustic echo sounders advanced considerably as a result of acoustics research in World War II that was directed toward the detection of submarines. That research resulted in improved electronic circuitry and in improved materials for use in constructing acoustic transducers, which are necessary to convert between electrical energy and mechanical (acoustical) energy, and vice versa (Tucker, 1966). Those improvements led to scientific investigations to better understand the transmission of sound in the oceans (Horton, 1957) and the physical mechanisms involved in generating echoes through the interactions of sound with the seabed (Urick, 1956; Lurton, X. 2002). These investigations demonstrated that the interactions at the seabed depended on the acoustic frequency, the angle of incidence, and physical properties of the seabed, like roughness, porosity and grain size (Hamilton, 1971). In 1958, acoustic waves were first used to purposefully map geologic surface features of the seabed utilizing acoustic backscatter (Chesterman, Clynick and Stride, 1958).

BASIC PRINCIPLES OF SONAR SYSTEMS

All sonars must have the capability to generate electrical signals that are converted to acoustic energy via a transmit transducer thereby emitting into the water column a short burst or pulse of acoustic energy at a particular frequency. All sonars must also have the capability, via a receive transducer, to convert the acoustic energy of the returning echoes into electrical energy. Additionally, all sonars require the ability to associate time, particularly time relative to the time of transmission, with the returning echoes. The details of the transmit transducer, receive transducer, and the processing/interpretation of the echo returns are what distinguishes a particular sonar as vertical beam, multibeam, or side scan, etc.

Acoustic Sources

If a short pressure fluctuation were to be inserted at a point in the water column that is a large distance from either the surface or bottom of the sea, that pressure fluctuation would spread equally in all directions as a spherical wave. This is termed omnidirectional, because the pressure fluctuations are the same in all directions projected from the source. As the radius of the spherical wave increases, the cross-sectional area over which the pressure fluctuation is spread increases according to the squared distance from the point of origin.

This is the basis for the well-known "inverse-square law" which describes the decrease in the pressure fluctuation of an acoustic wave as it moves through the water. Assuming that the seabed below the point of the initial pressure insertion is horizontal, the intersection of the expanding spherical shell of the pressure fluctuation starts as a point, which expands to a circle of radius "R" and then transforms into an expanding annulus of width "R". Echoes can only be generated where the spherical shell is intersecting with the bottom. The vertical angles between the intersection points and the initial insertion point are continually increasing from an initial value of zero. Echoes resulting from the interaction between the pressure fluctuation and the seabed will propagate back toward the insertion point of the initial pressure fluctuation and over time will arrive from a continually changing vertical direction. All of the echoes from any given annulus will arrive at the insertion point at the same time. In order to identify which specific section of the seabed generated a particular echo, it is necessary to estimate the vertical and azimuthal angle of arrival of any particular echo. Those angular estimates are not possible to make if the echoes are received using an omni-directional receiver. In order to estimate the vertical and azimuthal arrival angle of an echo, it is necessary to use receive transducers that are directional and it is also preferable to use a directional transmit transducer.

In the case of a sonar system, directionality of the transmit and receive transducers and the techniques of achieving that directionality is one of the major factors that distinguish one sonar type from another.

Directional Transmit/Receive Transducers

It has already been stated that acoustic energy will spherically radiate from a point source. Let us consider what would happen if two point sources, in close proximity to each other, were activated at a particular frequency (local pressure caused to alternate periodically between being above and below the local ambient pressure) using the same driver. There would be a set of spherical waves expanding around each of the point sources. Since the sources are driven periodically, the spherical waves might be visualized as a set of expanding concentric spherical shells where adjacent spheres alternate between being an increase in pressure and a decrease in pressure. Since there is a set of expanding spheres centered on each of the point sources, the shells must intersect at a number of places. If at the intersection between two shells, each shell is an increased pressure shell, the pressure at that point in space will be doubly increased relative to the ambient pressure. Likewise, if at the intersection between two shells, each shell is a decreased pressure shell, the pressure at that point in space will be doubly decreased relative to the ambient pressure. The third possible combination of two intersecting shells is the combination where one is an increased pressure shell and the other is a decreased pressure shell, resulting in the pressure at that intersection point being the ambient pressure. Once that mental picture has been formed, imagine that the two sources were activated by two different drivers operating at the same frequency such that the pressure at one point source is being increased relative to ambient pressure while the other point sources is decreased relative to ambient pressure. The radiating concentric shells will be essentially as before, but with one important difference. At the shell intersections where both shells were previously either increased or decreased pressure relative to ambient pressure, the resultant pressure will now be ambient rather than a pressure that is doubly increased or decreased relative to ambient pressure.

Figure 2 illustrates this point in two, rather than three, dimensions. In the right half of the figure, the phase of one of the point sources has been shifted by one-half a cycle relative to the cyclic pressure of the other point source. The darker areas represent increased pressure and the white areas represent decreased pressures, relative to ambient pressure. The figure demonstrates how the simple act of changing the relative phase angle between the two point source drivers has completely changed the two-dimensional spatial patter n of pressure fluctuations relative to ambient. If this two point source example were expanded to a series of point sources regularly spaced in a straight line, there would still be concentric shells of pressure increases and decreases around each point source. There also would be a complicated set of points in space where all of the shells would intersect with different combinations of pressure increases and decreases relative to ambient. As in the two point source example, the relative phases with which the individual point sources are driven can dramatically alter the three-dimensional spatial pattern of pressure fluctuations relative to ambient. Selecting the proper combination of relative phases can cause the pressure to be zero or near zero everywhere in space except along a particular angle from the long axis of a line drawn through each of the point sources. In this manner a transmit transducer can be caused to direct a spherically spreading acoustic pulse into a

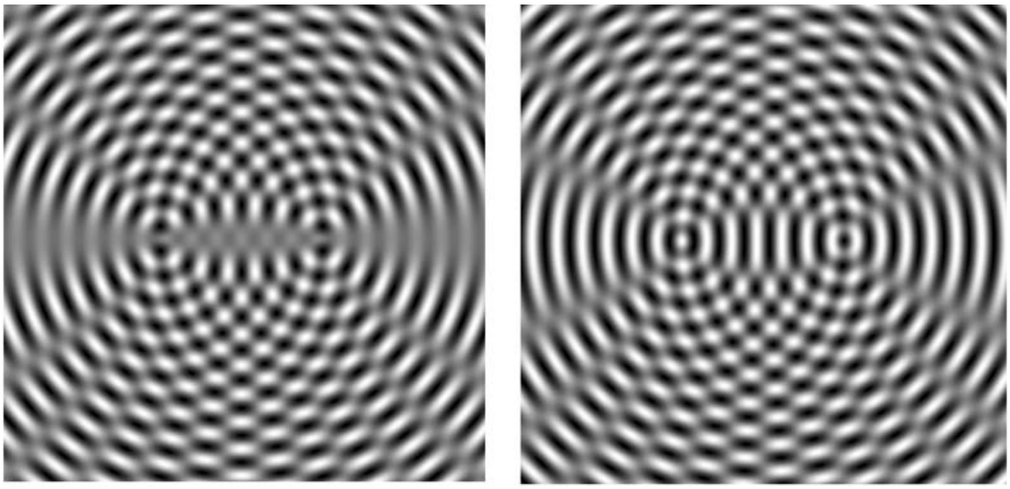


Figure 2. Interference Pattern from Two Wave Sources

particular direction, rather into all directions as was the case with the omni-directional point source. Since echoes can only be generated from sections of the seabed where the spherically spreading pressure fluctuations from the transmitter have intersected with the seabed, it is possible to reduce the uncertainty in which specific section of the seabed generated a particular echo.

The main lobe of a transmit/receive transducer is defined as having a beam width equal to the angular sector between the half-power points of the transducer response. The characteristics of the main lobe and associated side lobes of a transmit/receive transducer depend on the actual frequency and physical size of the transducer. For example, the width of a transducer's main lobe in a given plane will be reduced as the dimension (measured in acoustic wavelengths) of the transducer in the perpendicular plane increases. When discussing the physical dimension of a transducer like its length, width or diameter, it is common practice to express the dimension in multiples of the acoustic wavelength. (Urick, 1983). In the case of a horizontal looking, rectangular shaped transducer the vertical beamwidth is controlled by the vertical height of the transducer, whereas, the horizontal beamwidth is controlled by the (horizontal) length of the transducer. The angular width of a line shaped transducer's main lobe in a particular direction is roughly 50 degrees divided by the extent of the transducer in that direction, expressed in number of wave-lengths. In the case of a circular transducer the beamwidth in the direction perpendicular to the transducer face is controlled by the diameter of the transducer. The angular width of a circular transducer's main lobe is roughly 60 degrees divided by the diameter of the transducer, expressed in number of wavelengths.

A receive transducer, like the transmit transducer above, can be caused to respond only to acoustic energy that arrives at the receive transducer from a particular direction relative to the long axis of a line drawn through each of the linearly arranged point receivers. To accomplish this feat, it is necessary that the electrical signals from each of the point receivers be phase shifted relative to each of the other point receivers and then summed to provide one composite electrical signal. If a directional transmitter and a directional receiver are mounted such that their main lobes are co-aligned, then it is possible to deter mine with considerable assurance which specific section of the seabed generated a particular echo.

Acoustic survey systems are generally constructed such that the transmit/receive transducers have negligible response in one hemisphere and finite response in the other hemisphere. They are mounted in such a manner that the responsive hemisphere is aimed in the direction where echoes of interest might be generated, like the seabed. The basic physical shapes of the transducers used in acoustic survey systems are circles and lines, both curved and linear. The lengths of the line transducers are usually ten to twenty times their width.

The transducer design and its associated beam characteristics fundamentally enable or restrict the ability of a particular type of sonar to associate a specific and unique direction, relative to both nadir and the heading of the vessel, with each echo that the system receives. An acoustic survey system can only respond to echoes that are generated in the region on the seabed where the projection of the main lobe of the transmit beam onto the seabed and the projection of the main lobe of a receive beam onto the seabed coincide.

TYPES OF SONARS

Four types of sonar survey systems are discussed. Vertical beam sonar, multibeam sonar, interferometric sonar, and side scan sonar broadly represent the types of sonars that are used to obtain information about the configuration and condition of the seabed. There are important differences and obvious similarities in the functional designs of these four types of sonar.

Vertical Beam Sonar

Vertical beam sonars are primarily designed to produce quantitative information about water depths. Vertical beam sonars have one, and sometimes two, transducer(s) that are each used for both transmitting and receiving acoustic energy at a given frequency. The vertical orientation of the beam(s) means the transmitted acoustic waves will most likely interact with the bottom at near vertical incidence, which will maximize the energy in the echo returns. The received echoes are processed to deter mine the onset time of the first echo's arrival defined by the "leading edge" of the echo envelope waveform. The time measured by a vertical beam echo sounder is associated with the shortest distance from the ship to a point on the seabed. Depending on characteristics of the transducer and the configuration of the local seabed, that distance may not be the depth directly beneath the survey vessel. However, it is assumed to be the depth directly beneath the survey vessel.

In detecting the vertical beam sonar echo return, one is looking for a significant rise in voltage level above the mean level of the noise fluctuations that are also present in the output of the receiving transducer. The ability to distinguish one arrival time from another is limited by the bandwidth of the receiver. Wider bandwidths are associated with greater ability to precisely measure the arrival time of an echo. The amount of noise present in the output of the receive transducer depends on both the amount of acoustic noise in the water and the bandwidth of the receiver. The engineering aspects of designing and building a vertical beam sonar deal with the tradeoff between time resolution and rejection of noise which allows weaker echoes to be reliably detected. Other factors that the sonar engineer may change to improve the vertical beam sonar performance for a particular application, like measuring into the seabed (sub-bottom profiling), are acoustic frequency, transmit power, transducer beam width, and the signal processing technique (Urick, 1983; Chramiec and Morton, 1970; Mayer and LeBlanc, 1983).

Vertical beam echo sounders look principally in the direction of the main lobe, which is directed vertically toward the seabed. Vertical beam echo sounders generally have main lobe angular widths between five and twenty-five degrees. Since vertical beam sonars are characterized as looking in only one direction, it is therefore evident that for each transmitted pulse, there is only one area on the seabed where transmit and receive beams coincide. This provides a high degree of confidence, but not an absolute guarantee, that the echoes measured in a vertical beam echo sounder originate from a point that was located in the direction that the main lobe of the transmit/receive transducer was pointing. If a narrow main lobe is not orientated vertically, there will be a horizontal displacement on the seabed between where the leading edge of the echo is generated and where the leading edge of the echo would have been generated if the beam were orientated vertically. The result is that the measured depth is vertically offset from true depth. The vertical offset associated with a non-vertical beam will always make the measured depth appear to be deeper than it is and the offset will scale with true depth. Figure 3 illustrates an example where a depth offset is produced as the result of a horizontal displacement caused by vessel roll.

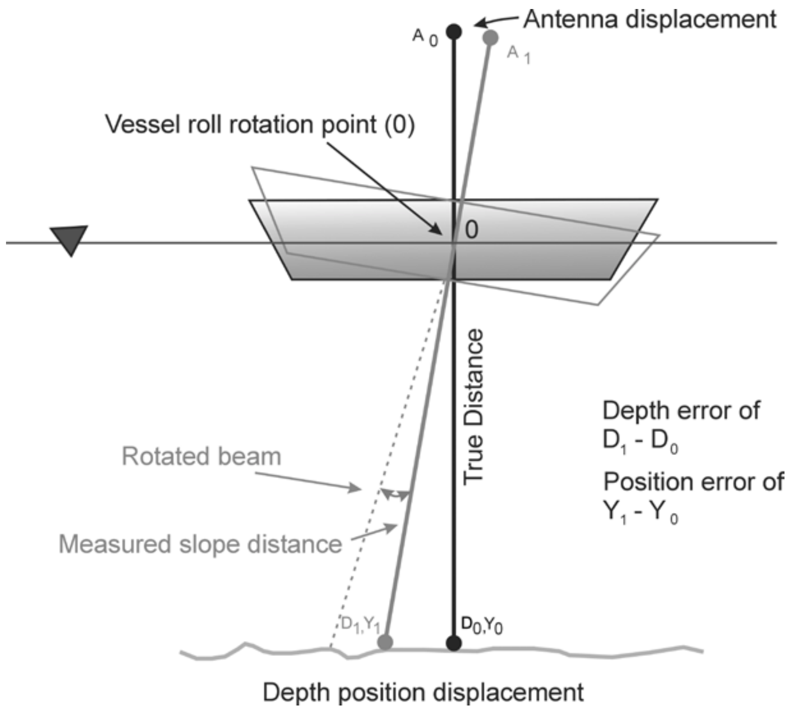


Figure 3. Horizontal Displacement and Depth Offset Caused by Roll Rotation of Vertical Beam

Since the reduction to half-power in the transducers angular response occurs on both transmit and receive, the half-power point specified for the transducer is actually the quarter-power point for the system throughput. As a word of caution, relentless pursuit of narrower and narrower beamwidths comes at the cost of greatly increasing the size of the transducer or greatly reducing the operating range of the sonar by greatly increasing the frequency to the point where the acoustic energy suffers increased attenuation by absorption. Furthermore, if a very narrow beam width is achieved, then even small values of vessel roll and pitch can negate the basic assumptions of vertical beam echo sounders, which are that the received echoes were generated directly beneath the vessel and consequently that the time after transmit of the leading edge of the echo relates to the depth directly beneath the vessel (MacPhee, 2004).

To achieve additional confidence in the accurate delineation of the sea bottom with vertical beam echo sounders, a narrow beam transmitting/receiving at one frequency may be operated in conjunction with a broad beam transmitting/receiving at another frequency. There are numerous echo sounders on the market that incorporate two simultaneous vertical beam depth measurements at different frequencies (for example 50 and 200 kHz). In such dual frequency vertical beam echo sounders the beamwidths may be the same, but that is the exception rather than the rule. Usually the lower of the two frequencies has a broader beamwidth.

The received echoes in a vertical beam depth sounder may be subjected to various signal processing schemes, which provide information that allows the user to infer variations in the interaction of the transmitted acoustic pulse and the seabed that might, in turn, imply spatial variations in the composition of the seabed.

A notable variation of the vertical beam echo sounder is the multiple vertical beam echo sounder, or sweep sonar. The bottom coverage is a function of transducer spacing, beam width, and water depth. However, the dependence of its bottom coverage on water depth is much less than that of multibeam sonar. That fact makes a sweep sonar attractive for surveys in very shallow water. Sweep sonar is simply a series of standard single beam transducers vertically mounted on a boat, barge, or other stable platform. Sweep systems may use any number of transducers. Two or more transducers may be mounted permanently in the vessel hull. Additional transducers may be mounted on “over-the-side” outriggers or, more commonly, from hinged, retractable booms deployed to port and starboard. The more common systems deploy between 3 and 12 transducers on combinations of hull and retractable boom mounts. Figure 4 illustrates a sweep sonar with two hull mounted transducers and 12 transducers mounted on booms.

Sweep systems are normally used on shallow surveys where sea state conditions are typically calm. Thus, full X-Y-Z inertial motion sensors are rarely added to a sweep system unless sea states cause excessive errors. Roll correction may be required to correct for vertical motion at the outer transducers. However, to maintain the full positional accuracy of the navigation system for each of the multiple soundings, it is essential that corrections be made for eccentricities due to yaw.

Multibeam Sonar

Multibeam sonars are primarily designed to produce quantitative information about the water depths. Multibeam sonars are first characterized as having significant system response and the ability to measure depths at angles that are non-vertical to the seabed, as well as, at nadir, which is the term used to describe "perpendicular to the seabed", or simply "vertical". Secondly, multibeam sonar is typically characterized as having separate transducers for transmit and receive. All multibeam sonars measure travel times between the echo sounder transducer and the seabed using a transmitted acoustic pulse. One of the major differences between multibeam and the other types of sonars is the manner in which the sonar processes/ interprets the echo waveforms that are received subsequent to the pulse transmis- sion (Heald and Pace, 1996). Conventional multibeam sonars measure the acoustic time of flight to the seabed as a function of angle from nadir. Through the use of trigonometric functions, the travel times are converted to a set of points, each with a vertical and horizontal coordinate, relative to the multibeam transducer (depth and position). Seemingly minor errors in the beam angle relative to nadir can result in unacceptably large depth errors. Because of the non-vertical measurement geometry, it is absolutely essential that full X-Y-Z inertial motion sensors, as discussed in Chapter 10 of this book, be installed and operated on the survey platform along with the multibeam sonar.

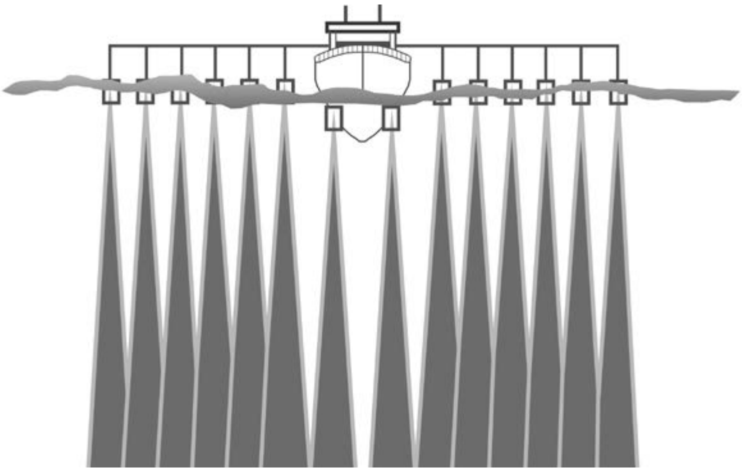
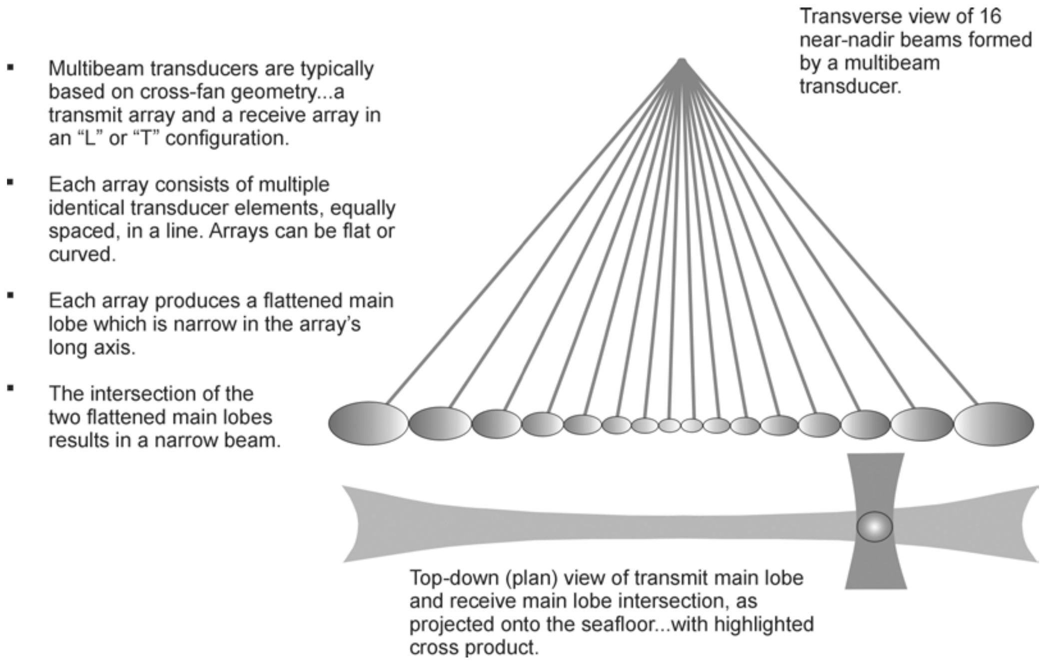


Figure 4. Sweep Sonar

The first multibeam sonars were designed in the mid-1960's and deployed for military applications, they were known as SASS, for Sonar Array Sounding System (Glen, 1970) (Satriano, 1991). In 1977, the first non-military multibeam bathymetric sonar was placed into service (Farr, 1980) (Renard and Allenou, 1979). Being deep water systems, the frequencies of SASS and other early multibeam sonars were necessarily low. The operating frequencies of subsequent shallow water sonars were considerably higher than the frequencies of the early deep-water sonars. By 1990, there were multibeam sonars operating at frequencies as low as 12 kHz and as high as 455 kHz (Harre, 1992; Steenstrup, 1992).

A conventional multibeam sonar has a single linear transmit transducer orientated along track. Its width and length are such that the entire width of the depth measurement swath is insonified by the same acoustic transmit pulse. The main lobe of the transmit transducer is narrow in the along track direction (horizontal plane) and broad in the cross track direction (vertical plane). The receive transducer is orientated cross track and has multiple beams, each with its own main lobe that is relatively broad in the along track direction (horizontal plane) and narrow in the cross track direction (vertical plane). For each transmitted pulse, there are a large number of locations on the seabed where the projected main lobe of the transmit and the projected main lobe of a receive beam coincide. Collectively the multiple locations comprise the entire measurement swath, as shown in Figure 5.

The technique used in a multibeam sonar to measure the acoustic time of flight may employ the amplitude of the echoes received in a given beam or the relative phases between the echoes received on adjacent beams. The amplitudes of the echoes received in each of the several beams are also measured and associated with horizontal coordinates relative to the transducer (Talukdar and Tyce, 1991). With suitable processing the along track and cross track variations in the amplitudes of the received echoes provide qualitative information that may allow the user to infer spatial variations in the composition of the seabed. The variations in echo amplitudes may be presented in a planar view or presented as an overlay on the apparent surface of the seabed established by the multibeam sonar depths.



- Multibeam transducers are typically based on cross-fan geometry...a transmit array and a receive array in an "L" or "T" configuration.
- Each array consists of multiple identical transducer elements, equally spaced, in a line. Arrays can be flat or curved.
- Each array produces a flattened main lobe which is narrow in the array's long axis.
- The intersection of the two flattened main lobes results in a narrow beam.

Transverse view of 16 near-nadir beams formed by a multibeam transducer.

Top-down (plan) view of transmit main lobe and receive main lobe intersection, as projected onto the seafloor...with highlighted cross product.

Figure 5. Individual Beams in Multibeam Transducer

Interferometric Sonar

Interferometric sonar is another type of sonar that is primarily designed to produce qualitative information about depths and exhibits significant system response and the ability to measure depths at angles that are non-vertical to the seabed, as well as, at nadir. Consequently, it sometimes is grouped under the general term of multibeam sonar. The measurement geometry of interferometric sonar is similar to that of a side scan sonar. Consequently, it is sometimes called interferometric side scan sonar and grouped under the general term of side scan sonar. Interferometric sonar differs from multibeam sonar in that not only is the travel time of the echo measured but the vertical angle of arrival for each time sample of the echo must also be measured (Cloet and Edwards, 1986) (Denbigh, 1989).

Interferometric sonars have a single transmit transducer whereby the entire width of the depth measurement swath is insonified by the same acoustic transmit pulse. Interferometric sonars have multiple receive transducers, each with a relatively narrow main lobe response in the along track (horizontal) direction and a broad main lobe response in the cross track (vertical) direction. There is a small vertical separation between the several receive transducers which provides the physical geometry required to determine the vertical angles of arrival from the time samples of the received echoes. Because the geometry associated with echoes from near nadir is unfavorable for the accurate resolution of vertical angle of arrival, many interferometric sonars incorporate a vertical beam echo sounder to measure the depths directly below the vessel. As with a multibeam sonar, it is absolutely essential that full X-Y-Z inertial motion sensors be installed and operated on the survey platform along with the interferometric sonar.

Interferometric signal processing techniques include determination of the amplitudes of the backscatter from the seabed, as well as, determination of depths based on vertical angle of arrival. Those processing techniques provide a three-dimensional surface on which to view the along track and cross track variations in the amplitudes of the received echoes. Those spatial variations in echo amplitudes provide qualitative information that may allow the user to infer spatial variations in the composition of the seabed (Green, Hewitt, and Adams, 1993).

Due to the simplified design of the transducers and electronics, interferometric sonars are less costly than conventional multibeam sonars. The typically small transducer size means that they are quite portable and can be rapidly mounted onto small survey platforms, as well as, be configured for towing. However, if the transducer is towed, the roll/pitch and azimuth angles of the tow body must also be measured, as well as, the depth of the tow body.

Manufacturers of interferometric sonars state that their systems can typically measure depths over a swath that is up to ten times the depth, or more particularly, the height of the transducer above the bottom. The data density in a beam-formed swath system (multibeam), and thus cross track resolution will halve if depth is doubled. The data density of a phase measurement swath system (interferometric) is far higher, typically hundreds of times higher, and stays roughly constant with depth. Therefore, the interferometric sonar can afford to average or statistically filter through many real data points and still provide soundings in a high spatial resolution grid. However, they also tend to provide depth measurements that are less accurate and precise than depths measured with beam-formed multibeam sonar. Factors contributing to the uncertainties in depths from a shallow water interferometric sonar are: unraveling the true phase differences in light of the ambiguities in differential phases, interference from multipath arrivals, and interference due to simultaneous arrival of echoes with different vertical angles of arrival (like, echoes from both the sea surface and seabed).

Side Scan Sonar

Side scan sonar is a tool for qualitative observations, more so, than a quantitative measurement tool. The objective of side scan sonar is to provide a detailed presentation of the seabed features and manmade objects that may lie on the surface of the seabed, in the form of a plan metric image. The first side scan sonar was developed in 1960 at the Institute of Oceanographic Sciences (IOS) in England (Tucker and Stubbs, 1961). The first side scan sonar was a shallow water system. In 1969, ISO developed the Geological Long Range Inclined Asdic (GLORIA), side looking sonar for surveying in the deep ocean (Laughton, 1981).

As in multibeam sonar and interferometric sonar, a side scan sonar insonifies the entire measurement swath with the same acoustic transmit pulse. Actually there are two pulses, one transmitted from a continuous line array transducer looking to port and one from a continuous line array transducer looking to starboard. The main lobe of the (port and star- board) transmit transducer is narrow in the along track direction (horizontal plane) and broad in the cross track direction (vertical plane). Like vertical beam echo sounders, conventional side scan sonars use the same transducer for receive and for transmit. This provides a high degree of confidence, but not an absolute guarantee, that the echoes received by the side scan sonar originated from points that are located in the direction that the transducer is pointing.

The spatial resolution capabilities of side scan sonars are different in the cross and along track directions. Furthermore, the cross and along track resolutions each vary with the cross track distance from nadir and the character of those variations differs between the two directions. The along track resolution is determined by the horizontal beamwidth of the transmit/receive transducer and changes linearly with slant range. The cross track resolution is determined by the sonar's basic range resolution and by geometric effects that vary nonlinearly with slant range, based on the height of the tow fish above the bottom and the cross track distance from nadir. The cross track resolution may be 50 to 100 times worse directly under the tow fish (zero cross track distance) as it is at the maximum cross track range.

The basic range resolution of a side scan sonar, as well as a vertical beam echo sounder and a multibeam sonar, is determined by the bandwidth of the transmit pulse. In most systems the bandwidth of the transmit pulse is determined by the time duration of a short transmitted tone burst of a given frequency. However, in some designs the bandwidth is defined by the bandwidth of a long frequency modulated transmit pulse. The basic range resolution in meters is one-half the speed of sound divided by the bandwidth.

In the design of a side scan sonar a high premium is placed on achieving transmit/ receive beams that are narrow in the along track direction. Side scan sonars tend to use high frequencies in order to achieve narrow beamwidths with transducers of moderate length. Due to the high frequencies of side scan sonar; the useful operating range of a side scan sonar is typically less than 200 meters to either side of the tow fish. A notable exception is GLORIA II, which operates at a frequency of 6.5 kHz and has a maximum imaging range of 60 km (Mitchell, 1991). If the objective of a particular side scan sonar survey is to detect small objects, then the operating range may be limited by the spatial divergence of the beam in the horizontal plane as the acoustic pulse travels farther from the tow fish. For maximum ability to detect specific small targets at any given range, the along track width of the transmit/receive beam, at that range, should be less than the least cross section of that specific target, and the range resolution should be much less than the largest cross section of that specific target. Delineation of small details on large complex targets requires both narrow beamwidths and wide bandwidths.

The plan metric image of the seabed obtained via side scan sonar will almost always contain spatial variations in the intensity of the received backscatter signals. There are several possible effects that explain the majority of the spatial variations observed in the intensity of the received signals. The first possible cause of the spatial variation is an actual spatial change in the various materials that comprise the seabed. The relative backscatter characteristics differ for different materials. For example, rock and gravel will backscatter more of the incident acoustic signal than sand will backscatter. Sand will backscatter more of the incident acoustic signal than mud will backscatter, etc. A second possible cause of the spatial variation is a change in the angle between the propagation direction of the outgoing (transmitted) acoustic pulse and the seabed, which is designated the incidence angle. The incidence angle varies systematically from ninety degrees directly below the tow fish to approximately five degrees at the maximum slant range expressed in the side scan imagery. Portions of the seabed with slopes that face toward the transducer on the tow fish (incidence angle is closer to ninety degrees) will backscatter more of the incident acoustic signal than surfaces with slopes that face away from the transducer (incidence angle is closer to zero degrees) will backscatter.

If the seabed is flat and the vertical beam pattern of the transmit/receive transducer approaches omni-directional and the seabed is continually comprised of the same material over the entire cross track extent of the side scan imagery, then any variations in the intensity of the side scan sonar received signals that are observed along the survey track line can readily be attributed to variation in the material composition of the bottom. However, in general, most of those conditional statements are not true and the side scan imagery contains spatial variations that are due to local changes in both the incidence angle and the composition of the seabed. Consequently, manual interpretation of side scan sonar imagery requires considerable experience and first-hand knowledge about the particular backscatter characteristics of various rock types, gravels, sands, and characteristic bed forms associated with them such as bedding, jointing, ripple marks, sand waves, etc. (Flemming, 1976; Fish and Carr, 1990).

A side scan sonar is typically towed close to the seabed to control the geometry of the interactions between the acoustic transmit pulse and the seabed. When a tow fish is close to the bottom, the incident angle will change quickly from ninety degrees into a range of incident angles where the variation in backscatter is less sensitive to small changes in incident angle. The higher the tow fish is above the bottom the longer the incident angle is in the range where the variation in backscatter is more sensitive to small changes in incident angle. The geometry associated with towing the side scan sonar close to the bottom also enhances the generation of “shadows” behind areas of the seabed that distinctly rise above the surrounding area and consequently may represent a feature that warrants further investigation.

CALIBRATION PROCEDURES

In a sonar there are only a few things to calibrate, namely the operating frequency, the pulse length, the transmit power, the main lobe amplitude of the transmit pulses, the main lobe sensitivity of the receive transducer, beam patterns of the transmit/receive transducer(s), and the accuracy of the time base. A user typically does not have the resources to calibrate many of these factors, and therefore relies on the manufacturer for the information. Even there, the nor mal practice is for manufacturers to provide typical or nominal response data, as opposed to the response function of a particular set of transducers and electronics.

Sound speed within the water column between the transducer and the seabed is an important parameter that affects the accuracy of sonars. It could be viewed as an extension of the accuracy of the sonar’s time base. In a vertical beam echo sounder the measured distance (depth) is the product of the total travel time, which transpires between the transmit pulse and reception/detection of an echo, and the average sound speed along the travel path from the transducer to the seabed and back to the transducer. In multibeam and interferometric sonars the distance measurement is further complicated by gradients in sound speed, which will cause the acoustic energy to travel along paths that are curved lines rather than straight lines. Errors due to sound speed are typically addressed by regularly measuring vertical profiles of sound speed at intervals in space and time throughout a survey.

Calibration becomes an issue when a particular sonar is incorporated into a survey system. In the instance of multibeam sonar and interferometric sonar, that means interfacing with additional equipment such as a vertical reference unit, heading device, navigational unit, and a data acquisition computer. The parameters that need to be calibrated are the locations, relative to the roll/pitch center of the platform, of the sonar transducer, the navigational (GPS) antenna, and the vertical reference unit, as seen in Figure 6. Inaccuracies in these parameters impact the accuracy with which the measured acoustic travel times are converted to vertical and horizontal positions. There are also three angles that must be determined when the sonar and associated instrumentation are installed on the survey platform.

The exact offset angle between the azimuthal mounting of the transducer and the heading unit must be known in order to accurately convert acoustic travel times into horizontal positions relative to the transducer. There is a calibration procedure, called a patch test (see Figure 7), which is used to calibrate the offset angle between the azimuthal mounting of the transducer and the heading unit. The exact offset angle

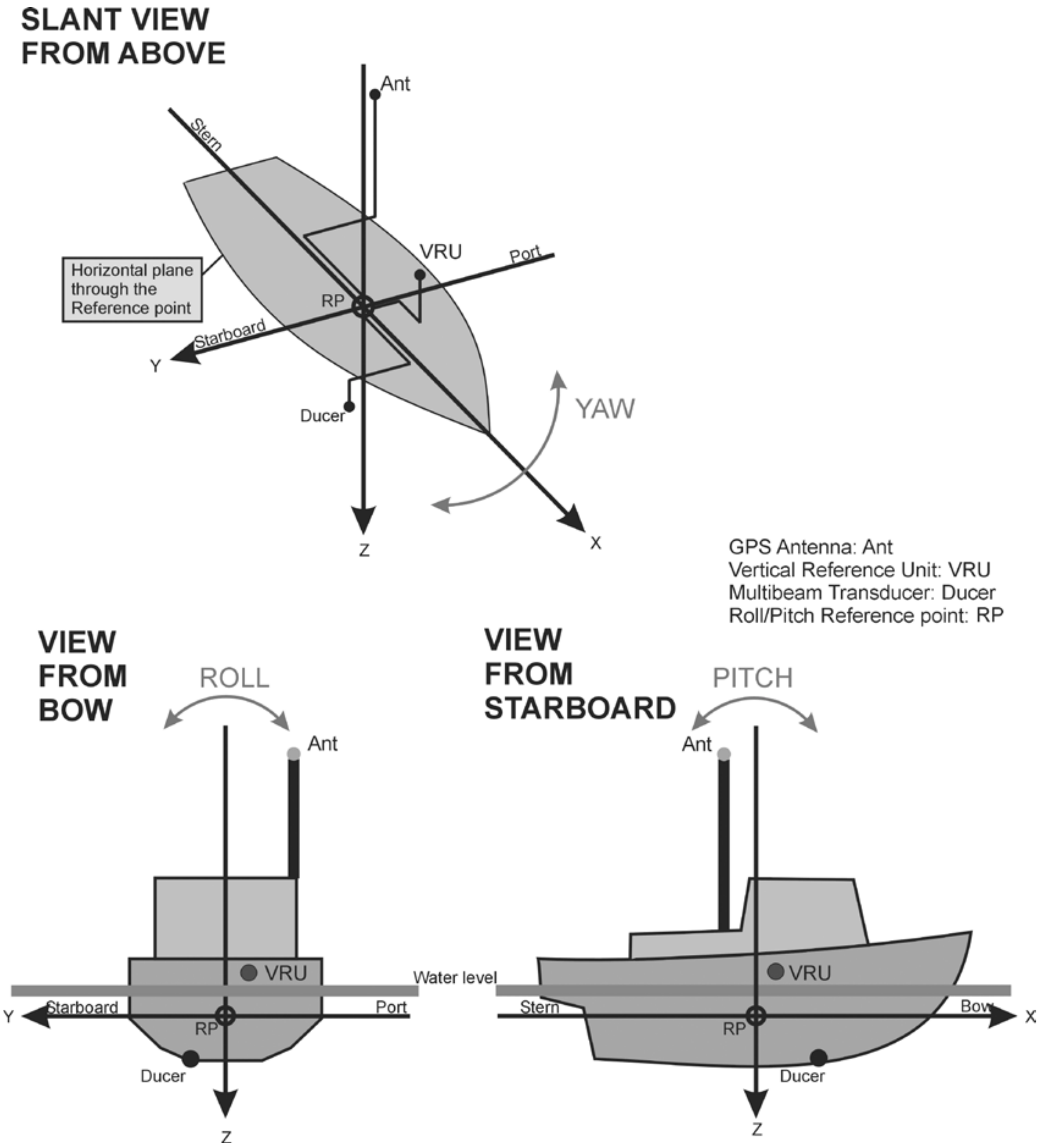


Figure 6. Vessel Motion Nomenclatures

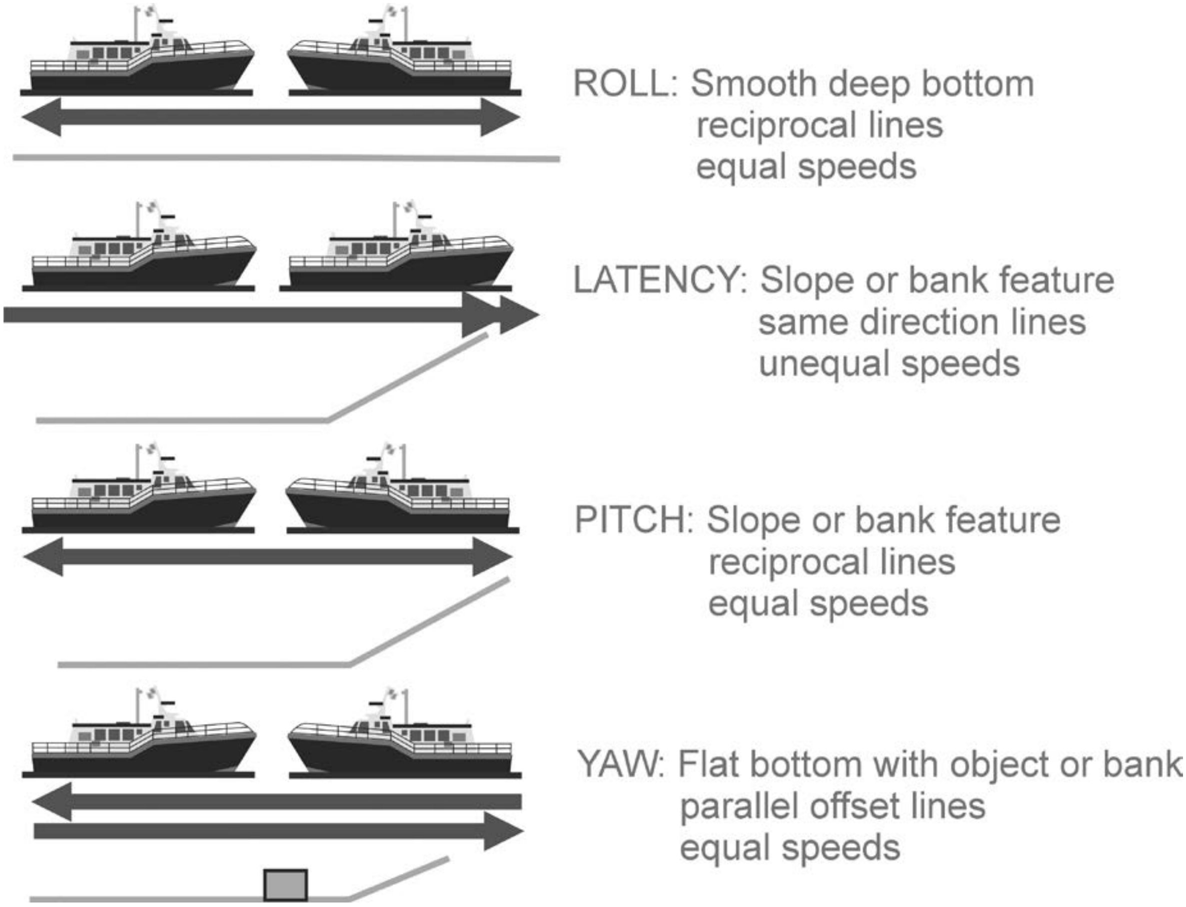


Figure 7. Time and Alignment Errors - “Patch Test”

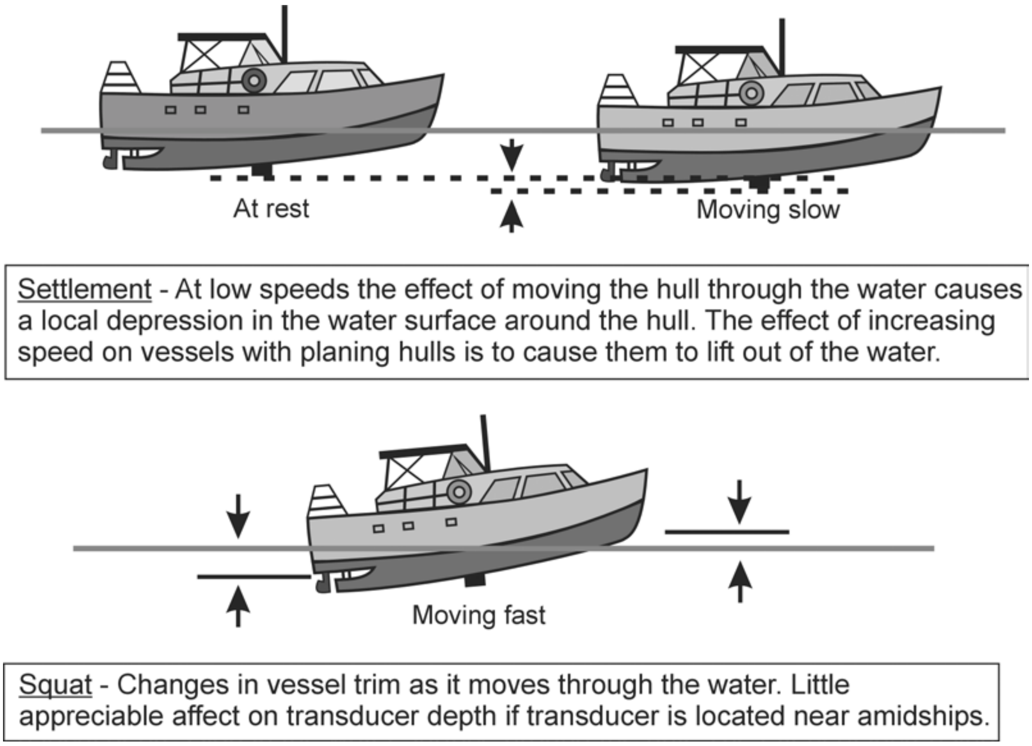
between the vertical angles (roll and pitch) of the transducer and the reference plane of the vertical reference unit must be known to accurately convert the acoustic travel times into vertical and horizontal positions relative to the transducer. Seemingly minor errors in the beam angle relative to nadir can result in unacceptably large depth errors. The patch test includes provisions for determining the offset angle between the vertical angles (roll and pitch) of the transducer and the reference plane of the vertical reference unit (Wheaton, 1988) (Godin and Ramalho-Marreiros, 1998).

The final calibration parameter (also determined during the patch test) is the time latency, which is the difference between the actual times when a measured parameter is reported from the depth sensor (sonar), the navigational unit (GPS), and heading unit is true and the times which the data acquisition computer associates with those reports. For ex- ample if the survey vessel is running 5 meters per second and there was a one second time lag between when a GPS measured position is true and the computer time that is assigned to the GPS measurement, then the horizontal positions that are assigned to any particular sounding will be in error. The assigned positions will be displaced from the true positions by 5 meters in the direction the ship was traveling. In many gyroscopes, flux gate compasses and GPS heading devices, the output of the sensor is smoothed with a low pass filter to reduce unrealistic short-term fluctuations. The low pass filtering causes the output heading values to be presented at times after they were the true values for vessel heading. Timing latency in heading values will impact the horizontal positions assigned to any soundings that are taken while the vessel heading is changing.

A patch test calibration should be done each time the installation of the survey system is modified. For example if the vertical reference unit were to be replaced, that would because to perform a patch test to determine the roll/pitch offset angles between the transducer and the vertical reference unit.

As shown in Figure 8, when a vessel's speed increases, it generally settles and squats (changes pitch trim), causing errors in depth measurement that must be corrected. In multibeam sonar the former is corrected by using settlement correctors and the latter is corrected by using the vertical reference unit. In a vertical beam echo sounder, the effects of both settlement and squat are corrected by using a set of correctors. A settlement/squat test should be performed at least annually to deter mine the relation between boat speed and transducer height above or below the static sounding reference plane. It is important that the positions of the GPS antenna and the sonar transducer relative to the pitch center of the vessel be known accurately. Otherwise the effects of settlement and squat may cause depths to be reported that differ significantly from their actual values. R TK GPS systems which provide direct (absolute) antenna-transducer elevation eliminate the need for the settlement corrections, as the antenna height will record the settlement in real-time. How- ever, if the R TK GPS system is set up to provide only the antenna height and is not configured to resolve the transducer elevation, then the squat correction must still be applied.

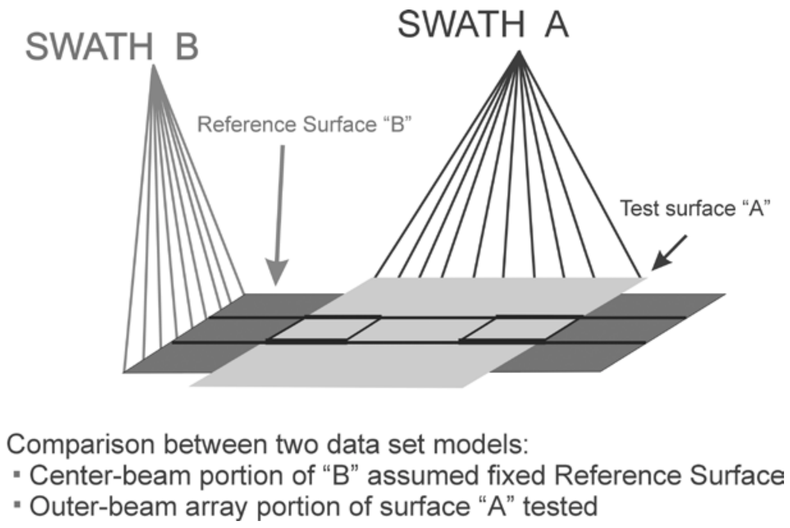
Often it is desirable to establish a performance measure for each beam in a multibeam sonar. That performance measure can readily be accomplished by surveying a flat section of seabed in two perpendicular directions followed by comparing the data for internal consistency. First the area is surveyed using closely spaced survey lines like Swath B on Figure 9. Those swaths are processed into a gridded surface using primarily the central beam depths from the several swaths. Such a surface is designated as Reference Sur face "B" in Figure 9. The same area of seabed is also surveyed using track lines like Swath A, which are perpendicular to the survey lines used to develop the Reference Surface B. In this configuration the depths measured with each beam in Swath A can be measured with each beam in Swath A can be compared to the spatially corresponding depths of the Reference Surface B. The differences between the Reference Surface B and depths measured in a particular beam of Swath A are expressed as the root mean square (RMS) of the differences. The Swath B and Swath A data sets should be acquired in a span of time that is too short for there to be changes in the water level and/ or sound speed profile. With environmental factors constant, the depth differences are attributable to the slant range measurements of the bathymetric sonar, which are processed to depths using the vertical reference data. Low RMS values are desirable and necessary to satisfy the IHO



Settlement - At low speeds the effect of moving the hull through the water causes a local depression in the water surface around the hull. The effect of increasing speed on vessels with planing hulls is to cause them to lift out of the water.

Squat - Changes in vessel trim as it moves through the water. Little appreciable affect on transducer depth if transducer is located near amidships.

Figure 8. Illustration of Settlement and Squat



Comparison between two data set models:
- Center-beam portion of "B" assumed fixed Reference Surface
- Outer-beam array portion of surface "A" tested

Figure 9. System Test Using Comparisons Between Surfaces

depth measurement requirements.

If the RMS differences in any particular beam(s) are not less than seventy percent of the required specification, then it is doubtful that a hydrographic survey containing depths measured in those particular beams will meet the required survey accuracy. The seventy percent rule of thumb is based on equally dividing the total allowable uncertainty between the measurement of depth and the knowledge of water level that is necessary to translate the measured depths, acquired relative to the actual water level, into depths relative to the MLLW chart datum.

During actual survey operations, the essence of this specific test can be accomplished through the use of cross line checks during the survey. However, in an actual survey the constraint for the same water level and sound speed profile are rarely met. Consequently cross line checks exhibit elevated values of RMS depth differences, compared to those observed in a specific test between comparison surfaces.

Even when all of the factors which impact on the accuracy of a sonar's distance measurements are known, the measured depths reported by the sounder will undoubtedly be biased, relative to the charting depths. That is because the measured depths are relative to the sea surface at the times when each of the measurements were made and the depths for charting must be relative to the chart datum. In the U.S. the chart datum is mean lower low water (MLLW), whereas internationally it might be MLLW or lowest astronomical tide (LAT). The water level at a given time and location of a depth measurement is a function of a predictable astronomical (tidal) component and a meteorological component, which is much less predictable.

Depths measured with respect to the local mean water level must be reduced to the chart datum by applying either predicted tides or measured tides. Alternately, real-time kinematic GPS with rapid ambiguity resolution (R TK-GPS) may be used to determine the depth, directly with respect to the WGS-84 ellipsoid (Krabill and Martin, 1987), and later after applying the ellipsoidal height of MLLW, deter mine the depth relative to chart datum.

The collection and application of an accurate water-level time series for the survey time and location are as important as any of the other sonar calibration procedures, because the accuracy of the water-level time series measurement and its relationship with MLLW is a critical component of the accumulated errors in converting a sonar's acoustic time of flight into a charted depth.

PLANNING CONSIDERATIONS

Good survey products begin with proper planning of the data acquisition. Planning begins with understanding the survey requirements and the characteristics of the area to be surveyed. Planning culminates in the determination of the procedures, equipment, and software, which are linked and should always be considered carefully, so as to optimize the survey efficiency and effectiveness.

Often one is constrained to conduct a particular survey with the equipment on hand, rather than rent or purchase new equipment that might be particularly suited to a given survey. In such cases, consideration must be given to the capabilities and limitations of a given system and how to design the survey to maximize the results. The design of the survey will require a choice of line orientation, line spacing, vessel speed, and sonar ping rates. Those will in turn depend on the distribution and configuration of depths in the survey area, as well as the particular system that will be used to conduct the survey. Line orientation and line spacing may also depend or the relative importance of imagery and bathymetry in meeting the objectives of the survey. Any particular survey might be for one or more of the following reasons:

hydrography, regional bathymetry, engineering applications, geologic studies, military application, habitat mapping, etc.

Hydrography surveys are conducted for the purpose of safety of navigation and requires very accurate bathymetry and the detection of all hazards to surface navigation like wrecks and obstructions. This type of surveying is most often conducted with a multibeam sonar and/or a sweep sonar, which might be augmented with towed side scan sonar to ensure full coverage of the seabed. Regional bathymetric surveys are conducted to determine the location and orientation of depth contours in water depths and areas where safety of surface navigation is not a major concern. This type of surveying might be accomplished with an interferometric sonar, a vertical beam echo sounder, or a multibeam sonar. Because this type of survey is most often in areas of open water and possibly at considerable distance from a port, a sweep sonar is generally inappropriate and imagery is acquired only if that parameter is an output of the specific survey system.

Surveys conducted for engineering applications include: pipe line and cable routing, dredging and site selection for offshore platforms. This type of surveying must acquire information about bathymetry, sediment type, and the presence of abrupt features like rock outcrops. Systems most likely to be employed are multibeam sonar, vertical beam echo sounders (for sediment analysis), and side scan sonar.

Geologic studies, both for mineral exploration and research require bathymetry as well as identification of characteristics of the seabed that can potentially convey information about the geological processes that may have occurred in the past as well as geological processing that might be currently active. This type of survey might be accomplished with a towed interferometric sonar or a ship borne multibeam sonar, both of which will provide a level of detailed imagery to supplement the bathymetry.

Mine counter measures is one military application that requires survey data. In surveys of this type, the ability to identify different sediment regimes and to detect targets of appropriate sizes and shapes are paramount in determining the selection of a sonar system. Side scan sonar, because of its superior ability to provide detailed imagery of the seabed and objects on the seabed, is a prevalent technique for this type of survey.

Vertical beam echo sounders and side scan sonars are widely employed in habitat mapping based on their ability for the identification/characterization of sediments by analysis of the individual echo waveforms or statistical analysis of “spatial patterns” in the backscatter imagery.

QUALITY CONTROL

The higher the confidence with which the hydrographer can state the survey results, the more likely that the survey has been per formed correctly. A quality control plan, or a control process, ensures that the final data will meet the desired specification when designed, implemented, and followed.

One vital factor, which has considerable influence on the quality of the sonar data, is the sonar operator. The operation of the echo-sounder is carried out by hydrographers, who in the course of a hydrographic survey must review the incoming sonar data and set echo sounder system parameters like range scales, pulse lengths, transmitted power levels, and receiver gains in order to maximize the quality of the survey data that are acquired. Since hydrographers are expected to make the correct decisions regarding the operation of the echo sounder, they must be given specific training. It is not sufficient that the hydrographers simply understand the instrumentation. If the hydrographers are to collect meaningful data, then they must know which data are meaningful. Their training must provide some back- ground in underwater acoustics, marine geomorphology and perhaps even a bit of marine biology, as well as, extensive training in the operation of the sounding system and the on- line data quality control tools.

The quality control of hydrographic survey data requires an understanding of basic seabed conditions in the survey area and whether or not to expect the existence of man- made objects. The more complete that understanding, the higher the resultant confidence will be that features with a certain size and shape, will be mapped correctly. Thus, a hydrographer should reasonably expect that sand waves are found off a rocky sandstone headland, and that man-made objects generally are not found in a recently glaciated region. Extend- ing this analysis, the hydrographer can estimate the likelihood of a given type and/or size of feature being detected, given the survey procedures and survey equipment that were employed. When absolute knowledge of the presence or absence of hydrographically significant objects is needed, then the hydrographer can focus resources on those areas which reflect the largest concern, and apply the appropriate procedures to locate the objects.

In addition to the extra attention that is necessary for potential problem areas in a survey, it is important to maintain the practice of acquiring data on survey lines that cross the main scheme of the survey (cross line checks) and comparing the resulting depths with those acquired on the main scheme survey lines. A patch test calibration, as discussed above, should be done when the character of the depths on either the main scheme survey lines or cross lines indicate that there might be something unnatural about the results. For example if the survey data always indicate that depths systematically decrease from port to starboard, regardless of heading of the survey line, that would be unnatural and indicate a problem with the roll sensor or the relative angle between the transducer and the vertical reference unit. Another example might be when the position of a particular localized feature, like a rock on the seabed that is measured on one survey line, does not agree with the position of the same localized feature that is determined on another survey line. This and the occurrence of a disjoint mismatch in a large-scale bottom feature, when viewed on different survey lines, may indicate one of several parameters about the installation of the sonar and its associated equipment have changed. Conducting a patch test calibration is just about the only way to resolve the root cause of such changes in performance of the survey system.

An important component of controlling the quality of survey data is for the sonar operator to assure that sound speed profiles in the survey area are adequately sampled in space and time. As part of this practice, it is necessary to maintain operator review of the swath data to quickly detect evidence that the sound speed profile being used to acquire/ process the swath data differs from the actual sound speed conditions. In general, it is a fairly safe assumption that the seabed is comprised of large flat facets that may be tilted in one direction or another. Therefore, when the seabed seems to curve upwards or down- wards to both port and starboard of the survey track, the sound speed profile of the water column is definitely not the same as the sound speed profile that is being used in the conversion of travel times at particular angles (beams) to vertical and horizontal positions. This situation should be remedied as soon as possible by measuring the local sound speed profile and using the new profile for converting acoustic travel times into depths and positions.

It is difficult to impossible with many of the current acquisition systems to re-process, in an efficient way, the raw acoustic information into new bathymetric solutions after data have been collected. Thus, primacy of quality control during acquisition must be maintained. Normally, the use of equipment and software operating manuals, augmented by hydrographer's notes from past experience with the equipment, form the basis for this control. Training, improved software, mentored data acquisition operation, and management-by- results will provide users with the requisite tools and incentives to ensure adequacy of nearly all data, and all of these measures prove their worth over time.

Once collected, data may be analyzed in several ways. Traditionally, the manual methods discussed in the post-processing section above have been built around a dual- operator approach similar to the land surveying method of observing-recording. One person performs the tasks, one person checks the values acquired, and the initial operator double- checks the final results. Denser data sets now provide more inherent information about the seabed, enabling the automation of the data inter-comparison and trending of statistical results, or stochastic analysis.

COST CONSIDERATIONS

The costs for most hydrographic projects are driven primarily by the availability of personnel and platforms. When there are large numbers of petroleum and other high-cost deep-ocean projects in progress, qualified hydrographic personnel become scarce and expensive. Vessel time is similarly tied to the ocean industry, where daily vessel lease costs are several hundred to several thousand Euros per day, dependent on vessel size and equipment. Another major factor is the working area; remote regions require higher mobilization costs and stricter adherence to project schedules, whereas surveys of harbors near major metropolitan areas are easier to both equip and man. Finally, the type of survey, as indicated above, has a very large effect on the potential costs of the work. Higher accuracy and confidences require more people with more knowledge to be involved in the work, thus increasing the project cost, and the length of the project affects the ratio of mobilization costs to overall survey production costs. The equation is not simple, and there are other factors that could affect final survey costs in measurable ways, but not in all situations. Surveying is a high-risk industry because it is closely linked to resource exploitation and risky commodity markets. Costs for a hydrographic survey can easily range from E 1,000 to over E 100,000 per square nautical mile, a substantial range to be interpreted by an inexperienced surveyor bidding on contract work or a potential customer interested in procuring services. Proposing an expensive, technically challenging solution to the survey task is not always required. Often the smaller one- or two-man survey firms, with only a vertical beam echosounder and analog side scan sonar, can do the job well and efficiently. Matching experience to the task at hand, these smaller firms can focus on one aspect of the hydro- graphic survey industry. They optimize their processes to the fullest extent, maintain their equipment through complete amortization, and thus maximize their profits while providing their customers with good survey products.

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