CHAPTER 6

Acoustic Multibeam Survey Systems

6-1. General Scope and Applications. This chapter provides guidance for the calibration, quality control, and quality assurance of multibeam survey systems used on surveys of Federal navigation projects and water control structures. Only general operating principles are outlined in this chapter. Comprehensive instructions for installing and operating specific multibeam systems, including the data acquisition, processing, and editing of data from these systems, are found in manufacturer's operating manuals and software processing manuals specific to those systems.

6-2. Background. The US Navy developed multibeam swath survey technology in the early 1960s for deep-water bathymetric mapping—i.e., the "Sonar Array Survey System—SASS." In the 1980s, this multibeam technology began to be developed for shallow water applications. In the early 1990s, John E. Chance (now Fugro) of Lafayette, LA, configured a multibeam system ("HI-MAP") for USACE revetment surveys on the Lower Mississippi River. This HI-MAP multibeam system was first deployed in support of USACE during the Mississippi River Flood of 1993, performing high water surveys over levee breaches in the St. Louis District. Subsequently, in the mid 1990s, USACE inland waterway and coastal districts began to acquire these shallow-water multibeam systems. Over 40 multibeam systems are currently deployed in 24 USACE districts (Table 6-1). It is expected that the use of multibeam systems will gradually supplant single beam systems for surveys of most deep-draft navigation projects. Multibeam systems, when coupled with digital side scan imaging systems, have also become primary strike, channel clearance, and shoal detection methods in USACE. When properly deployed and operated, the accuracy, coverage, and strike detection capabilities of multibeam systems now equals or exceeds that of traditional vertical single beam sounding methods. However, there are still many project applications where single beam systems are more effective and efficient than multibeam systems.

Table 6-1. Multibeam Systems Deployed by Corps Districts (2012)

New England - 2 systems	Los Angeles - 1	Galveston - 3
New York - 3	San Francisco - 1	Tulsa - 1
Philadelphia - 3	Portland - 2	St. Louis - 2
Baltimore - 1	Seattle - 1	Nashville - 2
Norfolk - 2	Vicksburg - 1	Louisville - 1
Wilmington - 1	Memphis - 1	New Orleans - 1
Savannah - 1	Huntington - 1	Detroit - 2
Jacksonville - 4	Buffalo - 1	Mobile - 4

6-3. General USACE Applications. Multibeam systems are primarily used to obtain complete coverage of deep-draft navigation projects; in particular, project condition surveys, dredging measurement, channel clearance, and constructed construction payment surveys. Multibeam systems can also be configured for waters-edge to waters-edge coverage (i.e., over 180 deg swath), allowing side-looking, full-coverage underwater topographic mapping of constricted channels, lock chambers, revetments, breakwaters, dams, and other underwater control structures. Most multibeam systems now collect acoustic backscatter information that can produce digital side scan imagery simultaneously with the topographic mapping data; an advantage in locating underwater rock, hazards, shoals, or other objects (strike detection)—see Appendix Q. Multibeam acoustic frequencies and signal processing methods may be configured to match the survey requirements--dredging measurement and payment, strike detection, structure mapping, bottom classification, etc. Some systems can provide near real-time data collection, filtering, editing, quality assessment, and display; along with near real-time (i.e., on board) data processing, plotting, and volume computations. Thus, final plan drawings, 3D terrain models, and dredged payment quantities can be completed in the field the same day the survey is performed. Additional USACE applications are described in Section II of this chapter.

SECTION I

Principles of Multibeam Depth Measurement

6-4. General. Multibeam systems generate a single sonar pulse from which detailed terrain or channel cross-section (swath) data can be developed, as illustrated in Figure 6-1. A single transducer forms a fan array of narrow beams that result in acoustic travel-time and angular measurements over a swath that varies with system-type and bottom depth--typically mapping an area 2 to 14 times the channel depth with each array pulse. Some multibeam systems can obtain 50 or more swath profiles (cross-sections) per second with hundreds of depths recorded on each profile/section, along with additional backscatter or snippet information with each depth. Multibeam systems can obtain 100% bottom ensonification coverage, and can provide high-resolution footprints when narrowly focused beams are formed. A variety of acoustic frequencies are available from manufacturers—100 kHz to 500 kHz being most common on USACE systems. Multibeam system internal depth accuracies are typically better than ± 0.8 ft (95% relative standard deviation) with repeatabilities usually well less than 0.2 ft (at 90-deg restricted array limits). Multibeam accuracies degrade at the outer beams—typically beyond 40- to 50-deg from nadir.

6-5. Depth Measurement Principles. All multibeam systems use the same basic approach to depth measurement. A lateral swath of sea floor is illuminated acoustically and the returning echo signals are processed into vertical depths. All outgoing and incoming sonar is transmitted and received at a single transducer head. Travel time estimates are converted into slant ranges, horizontal off-center distances, and then depth by applying beam angles and sound velocity profile and refraction corrections. Multibeam sonar systems employ various acoustic and electrical signal processing techniques to determine the slant range and angular measurements of seabed points along an array generated from a single acoustic pulse. These include amplitude

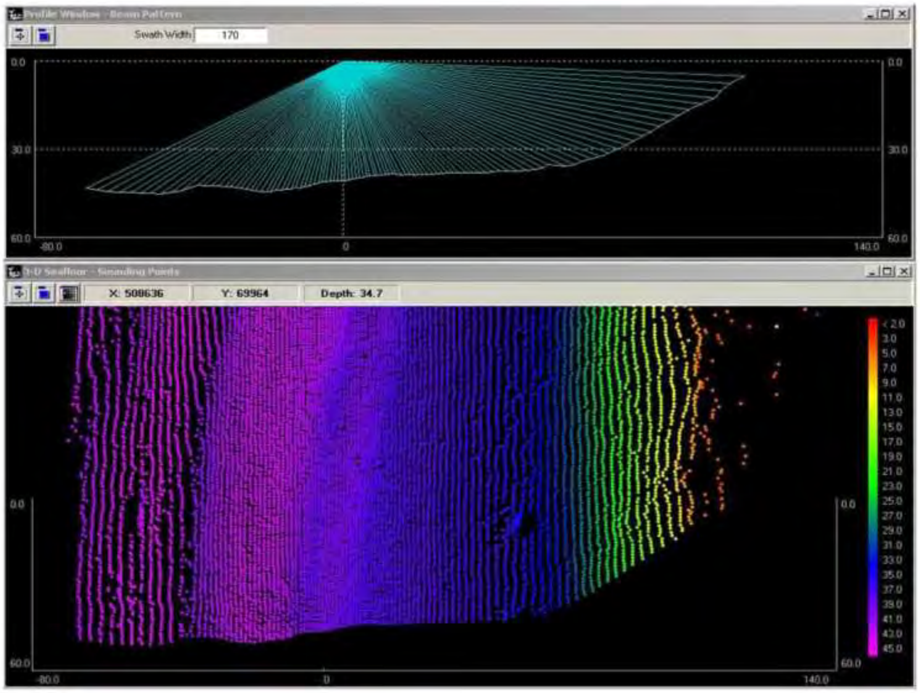

Figure 6-1. The upper image shows a real time display of a multibeam channel cross-section from a single ping. The lower figure shows a real-time plan view image of data collected along a channel and revetment bank on the Mississippi River. The multibeam transducer head was tilted to maximize coverage to starboard (up the revetment bank). Note that coverage spreads out on the outer ends of the port and starboard beams. (St. Louis District)

detection, phased array beamforming, interferometric (phase comparison), and various combinations of all these methods. The signal processing method(s) used on any particular multibeam system is often proprietary. In general, combinations of amplitude detection and transmit or receive beamforming are the most common methods. Phase comparison (interferometric) techniques may also be used directly or included within some proprietary systems. Many of these acoustic measurement techniques were derived from RF and radar signal processing.

a. Amplitude detection relies on finding the time of a beam's interception with the bottom, typically determined using a center-of-energy method, or matched filter method. Phase detection relies on finding the time of the zero phase crossing using two or more subsections of the receive array. Amplitude detection is typically used for the inner beams (e.g., 0 deg to 45-deg off-nadir) and phase detection is typically used for the outer beams (e.g., 45 deg out to 100-deg off-nadir)—see Figure 6-2. The changeover point between amplitude and phase detection is processed by various methods, such as absolute cutoff, real-time analysis of each beam, and combinations of amplitude and phase. Depth accuracy can change at the bottom detection transition points.

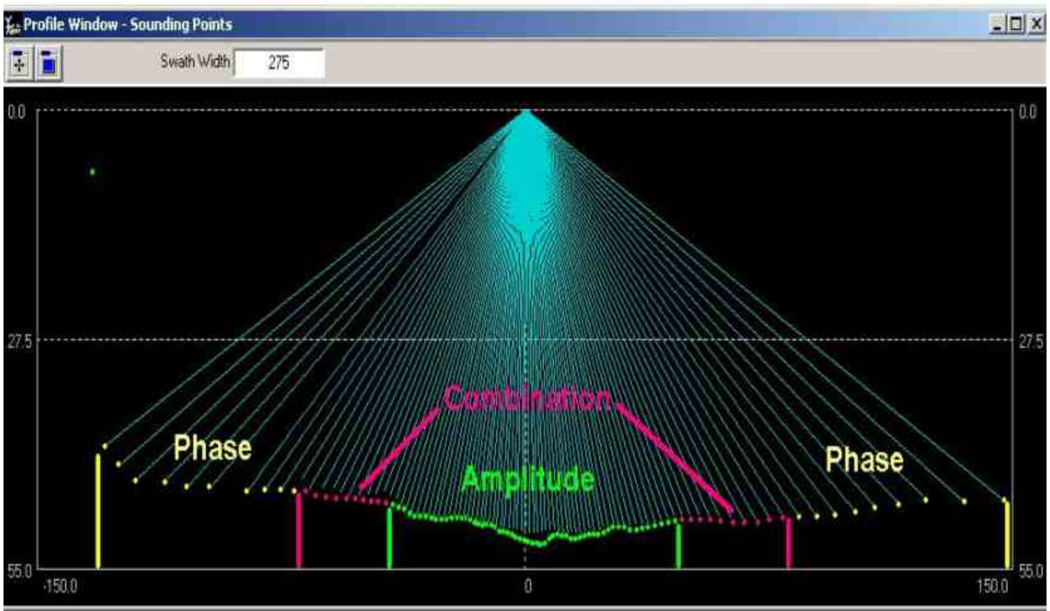

Figure 6-2. Amplitude and phase detection methods used in measuring depths over a typical multibeam array. The "combination" is the changeover area between phase and amplitude detection processing.

(1) Physical beamforming. A physically beamformed system uses a common projector and an array of receive elements physically pointed in the desired direction. Depth is determined based on the amplitude of the return signal (the center-of-energy detection method). Beam parameters are determined by the physical shape of the receive elements.

(2) Electronic beamforming. Electronic beamforming is generally based on electronic filter techniques to differentiate between individual echo contributions from different directions. Basically, each beam is formed by filtering out unwanted components. Depth is resolved based on center-of-energy or phase estimates. Electronic beamforming multibeam systems estimate the slant range to each echo event point based on the strength of the signal relative to a threshold. Electronic beamforming can be applied to either the transmit or receive cycles. To steer a transmit beam downward, multiple staves (elements) are sequenced with a slight delay. Each stave fires in sequence. The sum of the signals from each stave would then produce a wavelet in the desired direction. To steer a beam normal to the face (straight out), all staves would fire at the same time. In the case of a transmit beam formed system, each beam must be formed one at a time. The process of transmit beam steerage is slow since each beam must be formed in sequence. A better solution (and the one used by most electronic beamforming systems) is to apply this "phasing" principle to the receive signals, as shown in Figure 6-3. The angular acoustic wave front strikes each receive element, but at a different time and phase depending on

the angle of the return. By introducing a variable delay to each receive element's information, the phases can be aligned and the beam can be 'steered' in the direction of the return. In order to accurately apply the correct delay, three factors have to be known or measured: (1) the physical distance between each receive element, (2) the time of reception at each receive element, and (3) the instantaneous speed of sound at the receiver face. (R2Sonic 2010).

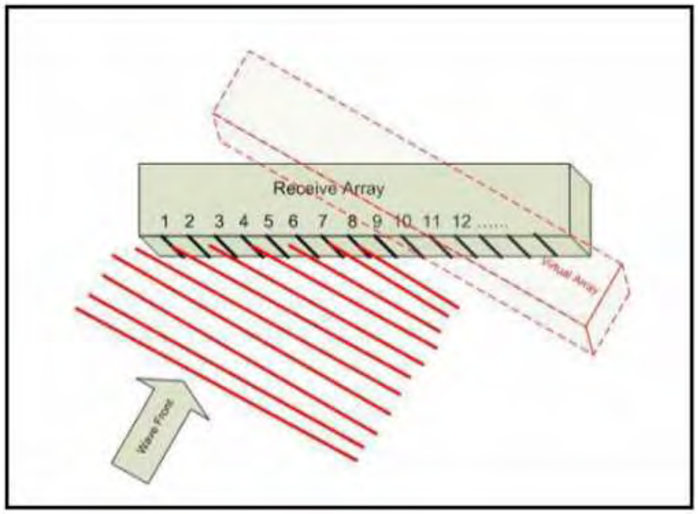

Figure 6-3. Electronic Beamforming. As the returning (reflected) wave progresses across the face, each receive element will see the wave at a slightly different time and thus a slightly different phase (R2Sonic 2010).

b. Interferometric systems (Phase Comparison). In interferometric multibeam systems, beam direction is determined by measuring differences in signal arrival times on an array of receive elements (phase differentiation). Interferometers provide range and bearing estimates to bottom depth points by detecting propagation delays from individual bottom spots to different transducer subsections. This is interpreted by the electronics as a phase difference in the signal. The phase difference is then converted to an angle or receive vector relative to perpendicular. Interferometry differs from the standard beam former in that the beams are created by a signal processor from data stored in the receive buffer. In interferometric systems, discrete beams are not physically formed--phase information from all directions are received and processed simultaneously. Interferometric techniques can provide high resolutions and a large number (hundreds) of beams within each ping array. The disadvantages of a purely interferometric multibeam echo sounder include: (1) phase tracking circuitry can become unstable and cause high data variations, (2) resolution depends on the internal detection rate (i.e., sophistication of the processing system), and (3) resolution and directivity near the nadir is poor.

c. Beam spacing. Beamforming multibeam systems are typically designed with between a 0.5 deg and 3.0 deg beam spacing. To increase resolution along the array, interferometric phase comparison techniques may be employed. The accuracy of a wide-swath multibeam is determined by the ability of a multibeam system to resolve the actual beam angle in varying situations. A major component of this is correcting refractions due to sound velocity changes in the water column.

d. Beam footprint size. Outer beam quality and accuracy is dependent upon footprint size. As with single beam echo sounders, the smaller the beam angle, the better the system is able to discern true depth and resolve small features. As the size of the footprint increases toward the outer beams due to beam spreading, the stability and accuracy of the data decreases, resulting in a degradation of data quality and accuracy in the outer portions of the beam array. For this reason, angular restrictions are typically placed on the use of outer beam data; which limits the amount of single pass coverage in multibeam surveys.

e. Signal parameters. Each individual bottom spot within the ensonified swath responds with a reflected echo signal in which signal parameters (amplitude, frequency, phase) are all dependent. These parameters are dependent upon the characteristics of the bottom, namely (1) bottom reflectivity and (2) slope angle of incidence of the beam. Other local environmental factors that may need to be adjusted on a typical multibeam system include acoustic absorption, acoustic spreading loss, pulse length, transmit and receive power settings, and related time varied gain (TVG). Estimating these and other settings, and their impact on depth measurement accuracy (uncertainty), is often difficult. The quality of the return signal is also dependent upon the primary projector/receiver characteristics and the geometrical and acoustic reflective properties of the particular bottom material. A multibeam sonar's bottom detection thus provides three pieces of information: (1) the angle of the beam along which the acoustic pulse traveled, relative to the sonar head, (2) the round-trip travel time of the acoustic pulse, and (3) a signal intensity time series of the bottom return. These three pieces of information must be integrated with the other sensor data (e.g., vessel velocity, acceleration, roll, pitch, yaw, and heave motions) to determine the total sounding solution (i.e., X-Y-Z) relative to an earth-fixed coordinate system—e.g., the NSRS or local construction station-offset-depth reference framework.

f. Vessel positioning requirements. Both code-phase US Coast Guard DGPS and carrier-phase (RTK) GPS positioning methods are used to control the horizontal location of the vessel, and ultimately the multibeam transducer. Use of either positioning method depends on a number of project-specific requirements. In distant offshore coastal areas where tidal modeling is uncertain, carrier-phase RTK may be needed to enhance vertical accuracy of measured depths. When the multibeam is deployed horizontally to map underwater structures, RTK techniques may be needed to maintain decimeter-level horizontal accuracy. RTK is also recommended to obtain more reliable and consistent "Patch Test" calibrations.

g. Correcting vessel motion effects (heave, roll, pitch, and yaw). Multibeam accuracy is critically dependent upon the ability of the complete system to compensate for pointing errors caused by vessel heave, roll, pitch, and yaw. Various types of inertial and inertial-aided GPS methods are used to measure these motion parameters in real-time. Across-track location of each bottom point is critical. In wider swath systems, even a small degree of roll error can cause large errors in the outer beams. Vessel heave due to waves must also be accurately measured and compensated for. These errors are further compounded due to beam spreading. Multibeam systems must be integrated with accurate motion reference units (MRUs) to correct for vessel motions. The inter-relationships between the positioning system, motion sensors, and the multibeam system, are critical. Quality control calibrations are essential to minimize errors due to these motion components.

h. Sound velocity and refraction. Since the array beams travel through varying water column temperatures and suspended materials (e.g., salinity) the refractive characteristics of each array beam must be determined and corrected. Thus, accurate sound velocity through the water column must be measured. Continuous (real-time) sound velocity measurements at the transducer head may be required on some systems.

i. Estimated accuracy. The propagated measurement uncertainties in depth measurements were described in Appendix D. Given the numerous parameters involved in a depth observation at various points along the array, estimating the resultant depth uncertainties is extremely difficult to quantify. Uncertainties tend to degrade away from nadir due to the velocity correction and signal processing methods described above. They can only be estimated from assumed uncertainties in the 40+ individual components that make up the overall uncertainty estimate. Many of these component estimates are, at best, educated guesses. Currently, the only practical method of estimating multibeam data quality is through Performance Tests that compare the multibeam data with more reliable near-nadir data from independent surveys—see details in Section VI in this chapter.

6-6. Overall System Requirements. Configuring an operational multibeam system requires the integration of various processors, sensors, and computers. In addition to the multibeam system itself (transducer and processor), the following primary peripheral devices are typically required on a complete system. All devices are linked through a computer with data acquisition and navigation software.

a. Positioning and navigation system. GPS (DGPS code or carrier phase). A survey Total Station may also be used for positioning in limited applications. Positional data is also fed to the vessel operator for real-time navigation.

b. Heading system. A gyrocompass is linked to the data acquisition computer, providing vessel azimuth orientation. (POS/MV systems may also provide this data.)

c. Motion compensation system. An inertial heave, pitch, and roll system provides real-time vessel motion data. Inertial-aided GPS systems (e.g., POS/MV) will provide this motion data.

d. Sound velocity probes. Sound velocities in the water column must be periodically measured. Some multibeam systems may require a real-time velocity probe at the transducer head.

e. Details on configuring, linking, interfacing, networking, and calibrating all these components are covered in manufacturer's operating manuals and software data acquisition manuals. Figure 6-4 depicts a typical configuration of the peripherals required for a complete multibeam survey system. The specific hardware and software shown is only for illustrative purposes—a variety of different (and equivalent) sources for these devices are available.

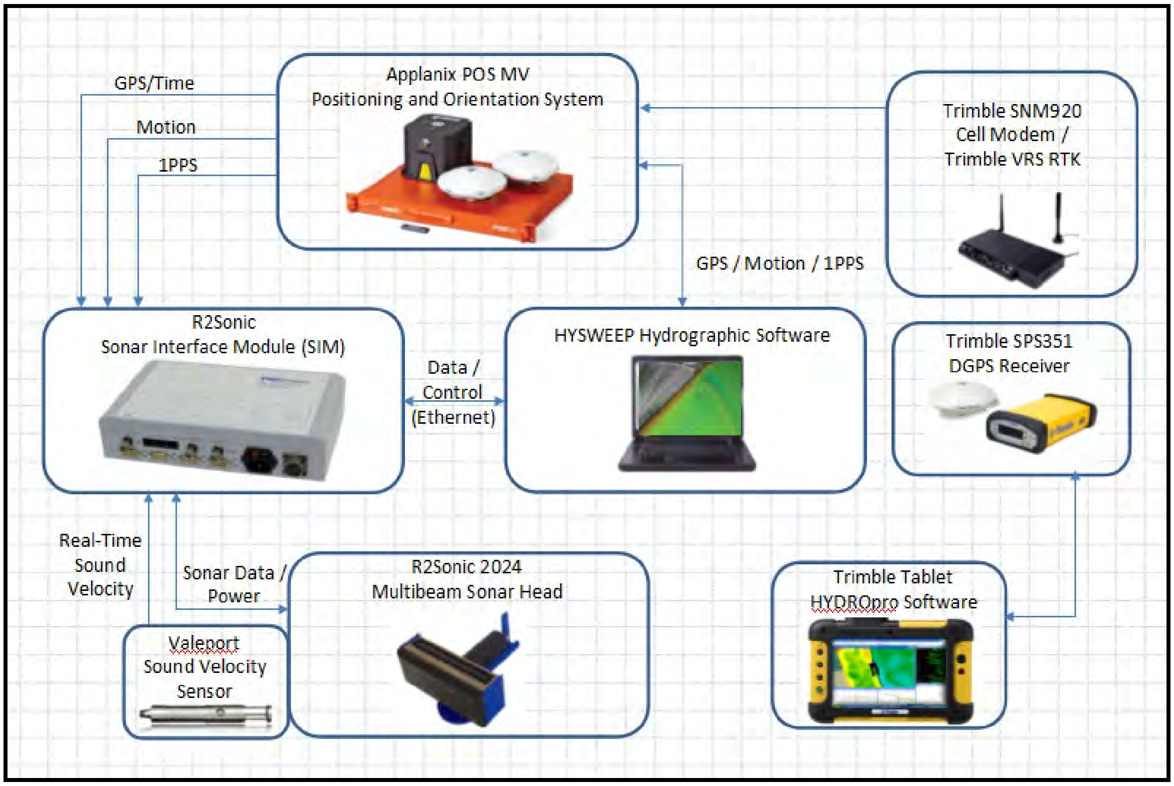

Figure 6-4. Typical configuration of a multibeam survey system. (Measutronics, Inc., Lakeland, FL)

6-7. References. The following references are recommended for more detailed descriptions of the operating principles of multibeam systems. They are also listed in Appendix A. Various manufacturers provide training courses that cover underwater acoustic theory and measurement principles relating to their specific multibeam system.

(1) "R2Sonic Broadband Multibeam Echosounders Operation Manual V3.0," (R2Sonic 2010). Basic general underwater acoustic principles, amplitude and phase detection theory, especially broadband multibeam systems.

(2) "Multibeam Sonar Theory of Operation," (L-3 SeaBeam 2000). Comprehensive multibeam signal processing techniques. Details various beamforming methods used in multibeam systems.

(3) "GeoSwath Product Information Bulletin," (GeoAcoustics 2002). Covers acoustic propagation principles, transmit beamforming, receive beamforming, multiple receive arrays, and phase comparison principles, advantages, and limitations.

(4) "IHO Manual on Hydrography." (IHO 2005). Details amplitude, phase detection, and interferometric techniques, including total propagated uncertainties of collected multibeam data.

SECTION II

Multibeam Applications and Utilization on USACE Civil Works Projects

6-8. General. Multibeam systems are primarily deployed on deep-draft navigation projects where full-bottom coverage is required. A typical example is a coastal navigation entrance project shown at Figure 6-5. Multibeam systems may also be employed on deeper portions of inland projects, and near USACE locks, dams, hydropower plants, reservoirs, river control structures, and revetments. Survey lines are normally run longitudinal with the channel or river alignment. The coverage of each swath is dependent on the depth and beam width. A typical 40- x 400-ft project can be covered with 3 to 5 lines, depending on the selected beam angle limits. (Refer to Section V in this chapter for estimating survey coverage). Vessel speeds are typically run slowly (e.g., 5 to 10 knots) in order to ensure 100% along-track ensonification, ensure multiple hits on potential hazards or shoals, or when collecting side scan imagery. At a nominal update rate of 40 profiles/sec in shallow water, and a 256 beam array, over 10,000 depths/elevations per second are generated; resulting in a large but densely detailed database for the subsequent processing and other engineering applications. Interferometric multibeam systems may obtain upwards of 50,000 depths per second. The tradeoffs to wide-swath, high-density data are increased editing and post processing time and the requirement for more sophisticated computer hardware.

6-9. Project Condition Surveys. Multibeam survey systems are primarily used for project condition surveys of USACE federal navigation channels, revetments, and other underwater structures where complete bottom coverage is desired to delineate the feature or structure. Multibeam sensors can be configured to detail coverage of pipelines, bulkheads, floodwalls, lock walls, revetments, breakwater riprap, and other similar underwater structures. Systems can be configured (or the transducer rotated) to provide up to 190-deg coverage, which would provide "water's-edge to waters-edge" coverage to both port and starboard. In some narrow projects, a single swath pass may provide full coverage.

6-10. Dredging Measurement and Payment Surveys. Multibeam survey systems that provide complete bottom coverage are recommended for use in most dredging measurement and payment surveys, i.e., plans and specifications surveys, pre-dredge surveys, post-dredge surveys, and final acceptance/clearance surveys.

a. Multibeam systems are an effective quality control process on dredging projects requiring 100% bottom coverage to assess and certify project clearance. The full digital terrain model (DTM) generated from a multibeam survey provides a more accurate and equitable (to the government and contractor) payment quantity than that obtained from traditional single-beam cross-sections. However, the use of multibeam systems on dredging measurement, payment, and clearance work requires rigorous quality control and assurance calibration, and attention to

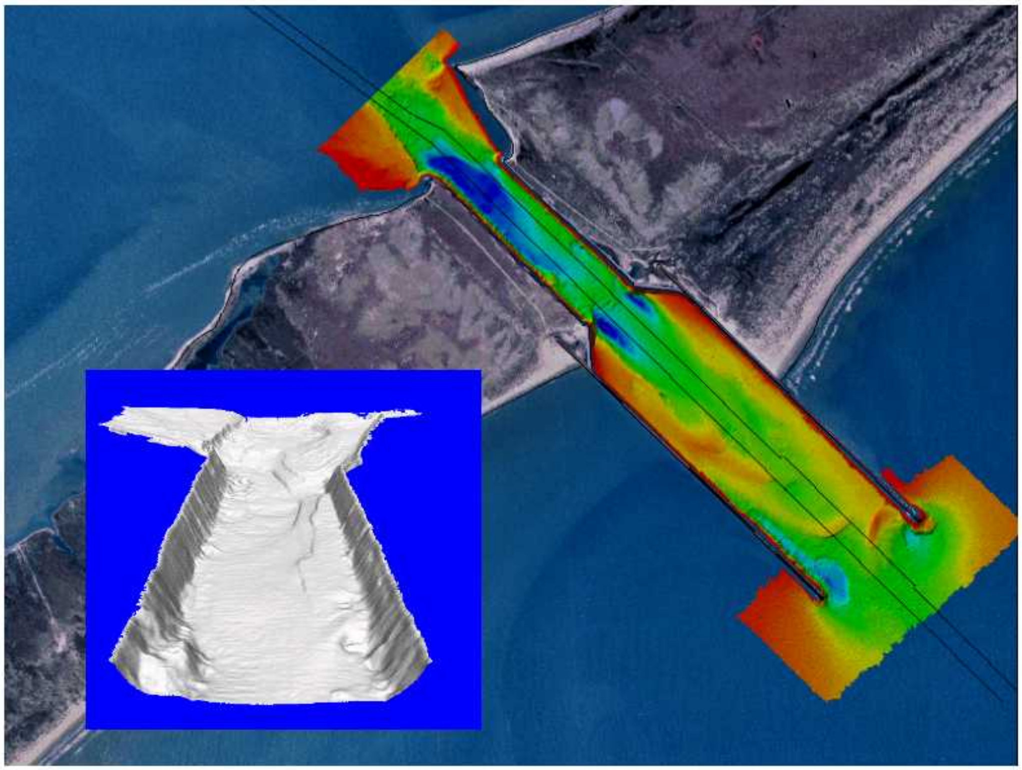

Figure 6-5. Full-coverage multibeam survey of coastal inlet navigation project and shore protection jetties. (Galveston District)

bottom type with respect to frequency. Any resultant biases that are not corrected can significantly affect volume computations. Multibeam systems are normally not used for payment or clearance on shallow-draft projects with sand or silt bottoms; however, less than 100% bottom coverage with multibeam may be acceptable in these shallow-draft projects.

b. Measurement and payment provisions in dredging contract specifications should clearly stipulate the type of multibeam survey system, acoustic frequency, navigation guidance system and software, data acquisition parameters (horizontal and vertical control, density, etc.), data processing and binning techniques, and mathematical volume computational method/software that will be employed by the government. In order to ensure consistency when performing measurement and payment surveys, commercially available software should be employed for data collection, data processing, data quality control, and volume computations.

6-11. Shoal or Strike Detection Applications. Multibeam survey systems represent an effective mechanism for detection of shoals, rocks, wrecks, debris, or other navigation hazards lying above grade in a navigation channel. The side-looking aspects of both the multibeam signal and the digital backscatter sonar imagery signal may be used for such investigation purposes. In order to enhance the probability of detection, and depending on documented system performance characteristics, 200% bottom coverage may be specified in order to ensure objects are ensonified from two aspects--and to confirm at least three multiple hits are obtained on these objects. Performance demonstration tests on simulated objects should be periodically performed to assure data detection quality and assess the need for overlapping coverage.

a. Emergency operations. Multibeam systems recording both topographic data and digital side scan imagery are recommended for locating underwater objects and marking objects for clearing after natural disasters. New York District successfully deployed multibeam systems along with towed side scan sonar to locate a downed aircraft in the Hudson River.

b. Multiple-transducer, boom-mounted, channel sweep systems are generally preferred for use over multibeam survey systems in shallow-draft (<15 ft), sand/silt-bottomed navigation channels. (However, especially with the ability to tilt the sonar head, multibeam systems are also a valuable tool that can be used in these same projects.) Multi-transducer systems will also provide 100% bottom coverage on shallow draft navigation channels, as will mechanical, or manual, channel sweeping techniques. Mechanical bar sweeps still remain an effective dredging quality control technique when rock is encountered—see Chapter 10.

6-12. Underwater Structure Investigation Surveys. Multibeam systems represent an effective tool for performing detailed investigations of the conditions of Corps locks, dams, and other underwater structures, such as bridge piers, revetments, intake structures, spillways, breakwaters, jetties, and sheet pile bulkheads. Refer to Chapter 9 and Appendix N for details and examples of structure investigation surveys.

6-13. Multibeam Side Scan Imagery. Multibeam systems generate side scan imagery along with the basic depth information. Multibeam side scan imagery is generally not as good as towed side scan imagery (see Appendix Q). The high aspect of a hull mounted transducer results in high grazing angles. These high grazing angles result in small shadows. Off-nadir beam amplitude imagery degrades quickly because of the poor intensity of the returned acoustic energy and is subject to "false target generation" in side lobe interference situations. The larger the beam footprint, the coarser the amplitude imagery. Amplitude imagery is also called “backscatter intensity” and can be exploited for bottom classification (reference Geocoder processing algorithms in HYPACK 2011). Angle independent imagery, or time series imagery, provides an image very similar to towed, low resolution, side scan sonar. The resolution is much higher and the data rates are much higher. Multibeam data acquisition that includes the angle independent imagery results in very large data files.

6-14. Miscellaneous Considerations.

a. USACE personnel training requirements. Multibeam system operators require considerable expertise in both surveying and on CADD workstations. Prior to using multibeam systems on USACE surveys, system operators should have completed specialized training. Presently, the Corps PROSPECT course on Hydrographic Surveying Techniques is not considered sufficient for multibeam training. Comprehensive training courses are available from: (1) the University of New Brunswick, (2) HYPACK, Inc., (3) University of New Hampshire-NOAA Joint Hydrographic Center, or (4) The Hydrographic Society of America seminars. Multibeam manufacturers also offer specialized training sessions.

b. Plant utilization and justification. Multibeam surveys may be obtained using either USACE hired-labor forces or through A-E service contracts. Commands considering procurement of multibeam systems should internally determine that such a system represents an effective and efficient utilization of floating plant, given the $200 K to $500 K investment for a complete survey-quality multibeam system with auxiliary sensors. Some factors that should be evaluated include: (1) proposed multibeam vessel, (2) system configuration (hardware and software), (3) estimated annual utilization (time and location), (4) FTE allocations, (4) system operator qualifications, (5) field data processing, editing, and plotting, and turnaround capabilities, (6) estimated daily plant and survey crew rental rate, and (7) comparative analyses between hired-labor and contract costs.

c. Calibration and quality control. Field quality control calibration of multibeam acoustic refractions and vessel motion is significantly more critical and complicated than that required for standard single beam systems. Recommended calibration requirements, procedures, and allowable tolerances are described in later sections of this chapter. Quality assurance Performance Tests are essential in order to assess and demonstrate data quality. These quality control calibrations and quality assurance Performance Tests must be processed and adjusted on board the survey vessel prior to and during the survey—after-the-fact checks in the district office are of little value if an uncorrectable field calibration problem is detected. This implies that near real-time field-finish data collection, processing, and editing must be established in the field in order to ensure the most cost-effective utilization of this technology.

SECTION III

Configuring Multibeam Transducers on Corps Floating Plant

6-15. General. Multibeam systems are mounted on a variety of Corps vessels, ranging from 22-ft up to 65-ft vessels. Numerous factors must be considered in selecting the type (and size) of vessel, mounting location, and projected utilization of a multibeam system. Districts procuring multibeam systems should consult other districts with operational systems as part of this decision process—especially districts with similar project conditions. Contacts with multibeam manufacturers and the USACE Marine Design Center in Philadelphia are also recommended. Some of these mounting design considerations are outlined below.

a. Vessel size. Multibeam systems are generally more cost-effectively utilized on small, mobile (trailerable) survey vessels up to 26 to 30 ft in length, with the transducer assembly externally mounted over the bow or either port and starboard sides. This allows the system to be rapidly deployed on remote projects. Permanent or retractable transducer mountings on large, non-trailerable, 30- to 65-ft survey vessels are generally recommended in situations where such a vessel is primarily based near a major coastal navigation project.

b. Mounting stability. A sturdy transducer mounting is required to eliminate any vibration at the underwater transducer head. In addition, the location should afford a smooth laminar flow at the head.

c. Transducer orientation calibration. A fixed transducer (i.e., hull mounted) minimizes the need for periodically calibrating the orientation parameters (Patch Test). Retractable transducer mounts should be designed such that they rigidly snap into the same underwater location each time they are deployed.

d. Lever arm calibration. Ideally, a multibeam transducer should be located as close as possible to the vessel's center of rotation, and as near as possible to the GPS positioning system antenna and inertial measurement unit. This is rarely possible in practice, especially on smaller vessels. Minimizing these lever arm distances between the transducer, positioning, and inertial units helps reduce errors inherent in these parameters. Measurement of these lever arm distances requires precise survey measurements (± 1 cm). These measurements are often difficult when visual access to any of the units is blocked.

e. Maintenance. Access to the head allows removal of marine growth and ease of repair to the transducer elements if necessary. Retractable or pivoting mounting systems provide such access as opposed to fixed hull mounts.

f. Vessel maneuverability. The ability to retract the transducer from the water allows the vessel to reach project sites at full speed and without danger from hitting underwater obstructions.

g. The following sections provide additional guidance, advantages, disadvantages, and illustrations of various multibeam installations deployed by Corps districts.

6-16. Fixed Hull-Mounted Systems. Fixed hull-mounted systems are installed on large vessels, usually those exceeding 30 ft in length. A main advantage of fixed mountings is stability—orientation parameters remain relatively stable, minimizing the need for periodic calibration Patch Tests. A main disadvantage is maintenance; requiring that the vessel must be lifted into dry dock for access to the transducer housing. Another disadvantage is that the fixed transducer is vulnerable to being hit by any debris in the water. In the 1990s, a number of districts with 65-ft survey vessels elected to install fixed hull transducer mounts. Few such systems are currently deployed on newer large vessels in USACE—retractable transducers on split hull catamarans are now considered more effective. Figure 6-6 depicts a fixed-hull installation of the Reson 8101 system on the Norfolk District 65-ft Survey Vessel Adams II. This system was installed in 1998. This represented an effective fixed-hull installation since this vessel is deployed on nearby deep-water navigation projects in and around Norfolk and Chesapeake Bay.

Figure 6-6. RESON SeaBat 8101 fixed hull-mounted installation on Survey Vessel Adams II. (1998 Norfolk District)

6-17. Through-Hull Transducer Mountings. A number of districts (e.g., Mobile, Portland, Jacksonville) have recently elected to procure 50 to 65 ft split-hull catamaran vessels with a retractable transducer mounting between the hulls. This is sometimes referred to a "moon pool" mounting. The transducer mounting is located near the vessel's center of motion to minimize underway rotation corrections and lever arm distances to the peripheral positioning and inertial motion units. The transducer is hydraulically lowered to its fixed underwater position. The mountings have rigid locks such that the transducer head is always fixed at the same location; thus minimizing the need for periodic Patch Test recalibrations. Since the transducer can be easily retracted, the vessel can reach remote project sites at full speed. As indicated in Figures 6-7 and 6-8, the head can be easily accessed for maintenance.

6-18. Bow-Mounted Transducers. Retractable bow-mounted transducers are typically used on smaller, trailerable vessels, although they may be used on any length vessel. They are either physically (manually) or hydraulically deployed to their underwater position, with a rigid locking mechanism. A disadvantage is that vessel motion at the bow (e.g., pitch) can be large; and that lever arm distances to the positioning system and inertial motion system are lengthy. The following figures (9 through 12) illustrate bow-mounted transducer installations.

Figure 6-7. Portland District S/V Redlinger. The S/V Redlinger is a 60-ft foil supported catamaran. Survey equipment includes an Applanix POS/MV, Simrad EM 3002, and an Odom CV100. The transducer is located just aft of the cabin.

6-19. Side Mounted Transducers. Side-mounted transducers are commonly installed on smaller vessels, such as that shown in Figure 6-13. Installations may be permanent or temporary. As with bow-mounted installations, vessel motion (especially roll) may be significant on side mounts. Vessel pitch may be significant on systems mounted near the stern. Thus, lever arm and vessel motion measurements (corrections) are demanding and critical

a. 45-Ft Survey Launch Vollert, Galveston District. Figure 6-14 depicts the installation of an Odom multibeam system aboard the Survey Launch Vollert. The Vollert is a 45-ft length vessel with twin diesels, a 12-ft beam, and 3-foot draft. This vessel is normally used to conduct hydrographic surveys federal navigation projects in the Houston, Galveston, Texas City, and Freeport areas. The multibeam transducer shown is side-mounted on temporary rigs near the mid section of the vessel. The guys shown in the figure were used in attempts to reduce vibration down at the head—a more rigid frame near the waterline is required to fully stabilize a side-mounted transducer.

Figure 6-8. Louisville District 30-ft survey boat with through hull mounted transducer (Reson 8125-H multibeam system).

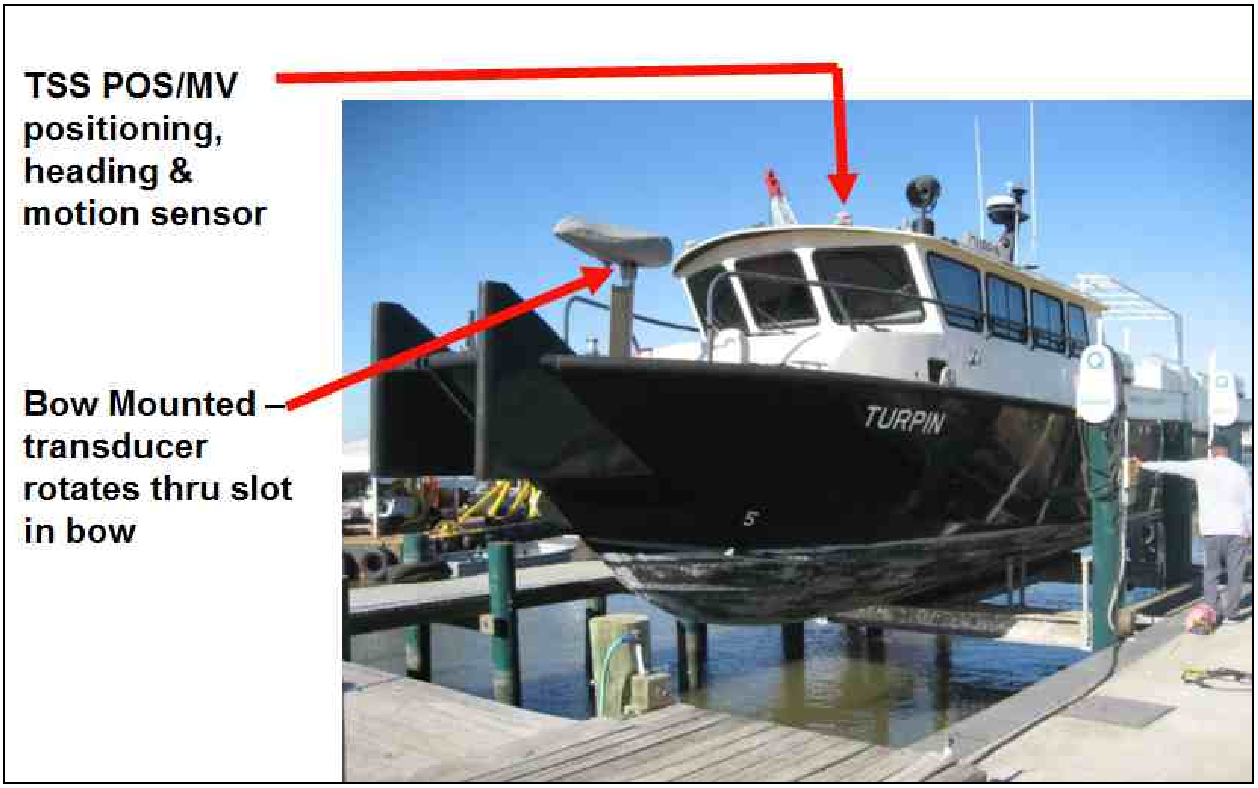

Figure 6-9. S/V Turpin with bow-mounted transducer.

Figure 6-10. Tulsa District retractable bow-mount. It is hydraulically deployed.

Figure 6-11. Bow-mounted transducer on an inflatable raft. This portable vessel is used for USGeological Survey multibeam surveys of the Colorado River in the Grand Canyon. It is manually deployed.

Figure 6-12. Bow-mounted transducer with an optional rigid (locking) tilt capability to providecoverage up to water's edge on revetments or lock & dam structures. This rigid tilt lock minimizes the need for Patch Testing at this optional setting. (St. Louis District S/V Boyer)

Figure 6-13. Typical multibeam transducer systems side-mounted on a rigid pole attached to the survey vessel. (Odom, Inc. and GeoAcoustics, Inc.)

Figure 6-14. Side mounted multibeam transducer on S/V Vollert. (Galveston District)

b. Portable side mount. Figure 6-15 illustrates a compact, lightweight multibeam transducer side-mount on a small vessel. The mount is attached to the hull in two places.

Figure 6-15. Side/aft mount of an Odom ES-3 transducer and inertial motion sensor. Mounting the GPS antenna directly above the transducer and motion sensor minimizes lever arm measurements and corrections.

6-20. <u>Stern-Mounted Multibeam Transducers</u>. Multibeam transducers can be mounted on the side near the stern or on the stern itself, as shown in Figures 6-16 and 6-17. Such mounting locations are often temporary—i.e., installed on a "vessel of opportunity" on a one-time project. Lever arm corrections and vessel motion measurements may be significant at these locations, and require demanding quality control and quality assurance testing.

Figure 6-16. New England District survey boat with aft/side mounted multibeam system. The GPS positioning antenna is located directly over the multibeam transducer.

Figure 6-17. Temporary stern-mounted multibeam transducer on a small skiff. In this case, engine propeller noise did not appear to affect the data quality. (Portland and St. Louis District)

SECTION IV

Quality Control Procedures for Multibeam Systems

This section provides recommended technical guidance for performing system alignments and quality control calibrations of multibeam sonar systems used on Corps projects.

6-21. Background. Many field calibration requirements for multibeam systems are similar to those required for single beam systems described in Chapter 4. However, some calibration and quality control procedures for multibeam systems are more critical and demanding than those required for single beam echo sounders. Periodic, precise calibration and verification testing is absolutely essential in order to assure multibeam derived elevations meet the prescribed accuracy tolerances for the project--especially near the outer beams of the array where refractive ray bending and vessel alignment and motion variations can significantly degrade the data quality. With improved resolution and increased beam coverage, there is a greater need for accurate sensors to ensure that the recorded depth is reduced to its correct position on the sea floor. This is accomplished by interfacing the multibeam system with position and attitude sensors, such as: (1) a high accuracy, geodetic quality GPS system (including heading and attitude RTK systems), (2) inertial motion reference units to monitor changes in position, velocity, acceleration, heave, pitch, and roll, and/or (3) a gyrocompass. In addition, the time synchronization for all these components is critical. For this reason, the system accuracy is comprised not only of the multibeam sonar accuracy but also the various components that make up the total system.

a. The components that make up a multibeam system must be periodically aligned, calibrated, tested, and monitored in order to ensure overall data quality. Quality control calibration tests are performed to measure alignment and timing biases in the transducer head, inertial measurement unit, gyrocompass, GPS antenna, etc. These calibrations are prescribed to minimize errors due to time latencies, roll, heave, pitch, and heading for the integrated suite of equipment.

b. Quality assurance Performance Tests on multibeam data (covered in Section VI) are periodically performed to determine if the quality control calibrations have been reliably performed, or need to be repeated. A Performance Test will provide a statistical estimate of the data accuracy (or "repeatability"). The test results should be checked against the statistical accuracy criteria prescribed for the particular type of survey.

c. Procedures for performing these calibration tests are outlined in this section and are more fully detailed in the hardware and software manuals provided with the individual sensors making up a multibeam survey system. These include acoustic refraction measurements (i.e., velocity casts and bar checks), system latency calibrations (time variances between positioning, depth, and motion sensors), vessel motion and heading sensor calibration (roll, pitch, yaw, and heave sensors), and various other vessel alignment and coordinate/datum corrections. Many of these calibration requirements are critical--failure to perform adequate calibration may render a survey invalid. Since many of the alignment and offset parameters are interrelated, failures at one level of test may require recalibration and/or retesting prior levels. Some calibrations are performed during initial equipment installation on the vessel; however, others must be performed on a more frequent basis--especially when dredging measurement and payment surveys are involved. It should be strongly emphasized that the software and procedures for calibrating, processing, editing, and thinning multibeam data are still being refined and will undergo modifications as new systems are acquired and performance is validated.

6-22. Initial Installation Alignment and Static Offset Measurements. Alignment and offset parameters must be measured for the various sensors making up the multibeam system, e.g., MRU and gyroscope alignment/offsets, transducer mounting angles/offsets, GPS antenna offsets, static and dynamic drafts, vessel settlement/squat, and estimated latencies. These measurements are made upon initial installation or upon replacement, removal, and reinstallation of a sensor. Alignment and offset corrections are entered in the software system setup modules.

a. Static offsets of the sensors (Lever Arm measurements). These are the distances between the various sensors and a designated reference point on the vessel (Figure 6-18). This entails physical measurement on the vessel platform--locating the relative X-Y-Z coordinates of the multibeam transducer, GPS antenna(s), gyrocompass, MRU sensor, POS/MV system, etc. These measurements should be performed with the vessel stabilized on a trailer or on blocks where more exact, stable measurements can be made. A total station and/or tape are used to obtain the measurements. The sensors should be measured from a reference point in the vessel. (On cutter suction and excavator dredges, the origin should be established at the trunnion point). This point is typically the center of gravity or the intersection of the pitch and roll axis. The center of gravity will change with varying load conditions of the vessel and thus must be chosen to represent the typical conditions while surveying. On large stable vessels, the center of gravity will slightly change vertically along an axis that contains the center of buoyancy. On smaller vessels, the center of gravity and the center of buoyancy may not be exactly aligned due to eccentric loading. This condition is to be avoided as it also contributes to the instability of the vessel itself. This information can be obtained from the blueprints of the vessel. This reference point (now the coordinate system origin) should be a place which is easily accessible and from where measurements to the sensors will be made. The coordinate system should be aligned with the x-axis along the vessel keel (positive forward), the y-axis abeam the keel (positive to starboard), and the vertical (z-axis) positive down. The offsets of the sensors are measured from the reference point to the center of the sensor. The center of the sensor can be found in the manufacturer's schematic for the sensor, or can be accurately measured with a tape. It is common for the acoustic and physical centers of a multibeam transducer to be in different places. The magnitude and direction of the measurement should be verified and recorded.

b. MRU sensor. If possible, the inertial MRU sensor should be placed on the centerline of the vessel, as close as possible to the center of gravity or the intersection of the roll and pitch axes of the vessel. If the MRU is offset from the keel, it should be accurately aligned parallel to the keel. Mounting MRUs on bow or side mounts is not recommended due to potential heave correction issues. The x-axis of the MRU should ideally match the x-axis of the transducer;

however, this is not always feasible on over-the-side mounts. Azimuthal misalignment of the MRU will result in the depth measurement being in error proportional to the water depth. Misalignment of the MRU sensor in yaw causes a roll error when pitching, and a pitch error while rolling.

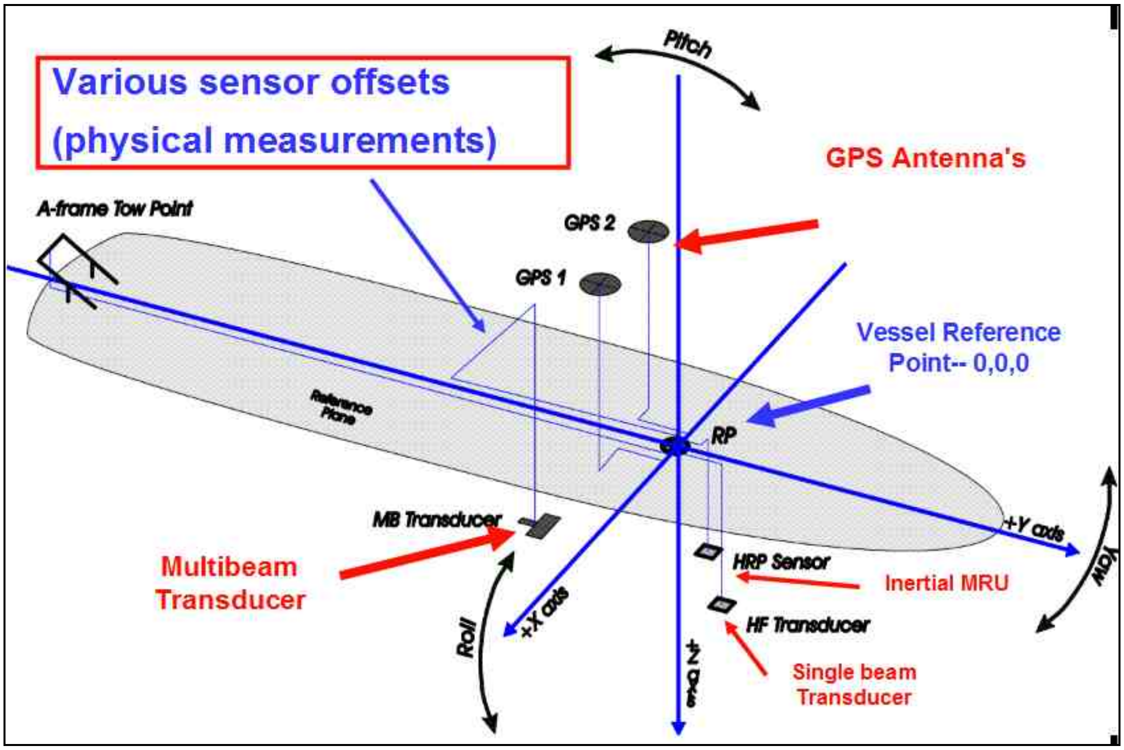

Figure 6-18. Lever arm offsets between various sensors on a survey vessel.

(1) MRU resolution. MRU system accuracy must far exceed the alignment resolutions of the orientation parameters in the vessel system. Thus, if the roll orientation has been calibrated by a Patch test and is believed accurate to ±0.1 deg, then the MRU sensor should have an accuracy to better than, or at least, this same level of accuracy. Most higher-end MRUs can achieve these accuracies.

(2) References. Refer to the "IHO Manual on Hydrography," (IHO 2005) for descriptions of the error magnitudes caused by roll, pitch, and yaw misalignments. If the transducer and MRU are collocated, many alignment corrections become far less critical.

c. Multibeam transducer. The multibeam transducer should ideally be installed as near as possible to the centerline of the vessel and level about the roll axis. However, in practice, the transducer is usually offset from the keel by varying amounts, and may be forward or aft of the center of gravity (e.g., side mounts, bow mounts, twin catamaran hull mounts, etc.). The transducer should also be precisely aligned with the azimuth of the vessel. The depth of the transducer head below the waterline of the vessel must also be determined. As in single beam systems, bar checks are performed to measure static draft variations, which may include a constant index error that would not be detected if only a physical measurement were made. Likewise, squat/settlement tests are performed to calibrate dynamic vessel variations. Longer-term fuel loading draft variations must also be monitored.

(1) With the over-the-side types of transducer mounts, it is imperative that the azimuthal alignment between the transducer and keel be as close as possible. This can be accomplished with the vessel on a trailer or blocks. Since this side mounted technique allows for raising the transducer at the end of each day of operations and lowering it at the start of the next day's survey, this type of mount should be periodically checked for any alignment changes. The frequency with which it is checked will depend on what type of surveying is performed and under what conditions. Hull mounted or retractable transducers are generally fixed (or rigidly lock) in place and will not need to be checked as frequently.

(2) The fore-and-aft angle of the transducer mount must be evaluated. Since most vessels underway will be lower in the stern, the transducer will generally need to be rotated slightly aft to compensate for this angle. The Patch Test (pitch) will check for this transducer angle. The resulting beam should ideally project nearly normal to the sea floor while conducting surveying operations.

d. Gyroscope heading. The gyroscope should be aligned with the x-axis of the vessel using an electronic total station and geodetic control points. This can be done with the vessel on a trailer or secured tightly against a pier where there is minimal wave action. The gyro should be warmed up and, if necessary, the proper corrections for latitude applied. Locate two points on the centerline of the vessel and position a target on each of them. Observe the two targets with the total station and synchronize the readings with the gyro readings. Several readings will be needed for redundancy. Compute the vessel's azimuth and compare with the gyro readings. Compute the mean and standard deviation of the readings. If the offset is more than 1 deg at the 95% confidence level, realign the gyro with the centerline and repeat the observations. If less than 1 deg, apply the correction to the gyro output. The processing may take longer than with the total station. (Use of a dual antenna CodaOctopus F180/190 or Applanix POS/MV orientation systems eliminates the need for gyro azimuth control.)

e. Positioning time delay (Latency). Time delay in the positioning is the time lag between the time positioning data are received and the time the computed position reaches the logging module. This results in a negative along-track displacement of the depth measurements. While surveying at slow speeds, this displacement will be small. In general, the processing time for the position will vary with the number of observations used in the final GPS solution. If the time imbedded in the GPS message will be used, then you must ensure the correct synchronization between this time and the transducer or signal processing clock. A Patch Test (described below) is performed to determine a constant latency correction.

6-23. Vessel Squat/Settlement, Draft, and Datum Variations.

a. Squat/Settlement measurement. The combined squat and settlement of the vessel should be measured at several speeds and a look-up table produced for correcting the transducer draft. This measurement is essential since a MRU will not measure the long-term change in elevation. A MRU heave sensor will record the sudden change in elevation but the measured heave will drift back to zero. The settlement can be measured with a level on shore and a 2- m level rod or stadia board on the vessel positioned over the MRU sensor. The vessel should make several passes at various speeds in front of the shore station and the rod elevation recorded. The elevation difference at each speed is noted and used as the draft correction while surveying. Ensure that the correct sign is applied when entering the correction in the software. (Refer to Chapter 4 for details on performing these measurements.)

b. Squat/Settlement measurement using RTK. An alternate method for determining squat/settlement makes use of carrier-phase RTK elevation difference measurement. This method is also described in Chapter 4.

c. RTK water surface elevation determination. If precise RTK is being used as an absolute elevation reference correction for the multibeam transducer, then there is no requirement to enter in a squat/settlement correction. Likewise, tide/stage data and dynamic draft corrections may also be eliminated. However, if RTK is used only to determine the tide/stage level, then squat and draft measurements must be input to the processor.

d. Short term dynamic draft measurements. Changes in vessel draft due to fuel or loading changes should be monitored throughout the day, and depth corrections applied if trim variations are significant. These procedures are identical to those described for single beam surveys. Heave corrections output from RTK and/or MRU systems must be monitored to ensure long-term sea swells or vessel turns do not bias the data.

e. Reference datum checks. Vertical datum NSRS/NWLON referencing requirements and calibration methods are described in ER 1110-2-8160, Policies for Referencing Project Elevation Grades to Nationwide Vertical Datums, and EM 1110-2-6056, Standards and Procedures for Referencing Project Elevation Grades to Nationwide Vertical Datums. RTK water surface elevation measurements should be checked at a NSRS or NWLON based staff gage at minimum twice daily. Tolerances should be within the ±0.1-ft range. With current RTK and RTN networks, this represents more of a blunder check that a calibration. Such a check becomes more critical when a local RTK base station is used. Horizontal position checks should also be periodically performed at a known control point, if available. However, when using RTK, a quick comparison with a local code DGPS network is usually adequate for a horizontal blunder check.

6-24. Patch Test (Residual Bias Calibration). Patch Tests are periodically performed to quantify any residual biases in the initial alignment measurements of the sonar head, MRU, and/or gyroscope. The Patch Test is a series of reciprocal lines run at varying speeds, depths, and bottom terrain in a small test area. It must be performed carefully and repeatedly to ensure that subsequent survey data collected is accurate and reliable. The Patch Test determines the vessel orientation alignment corrections for (1) positioning time delay or latency, (2) pitch, (3) roll, and (4) azimuth/yaw. The determined angular offsets and time delays will be used to correct the initial misalignments; thus, calibrating the sensor orientation system between each component and the vessel.

a. References. Detailed procedures for performing Patch Tests are covered in data collection software manuals, e.g., HYPACK and Caris. Multibeam system vendors also provide guidance on performing Patch Tests (e.g., see R2Sonic Operation Manual—R2Sonic 2010). Position and depth errors due to sensor and Patch Test calibration misalignments are detailed in Chapter 3 of the IHO Manual on Hydrography (IHO 2005). The procedures outlined below are extracted from these references. (Note that there are varying opinions among manufacturers regarding the sequencing of Patch Tests.)

b. Patch Test survey procedures. Reciprocal survey lines are run for each of the four Patch Test components, as shown in Figure 6-19.

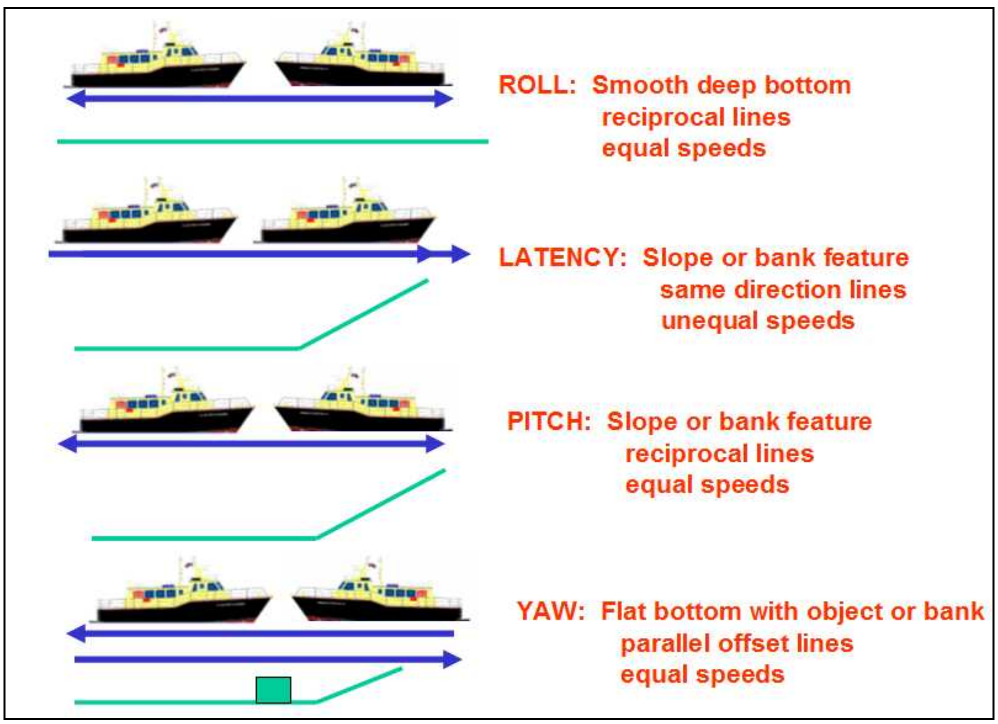

Figure 6-19. General overview of Patch Test runs. Refer to software operating manuals for details.

(1) Test site conditions. The weather and sea states should be calm to ensure good bottom detection and minimal vessel motions. Since most of the test lines to be run will be

reciprocal lines, it is important to have capable vessel steering and handling. Running on slack tides and slow currents is recommended. The lines should be run in deep water since the test results are less reliable in shallow water. The order in which the test lines are run is not important although it is recommended that at least two sets of reciprocal lines for each test be run for redundancy. Vessel speed should be regulated such that 50% forward overlap is obtained.

(2) Positioning. At minimum, survey quality code phase DGPS positioning must be used when conducting the Patch Tests. However, it is strongly recommended that carrier phase (RTK) positioning be used to perform these tests. This is because horizontal positioning accuracy has a significant impact on the repeatability of Patch Test results. For example, a 3-ft difference in DGPS positions during a test can cause a 0.4-sec latency variation and a 4-deg variation in pitch/yaw. Variations of this magnitude will not yield acceptable Patch Test calibration consistencies.

(3) Positioning time delay test and pitch bias test. Two pairs of reciprocal lines are run at different speeds to check for biases in both positioning time delay (latency) and pitch bias. Latency is determined from runs made over the same line in the same direction, but at differing speeds. (Both of these biases may exist simultaneously and must be discerned and separated during the test data processing.) These lines should be run in an area with a smooth, steep slope—10 deg to 20 deg, if possible. The slope should ideally be at least 200 m long in order to obtain good samples. A channel side slope may have to suffice if no other relief is available. At least two pairs of reciprocal lines should be run both up and down slope, at velocities differing by at least 5 knots to best assess the time delay. The greater the difference in velocity, the more accurate the test. Pitch is determined from the runs made over the same lines at the same speed in opposite directions.

(4) Roll bias test. In an area of flat topography, run at least one pair of reciprocal lines approximately 200 m in length to test for roll biases. Roll bias will best show up in deep water. Depending on the type of multibeam system, these lines should be run at a speed to ensure significant forward overlap of the beam's footprint. The beam width can be found in the manufacturer's specifications.

(5) Azimuth (Yaw) offset test. At least two adjacent parallel pairs of reciprocal lines shall be run normal to a prominent bathymetric feature such as a shoal or channel side slope, in shallow water. Do not use a feature with sharp edges such as wrecks since there is more ambiguity in the interpretation. The adjacent lines should have an overlap of about 15% and the feature should be wide enough to ensure adequate sampling. This width is generally greater than three swath widths. These lines should be run at a speed to ensure significant overlap of the beam forward footprint--use the same equation as that for roll bias.

c. Patch Test data processing and adjustment. Numerous survey software routines have been developed to automatically calculate system latency, roll, pitch, and yaw biases in multibeam systems, using best-fit image matching techniques. The adjustment procedure outlined below uses the entire data set collected from the Patch Test lines with minimized thinning. Visualization of the data is important. In addition, the position and attitude data should be checked for errors, especially noting the time-tag errors. Cleaning of the bathymetry is usually not necessary since individual soundings will not be adjusted but rather clusters of data points will be analyzed.

(1) Processing sequence. The procedures to process the Patch Test data should be in this order: (1) latency, (2) roll, (3) pitch, and (4) yaw. Latency is processed first and the bias value entered into the software. Processing of the remaining three parameters is an iterative process, in that same order. This is due to the interrelationships between the parameters.

(2) Positioning time delay (latency) bias. This delay is computed by measuring the along-track displacement of soundings from the pair of coincident lines run at different speeds over the steep slope or other prominent topographic feature. Lines run in the same direction should be used to avoid the effect of pitch offset errors. The survey lines are processed, plotted, and compared while assuring that no corrections are made for positioning time delay, pitch error, roll error, and gyro. The time delay is then averaged by getting several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or achieve a minimum difference. The latency bias is applied before the remaining biases are tested. This should actually be an average of biases from repeated latency tests. Note that latency biases are (should be) zero (0) when UTC time-tagged GPS positioning systems are used.

(3) Pitch offset bias. The pitch offset bias is determined from the two pairs of reciprocal lines run over a slope at two different speeds. The important characteristic of pitch offset is that the along-track displacement caused by pitch offset is proportional to water depth. Thus, the deeper the water the larger the offset. Pitch bias errors will impact both the depth and its position. The lines are processed while only applying the positioning time delay correction and the static offsets of the sensors. The pitch offset is then averaged by taking several measurements of the displacement in the along-track direction. This process is performed iteratively until the profiles and contours match or reach a minimum difference.

(4) Roll offset bias. Roll bias is computed using the pairs of reciprocal lines run over a flat, deep area. Generally, this offset is the most critical in deeper water and should be carefully measured. Roll errors directly induce errors in depth measurements, especially in the outer beams. The roll offset is averaged by several measurements of the across track displacement along the test swaths. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

(5) Azimuthal (Yaw) offset bias. Parallel lines run normal to a bathymetric feature will be used for the measurement of the azimuthal offset. Errors in azimuth alignment cause positional errors in the depth locations. One pair of adjacent lines run in opposite directions is

processed at a time to remove any potential roll offset. The azimuthal offset is averaged by several measurements of the displacement over the feature and knowing the across-track distance at the location of the measurements. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

d. Patch Test repeatability and resolution. Due to various positioning accuracies, MRU resolutions, poor feature recognition, shallow depths, terrain variations, etc., the numerical result from an image match on a Patch Test parameter can have a high uncertainty. For example, repeated Pitch and Yaw Tests may vary by ±1 deg or more. Roll biases are usually more repeatable, typically at the 0.1-deg to 0.2-deg levels. Likewise, latency repeatability is usually at the 0.1 sec level. Therefore, Patch Tests must be performed over different conditions and times in order to arrive at an average, longer term, correction for each parameter. For example, if the average of 20-yaw bias tests are performed over a year's time is 3.1 deg, and the standard deviation of all these tests is ±0.4 deg, the repeatability of the tests is only about a half degree. However, the "standard error of the mean" of the long-term (20-test) average is ±0.1 deg. Thus, the long-term average yaw bias value of 3.1 deg has a confidence of about ±0.1 deg. Its "resolution" or long-term "estimated accuracy" is to the nearest 0.1 deg A minimum of 10, and preferably more, Patch Tests should be performed to obtain reliable average biases. A log of these repeated tests should be maintained on the vessel. Obviously, and changes or modifications to the sensors requires a restart of this accumulative averaging process.

e. Automated Patch Test. Figure 6-20 depicts screen displays of automated Patch Test residual bias computations in HYPACK. See the "HYPACK Hydrographic Survey Software User Manual," (HYPACK 2011) for additional details on running these calibration tests. The results are input directly into the real-time processing system. Additional examples of Patch Tests from Philadelphia District are shown in Appendix F.

f. Frequency of Patch Tests. Patch Tests are always required at the initial installation of a multibeam system on a vessel. After initial installation, or after any equipment modifications, more frequent Patch Tests should be performed to verify the consistency of the computed residual biases, and to establish a long-term averaging trend for each bias as discussed above. Depending on the stability of the transducer mount, and the consistency of long-term averages, subsequent tests may only need to be periodically performed. Specifying "periodically" is problematic. Fixed-hull and rigid retractable mounts in moon pools will usually be stable and the Patch Test residual biases are not as likely to vary. Thus, monthly or quarterly checks may be adequate. If repeated Patch Test bias results are not consistent, or Performance Test results are outside tolerances, then more frequent tests are recommended, along with determining the source of the inconsistencies. When a critical dredge measurement and payment survey is begun, a Patch Test is recommended, if only for the record. Patch Test results, as with all other survey calibration tests, should be recorded in a bound survey book maintained aboard the vessel.

6-25. Velocity Measurements. As in single beam systems, the velocity of sound in the water column must be accurately measured. However, in multibeam systems, velocity measurements are significantly more critical due to the effects of refraction ("ray bending") in the outer beams (Figure 6-21). Changes in sound velocity throughout the water column require corrections to each beam in the array for refraction. In addition, many beamforming systems require continuous velocity measurements directly at the transducer head in order to steer the beams.

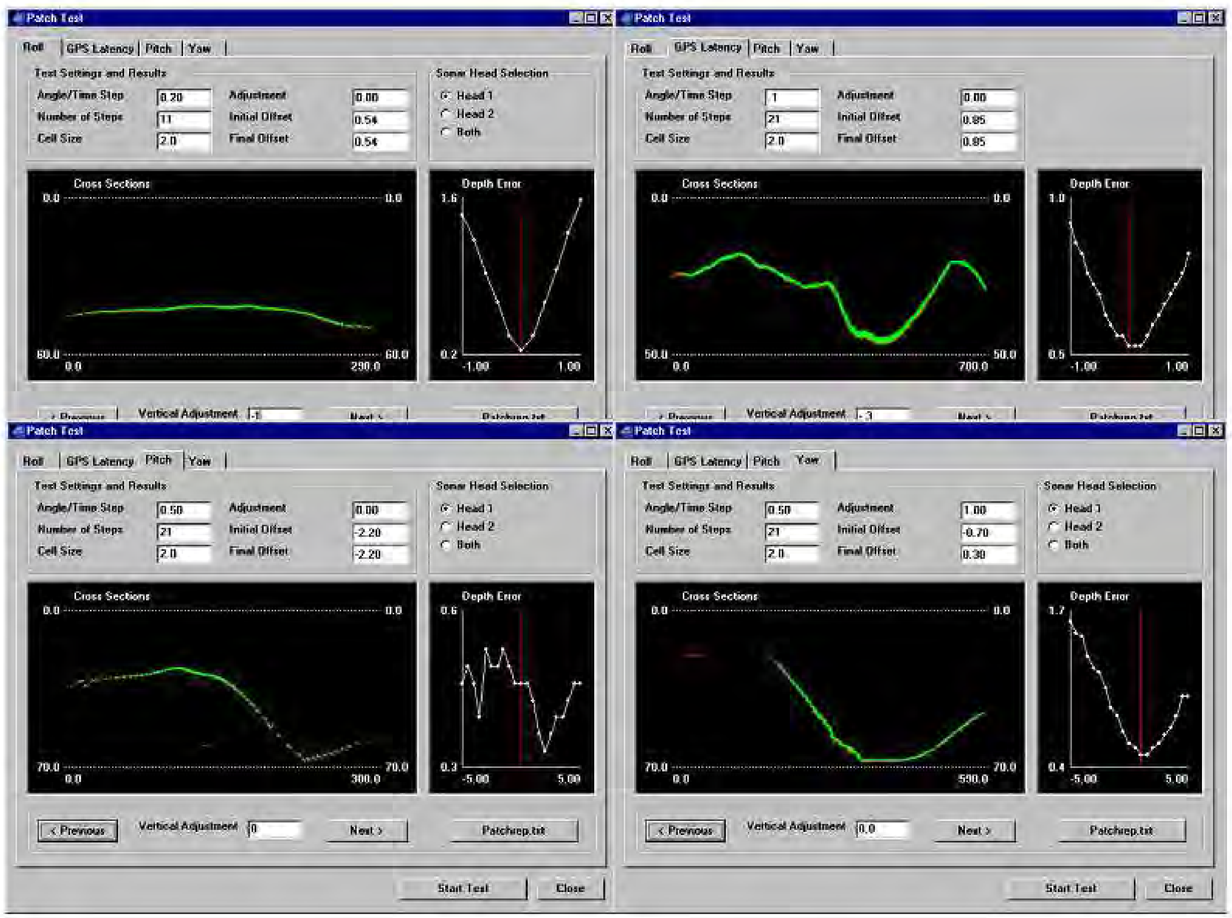

Figure 6-20. Automated Patch Test parameter computations--roll, latency, pitch, and yaw. Note that roll and latency tests on the top row provide the highest image matching resolutions. Pitch and yaw resolutions (bottom row) are typically coarser. (HYPACK, Inc.)

Since sound velocity in the water column can vary spatially and temporally, improper or inadequate determination of sound velocity corrections can often render multibeam data unusable. Velocity calibrations should be performed periodically during the day, no less than twice per day, and at more frequent intervals or locations if physical changes in the water column (e.g., temperature, salinity) are affecting data quality. This frequently occurs at coastal entrances or near power plant outfalls. In some areas, such as in Southwest Pass, LA, extreme salinity and temperature variations may require velocity observations every quarter-mile or closer (Figure 6-22). The quality of velocity data may be subsequently assessed through use of the "Performance Test" which compares overlapping survey data models. Beam angles should be reduced if velocity data and/or Performance Tests indicate uncertainty (i.e., excessive repeatability or bias) in outer beam depth measurements. Velocity profile data is entered into the survey data acquisition system, typically in real-time during the survey.

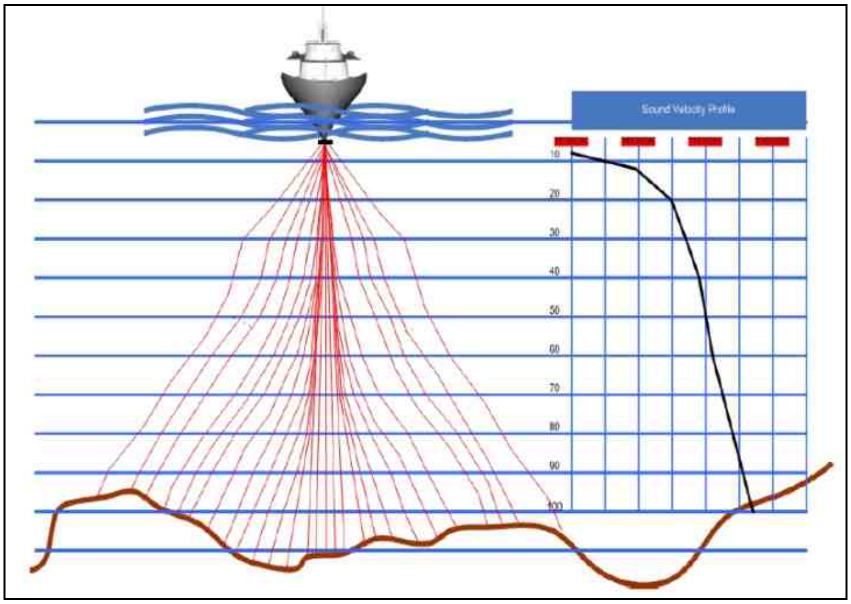

Figure 6-21. Outer beams are refracted due to varying sound velocities in the water column. These refractions on each beam must be corrected to obtain the location and depth at each point on the bottom. (R2Sonic)

6-26. Vessel Draft and Index Measurements (Bar Checks). As in single beam systems, a bar check represents the "reference quality control standard" by which multibeam echo soundings are ultimately calibrated. Upon initial installation, and periodically thereafter, a traditional bar check should be performed to calibrate the multibeam draft and index corrections and verify velocity corrections (from velocity meter casts) are accurate. The frequency of this calibration is a function of the repeated results, the stability of the system, and the nature of the survey. If periodic bar checks verify the draft/index corrections are holding constant, then less frequent checks are needed--perhaps every few months. Multibeam bar checks are performed similarly to single beam bar checks described in Chapter 4. It must be recognized that the acoustic reflectivity properties of a bar will differ from those of the bottom, which could inject a bias into the calibration. Some USACE districts have coated the check bar with foamed material in attempts to more nearly simulate bottom reflectivity conditions.

a. Nadir beam bar checks. Because of possible ray bending due to velocity changes, bar checks are typically performed under the center beams to quantify any draft or index errors in the system. As stated above, these need only be done on an infrequent basis, depending on the long-term stability of the results. This calibration is identical to that performed for single beam transducers. Figure 6-23 depicts a typical bar check over a portion of the multibeam array.

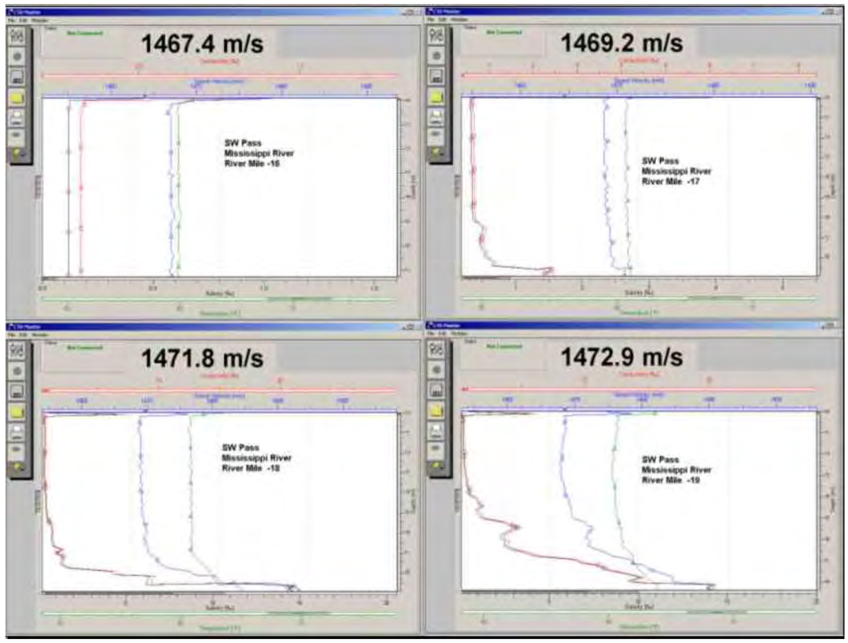

Figure 6-22. Typical conductivity/salinity, temperature, and depth (CTD) profiles at Southwest Pass, Mississippi River. Velocity profiles are shown to vary significantly over a relatively short distance (River Miles 16, 17, 18, and 19). (St. Louis District)

b. Outer beam bar/plate checks. The New York District has developed a quality assurance procedure whereby a small bar or single-line plate can be lowered from either side of the boat to perform a "blunder" or "confidence" check on the recorded multibeam data in the outer beams. Such a check can be quickly performed before or during each survey. Any portion of the multibeam array that is picked up can be used. Although not intended to definitively calibrate draft/index values like a bar check, this check will reveal gross biases. If biases exist between the plate/bar depth and the multibeam depth, then additional tests should be performed to determine the cause of the bias. It is recommended that this type of "blunder" check should be performed before each critical payment survey.

6-27. Beam Width Restrictions on Multibeam Systems. The coverage of multibeam systems is a function of swath width and water depth. Most systems provide coverage of two to approximately seven times the water depth. The number of individual beams (and footprint size) within the swath array varies with the multibeam manufacturer and operating principle. As outlined in previous paragraphs, the outer beams on each side of the swath are subject to more corrections and may not be useful for most dredging and navigation applications. The maximum angular extent of coverage must be verified, and accordingly restricted, by conducting some form of independent Performance Test. Thus, maximum allowable beam limits should be based on a Performance Test to verify the adequacy of the entire array. This beam array limit is typically determined from the HYPACK Performance Test software statistics, and is measured at the angular point where repeatability (bias) between the observed and reference data set exceeds a prescribed tolerance for the project. Depending on various factors, primarily velocity and bottom reflectivity variations, it may be necessary to restrict beam widths to less than the measured limits in the Performance Test.

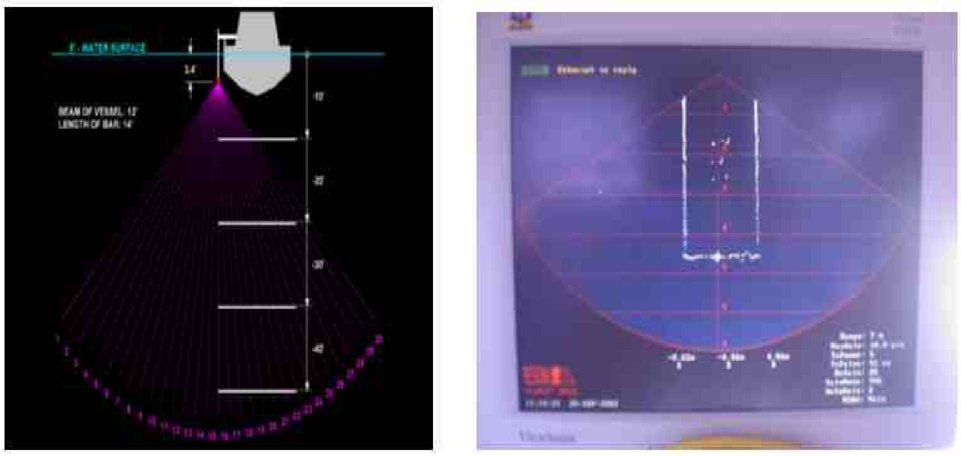

Figure 6-23. Bar check of a multibeam system. (Galveston District)

SECTION V

Multibeam Survey Data Collection, Editing, and Processing

Multibeam data are collected using commercial hydrographic survey software platforms, the most common in USACE being the HYPACK “SURVEY”software platform—see HYPACK 2011. Equipment configuration and line planning procedures are similar to those outlined for single beam surveys in Chapter 4. The main difference is that multibeam surveys may have more peripheral sensors to interface with the controller. This section provides a general overview of the collection and processing actions required for multibeam survey data.

6-28. Determining Coverage and Overlap. Most multibeam surveys are designed to obtain 100% bottom coverage (ensonification). Based simply on the project depth and beam array limit, a rough line spacing can be estimated. For example, with a 90 deg array in a 40-ft project, the line spacing is roughly 80 ft, not allowing for any off track steering. Using a nominal line spacing, survey coverage is performed by visually “painting the screen” or “mowing the grass” on a real-time screen display. The helmsman can then return back to fill in any gaps in the coverage.

a. Overlap. A survey line spacing may be computed to provide for a specified overlap between lines. This may help reduce gaps due to off track steering alignment. Alternatively, a line spacing it may be specified in order to obtain double acoustic coverage over the channel bottom. The multibeam line spacing ("L") and the number of longitudinal run lines ("N") for a typical navigation project can be computed using the methods shown in Figure 6-24. The depth ("d") is the average project depth. The sidelap ("s") should be set to the desired overlap between the parallel multibeam lines. Sidelap is intended to compensate for survey line steering limitations and/or duplicate coverage requirements. A 50% sidelap would provide duplicate (200%) bottom coverage if there were no steering misalignment. For a project condition survey where coverage is only required between the channel toes, a small sidelap allowance (e.g., 5 of 10 ft) may be made for vessel steering misalignment. As depth decreases up the side slopes, line spacing needs to be increased; however, only 100% coverage is normally required on side slopes.

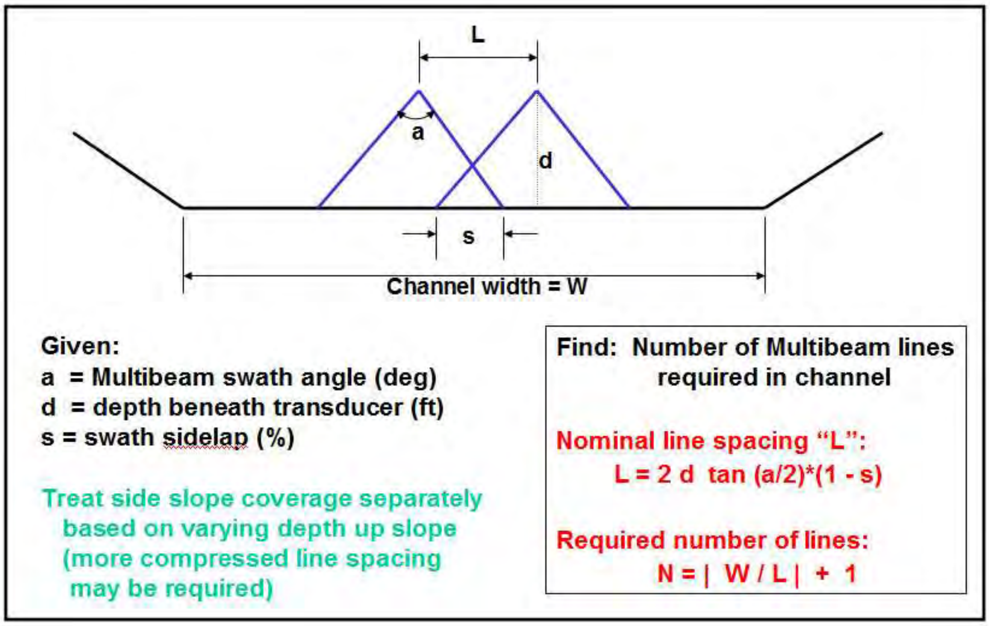

Figure 6-24. Computing multibeam line spacing on a navigation project given array width, project depth, and overlap requirements.

b. Example. The following examples illustrate line spacing computations for multibeam surveys:

Given: Project Condition Survey of 40- x 400-ft channel
(no coverage of side slopes required)
10% overlap between multibeam lines
a = 150-deg multibeam swath angle
d = 40-ft project depth
s = 10%
at 10% overlap, s = [2d tan (a/2)] · 10%) = 30 ft
Line Spacing: L = 2d tan (a/2) · (1-s) = 2 · 40 · tan (75 deg) · (1 - 0.1) = 269 ft … 270 ft
Number of lines: N = | 400 / 270 | + 1 = 2

Since the two lines easily cover the channel area, they would be spaced to provide overlap along the toes and with each other. If a 20-ft steering accuracy were assumed, then the two lines would be run along channel offsets (+) 85 ft and (-) 85 ft from the centerline. The line spacing in this case would only be 170 ft, resulting in considerable overlapping coverage in the channel center plus a 20-ft tolerance outside the toes. Running offsets + 100 ft would be adequate for this coverage as well. If, in the above example, a more realistic 120 deg multibeam array were used, then the line spacing would be reduced as follows.

Line Spacing: $L = 2d \tan(a/2) \cdot (1-s) = 2 \cdot 40 \cdot \tan(60 \text{ deg}) \cdot (1 - 0.1) = 125$ ft

The number of lines required to cover the channel between the toes is:

Number of lines: $N = | 400 / 125 | + 1 = 3 + 1 = 4$

If the multibeam array were restricted to 90 deg, as might be the case in a pre/post dredging survey, then the following line spacing would result for the same project:

Line Spacing: $L = 2d \tan(a/2) \cdot (1-s) = 2 \cdot 40 \cdot \tan(45 \text{ deg}) \cdot (1 - 0.1) = 72$ ft … use 75 ft

The number of lines required to cover the channel between the toes is:

Number of lines: $N = | 400 / 75 | + 1 = 5 + 1 = 6$

If duplicate coverage were required for this project, the sidelap would be increased to 50%, resulting in the following line spacing:

Line Spacing: $L = 2d \tan(a/2) \cdot (1-s) = 2 \cdot 40 \cdot \tan(45 \text{ deg}) \cdot (1 - 0.5) = 40$ ft

Number of lines: $N = | 400 / 40 | + 1 = 10 + 1 = 11$

The above computation is based on coverage between the channel toes. Additional lines may be required for side slope coverage. From the computed number of lines, an estimate of total lineal multibeam survey miles can be estimated. Given known survey speed, daily plant rental and crew rates, and mob/demob data, the time and cost to conduct the overall survey can be estimated.

6-29. Editing and Processing Multibeam Data. Collected multibeam data is processed and edited on a variety of commercial platforms and software packages. The most common platform used in the Corps is the HYPACK "HYSWEEP EDITOR." This editor operates similarly to the single beam editor described in Chapter 4. Multibeam array depths are time-tagged with the positioning and motion sensors, corrected for water velocity, refraction, draft, lever arm, and dynamic draft variations. This section provides only a brief overview of the "HYSWEEP EDITOR" process—refer to the HYPACK software "User Manual" (HYPACK 2011) for details on editing and processing multibeam data.

a. The data flow through the "HYSWEEP EDITOR" is shown in Figure 6-25. Multibeam processing is done in three phases:

Phase I: Review and edit data collected from various sensors, such as inertial motion, DGPS, RTK, velocity, various constant sensor corrections, and vessel track lines for overlap.

Phase II: Perform detailed review and edit of each sensor and sweep depth data. Sweep data are reviewed section by section. Various filtering options are employed to speed up editing.

Phase III: Grid cell matrices ("bins") are developed and a final review and edit is made. Output to user requested CADD or GIS format.

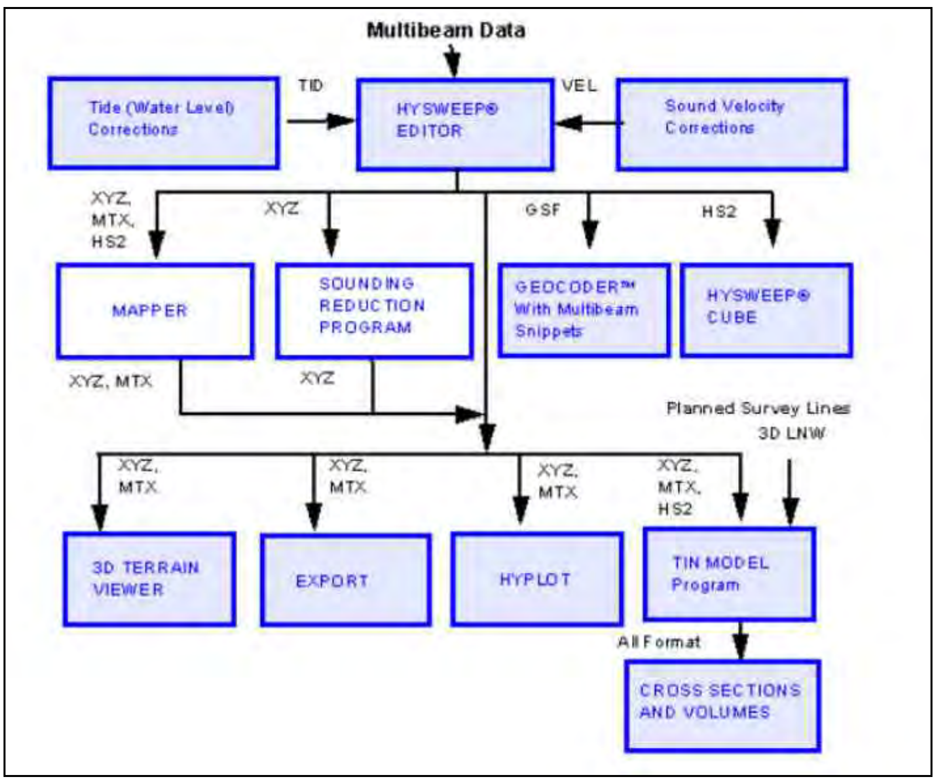

Figure 6-25. Multibeam data processing flow in HYPACK.

b. Generally, Phase I is performed aboard the survey vessel before the data are transmitted to the District Office. Phase II editing may be performed in the field or district office. Phase III is performed in the district office.

6-30. Editing and Filtering Data. Multibeam data typically contains many noise "spikes" that must be edited out of the database. Filtering and editing can be done in real-time, in post-processing, or in combination. Manual spike editing can be performed by viewing each ping's cross-section and editing out spikes from individual beams—a labor intensive process given 40 cross-sections/sec may have been collected. More commonly, a block dataset is viewed in 3D form and data spikes are edited out manually in the 3D model. This is still a labor-intensive process. Automated spike or data anomaly filtering can also be performed. Such "intelligent" filtering is usually based on setting up maximum data quality or magnitude changes. During this automated filtering process, data can also be thinned if desired. Given the increasing densities of collected multibeam data, coupled with requirements for small bin sizes, smart use of automated filtering and editing has become a practical way to process these large datasets. However, these automated filtering and editing routines must be used with caution in that valid strikes above grade may be erroneously eliminated.

6-31. Thinning and Binning Multibeam Datasets. In theory, there is no need to reduce the size of the collected multibeam dataset. The entire "raw" database could be used for project or dredging condition assessment, volume computations, etc. However, these large datasets are thinned for a number of reasons, such as: (1) plotting in plan view without sounding overlap, (2) dredge volume computations, (3) channel clearance strike plots, (4) controlling channel depth reports, (5) 3D visualization models, or (6) simply to reduce the data down to a manageable storage size. There are a number of methods for reducing (or thinning) the size of large, edited multibeam datasets. For basic terrain visualization requirements (i.e. non-navigation uses), various thinning routines have been developed that can reduce datasets by 95% or more; typically selecting representative depths based on gradient changes over large areas. In current USACE practice, multibeam datasets are thinned into a fixed matrix or grid cell during the "Phase III" editing process. The size of the matrix cell is selected based on terrain irregularity, dredge volume computation requirements, or to prevent overplotting adjacent depths.

6-32. Recommended Bin Sizes and Depth Selection for USACE Navigation Surveys. The following paragraphs contain guidance on bin sizes and depth selection for all types of navigation surveys, to include: dredging measurement and payment surveys, dredge clearance/acceptance surveys, plans and specifications surveys, project condition surveys, and other related navigation surveys. This guidance is based on over 10 years of collective multibeam data processing experience by the districts within the North Atlantic Division. Designated bin sizes for a project should be included in dredging contract specifications. These same criteria are also applicable to multiple transducer sweep systems.

a. Recommended maximum bin size. For new work deepening projects, a maximum 3-ft x 3-ft cell size is recommended. On critical projects (e.g., rock) a 1-ft x 1-ft cell size may be used. For maintenance dredging of soft material, a maximum 5-ft x 5-ft cell size is recommended. Evenly spaced grid matrices should be generated over the full dataset relative to an established (fixed) origin point to ensure that different organizations (or software) processing the same edited dataset will obtain identical results--e.g., dredged quantities.

b. Other civil works surveys. There is no specified maximum bin size or depth selection method for other types of non-navigation surveys. Bin sizes may be varied depending on the type of bottom or purpose of the project (e.g., beach sand transport studies, hydraulic studies) or final plan plot scale. In smooth, flat areas, bin sizes may be expanded to any level that will adequately depict the terrain. Bin sizes as small as 1-ft sq may be used for applications where maximum detail is required--e.g., underwater structure surveys or Performance Test Reference Surfaces. Instead of binning, more efficient data thinning methods may be used to generate a TIN model for 3D analysis.

6-33. Depth Selection Options from Binned Multibeam Data. Each bin (or cell) will likely contain multiple depths, depending on the density of the multibeam data and the number of overlapping passes made over the area. It is not uncommon for a 3- x 3-ft cell to have 50 or more depths if multiple passes were made over a suspected shoal area. Thus, an established method is needed to represent the depth within this bin. Presently, common selection options include: (1) a shot depth nearest to the bin center, (2) an average depth (placed at bin center), (3) a median depth, or (4) a minimum depth. CUBE depth selection options may also be considered.

a. Dredge measurement and payment surveys. The average or median depth within a bin is recommended for dredge payment surveys. These representative depths are subsequently used in TIN volume computations.

b. General plan drawings. The shot depth nearest the cell center is recommended to be shown as the representative depth on plan drawings, including those used for plans and specifications or project condition reports. Obviously additional thinning will be required to plot 3- x 3-ft bin depth data on a 1 in = 100-ft plan—only every 8 or 10 bin depths could be displayed at this scale.

c. Minimum depths. Minimum depths may be selected for channel condition reports, shoal or strike detection, or some dredge clearance purposes. Special caution must be exercised in using minimum depths in that the dataset will be significantly biased.

d. Figure 6-26 is an example of the representative depth options that can be selected from binned multibeam data on a navigation project. This guidance is also applicable to other bin sizes than those indicated. Additional guidance on depth selection options is covered in Chapter 2.

SECTION VI

Quality Assurance Performance Tests on Multibeam Systems

6-34. General. A Performance Test is used to evaluate the quality and confidence of multibeam data being collected. This test typically compares overlapping data sets from two different multibeam surveys--performed either by the same vessel or by different vessels. This test may also be performed by comparing multibeam data with that collected by another single beam or multiple transducer echo sounder--obtained by either the same vessel or different vessels. Other

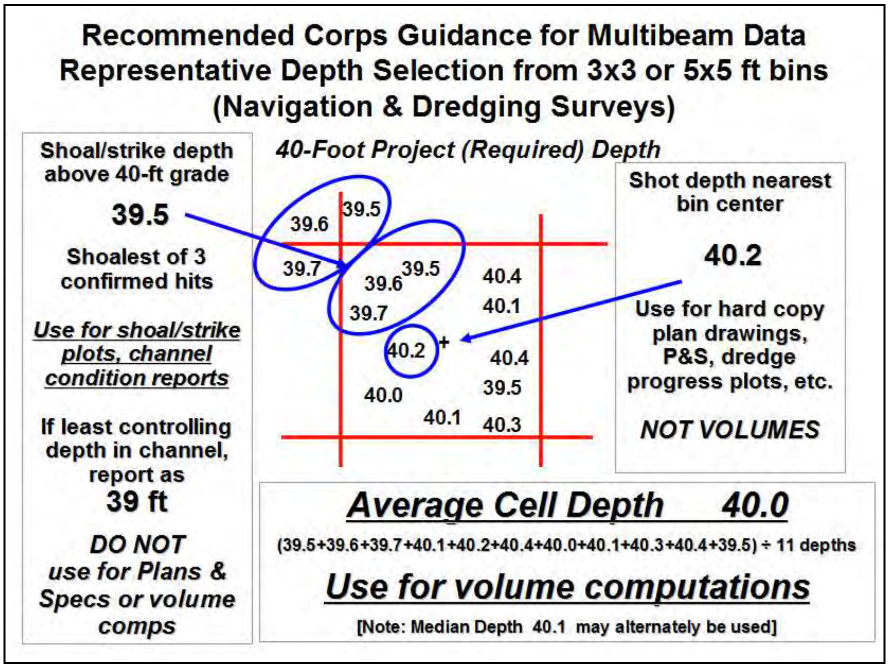

Figure 6-26. Representative depth selection options from binned multibeam data on a navigation project. This guidance is applicable to all cell sizes. The 39 ft reported controlling depth (CCR) was truncated to the nearest whole foot from the observed 39.5-ft shoal depth. In deeper draft projects with higher depth measurement uncertainty (e.g., standard deviations approaching ±1 ft), truncating, rather than rounding, is recommended.

comparison test methods are also used, such as matching multibeam bathymetry of a flooded Corps lock chamber against topographic data measured in the same lock chamber during a dewatered state. Object detection capabilities may also be verified by sweeping over simulated objects of known size; placed either in open water or in controlled lock chambers.

a. Purpose. The purpose of a Performance Test is to obtain an estimate of the accuracy (and, most importantly, repeatability) of a multibeam system dataset. These accuracy estimates can then be compared with defined accuracy standards for a particular type of survey, such as those recommended in Chapter 3. This test also partially checks the parameters and biases that were measured and computed during the previously described quality control calibrations (velocity profile calibrations, Patch Test bias parameters, etc). If performed over different tidal phases, it may also detect poor tidal modeling in the survey area. This is especially critical if RTK surface elevation methods are not being used.

b. Frequency of Performance Tests. Performance Tests should be conducted before a dredging measurement and payment survey project; however, they are not necessarily needed prior to individual surveys in that project. In high cost per cy rock cut channels, daily or twice-daily Performance Tests are recommended. (See Appendix F for New York District's mandatory QC and QA procedures on critical rock cut navigation projects.) For non-navigation surveys, Performance Tests may be conducted weekly, monthly, quarterly, or less frequently, depending on the long-term stability of the results, known variations in different project areas, etc. Performance Tests should also be conducted upon equipment installation or modification. Performance Test data reduction, processing, and statistical analysis should be performed in near real-time--i.e., on board the survey boat.

c. Undetected biases. Performance Tests conducted by the same vessel, the same multibeam system, and over a short tidal time period, are not truly independent but are only an assessment indicator--a constant bias in the system could go undetected. A more truly independent Performance Test is obtained when comparison surveys are run at different tidal phases, using different multibeam and single beam systems, by different vessels, in different locations, and differing sea state conditions. Such a test provides an estimate of "reproducibility" as opposed to "repeatability." New York and Philadelphia Districts have established fixed Performance Test sites where all their survey vessels have run repeated single beam and multibeam surveys. A composite of all these surveys has developed a "baseline" reference surface to which all subsequent tests are compared. However, this type of ideal test is not always practical if surveys are performed over wide geographical ranges. Typically, a Performance Test is done by a single vessel at the project site, comparing single beam and/or multibeam data from the same vessel. In this case, the test more properly indicates a level of "repeatability" in the data—see Chapter 3. Some of the biases that may not be detected when the same vessel and multibeam/single beam system is used in a Performance Test include:

(1) Squat/settlement bias. A constant error in the squat/settlement correction for the vessel will be undetected since the same vessel speed is run for all tests. Running different speeds might detect this error; however, it is probably small for most vessels. Use of RTK minimizes this potential bias.

(2) Draft errors due to undetected loading variations (dynamic draft). Use of RTK minimizes this potential bias.

(3) Tide/stage modeling errors (non-RTK control). When the comparison test is performed at the same time (tidal phase), errors in the tidal model will not be detected. However, performing the test at the same time will indicate the multibeam system is outputting quality data, independent of any tidal modeling errors. Performing the comparison tests at both the same and different tidal phases is strongly recommended, in that the independent quality of the multibeam system can be checked separately from any biases in the tidal model. As detailed in EM 1110-2-6056, errors in the tidal model can represent the major portion of an error budget for an individual depth measurement, and can easily mask the errors in the multibeam system. If Performance Test biases are small (< 0.05 ft) when run at the same tide phase, and large when tested over different times/phases, then a tidal modeling problem is indicated. No amount of multibeam QC calibration or QA performance testing will rectify this modeling error--the only

practical solutions are to correct the tidal model or utilize RTK direct elevation solutions, which also requires appropriate geoidal and tidal modeling corrections.

(4) Bottom reflectivity. Like single beam systems, multibeam systems can have varying biases due to bottom reflectivity and/or signal processing. These biases can be large, and may vary with beam angle and the signal processing method. They may vary geographically when seabed materials differ from place to place. In soft bottoms (unconsolidated sediments or fluff), multibeam depth measurements may be problematic and possibly unreliable. A constant depth error due to signal processing or bottom reflectivity biases is difficult to detect or calibrate. The most reliable Performance Test is to compare different acoustic systems over the same project area (e.g., different boats, multibeam versus single beam, different frequency systems, etc.).

(5) Given the above, obtaining an absolute (unbiased) Performance Test ("confidence test") on a multibeam system is not a simple task. When the same vessel (and survey system) is used for all USACE measurement and payment surveys on a project, the Performance Test procedures recommended herein will yield a good estimate of the data repeatability and confidence, and indirectly the accuracy of any pay yardage derived from a survey. This presumes any undetected biases are constant (and hopefully small) for both pre and post dredge surveys. To better check for any undetected biases, Performance Tests should be run against different survey vessels and acoustic systems.

6-35. Performance Test Procedures. The following paragraphs outline the Performance Test methods found in HYPACK software. Specific details are found in the HYPACK Operating Manual (HYPACK 2011).

a. Reference Surface and Check Line surface development. The procedure described below compares a "check line" multibeam dataset with a "reference surface" dataset complied from narrowly spaced multibeam data using only near-center beam data. The "reference surface" derived from independent vertical single beam data could also have been used, provided a reasonably dense single beam model is obtained. Failure of the Performance Test survey to meet the recommended tolerances requires corrective action--i.e., re-measurement, recalibration, patch testing, etc.

(1) Reference Surface (Figure 6-27). This is essentially a small survey run over an extremely flat area (less than 1 ft gradient) in water depths of not more than 100 ft. A flat bottom area minimizes the effect of positional errors on the test. It represents the "baseline" area. The bottom soil properties should be similar to the actual project. Performing the tests at slack tides will help minimize tidal biases. Four or five parallel lines are run with at least 150% bottom overlap--i.e., 25% sidelap. The line spacing must be close enough to ensure that the inner beams overlap enough to give redundant data. The beams outside a 45- to 60-deg swath width should be removed prior to editing. After these lines are run, four or five parallel lines are run perpendicular to the previously run lines with the same swath and overlap. The speed over the ground should be the same on both sets of lines. A velocity cast should be made in this area and the corrections applied. All the edited data in the Reference Surface are then binned at 1-ft x

1-ft cell sizes. The data in each cell are then thinned using the average depth of all the depths in a cell.

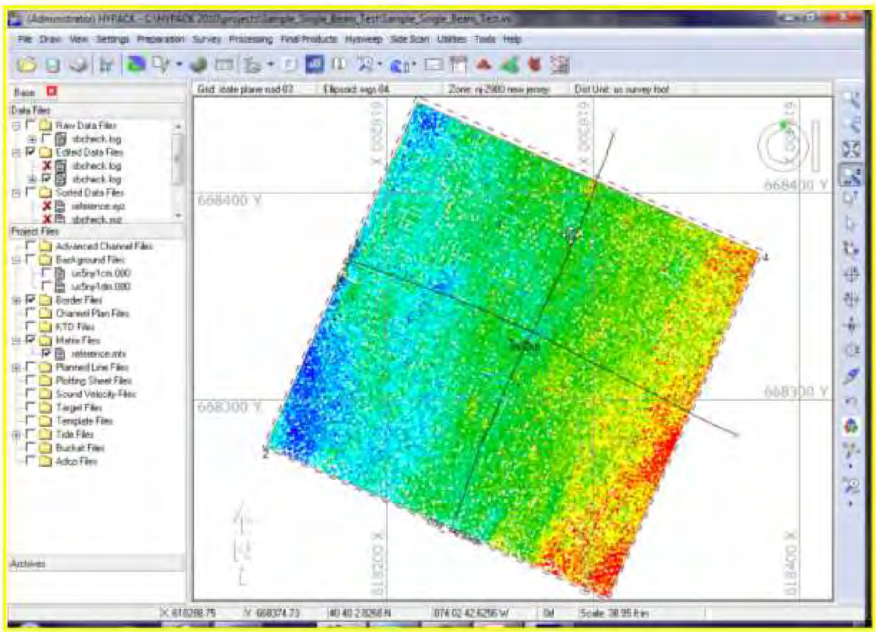

Figure 6-27. Color-coded Reference Surface binned into 1-ft x 1-ft cells. Multibeam line sets were run in each direction and restricted to less than ±45 deg (HYPACK, Inc.)

(2) Check lines. Multibeam "Check Lines" will be run such that the full beam array can be tested against the Reference Surface. At least two perpendicular multibeam swath lines should be run inside the reference surface. The vessel speed is the same as for the reference surface. Ideally, a more independent test is obtained when the Check Lines are additionally surveyed at a different time and tidal phase from that of the Reference Surface survey; however, this is not always feasible in practice. (Another alternative is to run single beam Check Lines-- either from the same vessel or another vessel-- to compare with the multibeam Reference Surface.) The beam width of the Check Lines is not restricted so that the data quality in the outer parts of the array can be assessed. A difference surface between the Reference Surface and the Check Line surface can also be created and statistics computed to assess overall performance.

b. Data processing and analysis. Performance Test data processing and analysis should include assessment of the following statistical parameters.

(1) Outliers. Depth differences between the Check Line surface and Reference Surface are computed at each beam point along the Check Line array (Figure 6-28). Excessive outliers in the dataset should be edited out during processing.

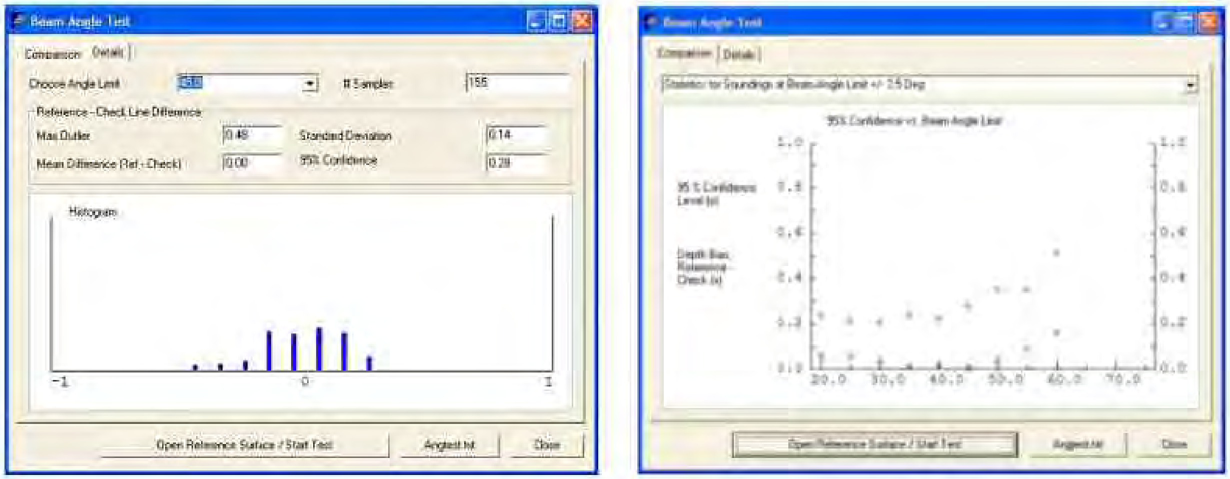

Figure 6-28. Statistical results of a Performance Test. Histogram on left shows dispersions and outliers in the Check Line beam angle set to ±45 deg. No significant bias was present at the 45 deg beam angle. The test on the right indicates that biases between the Reference and Check data surfaces are less 0.05 ft out to 50 deg from nadir. Note that the "standard deviation" and "confidence" statistics are not independent when the same vessel performs the test, and that they have no relationship to the overall survey accuracy. (HYPACK, Inc.)

(2) Mean difference or bias. The difference, or bias, between the Reference and Check surfaces should not exceed the maximum allowable tolerances specified for the type of survey. This is the most critical quality assurance check on the data in that a bias error (i.e., lack of repeatability) will adversely skew depths and related quantity computations. Excessive bias errors require immediate assessment and correction. They could indicate problems with the multibeam data (e.g., MRU alignment) or vertical tide/stage corrections. Given thousands of comparative data points on multibeam surveys, any biases between the Reference Surface and the Check Surface should be small; typically well less than 0.05 ft. The example test in Figure 6-28 shows biases computed at various beam angle widths. This type of plot may be used to determine the maximum beam width that should reliably be used—in this example, array beam width would likely be restricted to ±50 deg from nadir.

(3) Standard deviation and confidence. The standard deviation between the Reference and Check surfaces in Figure 6-28 is output as a one-sigma standard deviation. The standard deviation is simply converted to the "95% confidence" level by multiplying it by 1.96. (This example is not a confidence statistic that is usually based on the standard deviation of the mean statistic.) The existence of excessive outliers and biases will increase the overall standard deviation. Restriction of the beam array angle may reduce this error if most of the excessive outliers are in the outermost portion of the array. Results from this test may be used as an indicator of overall accuracy performance; however, these "95% confidence" statistics should not be confused with the estimated Total Propagated Uncertainty (TPU) of the depths since undetected biases may still be present in the data. Therefore, the nature of these statistics must be considered before setting any maximum limits on Performance Test standard deviations (or

confidences)—keeping in mind the difference between standard deviation and TPU—see Chapter 3.

c. Full-channel Performance Tests. Rather than use a small Reference Area described above, Performance Tests can be conducted over the entire project area, for example, a 3,000-ft acceptance section. Such tests may be multibeam v multibeam or multibeam v single beam. Surveys from different vessels may be tested over the project area. Surface models for each survey are tested against one another for biases and deviations. No survey will be considered the "Reference." Thus, determining which survey contains a bias will be difficult. However, if the statistics prove to be within allowable tolerances (Chapter 3), confidence in either survey (or vessel) will be high.

6-36. Multibeam versus Single Beam Performance Tests. Single beam versus multibeam comparisons are performed similarly to the previously described multibeam versus multibeam tests. The only difference is the Reference Surface is made up of tightly run single beam sections, e.g., 50-ft C/C over the 200-ft x 200-ft test area. Alternatively, the actual navigation project can tested against single beam cross-sections run every 500 ft to 1,000 ft. These Performance Tests are more independent than comparing the same multibeam system against itself, as described above. This is due to each system having different signal processing methods, gain and sensitivity controls, etc. The single beam and multibeam sounders are typically on the same vessel; however, comparisons to another vessel's single beam system will provide an even more independent comparison.

6-37. Real-time Quality Assurance Tests. This simply involves operator assessment of data quality as it is being collected, making visual observations of cross-track swaths (i.e., noting convex, concave, or skewed returns in flat, smooth bottoms), data quality flags/alarms from the GPS, RTK, or MRU systems, or noting comparisons between adjacent overlapping swaths or between independent single beams. Real-time software must have features that allow some form(s) of real-time quality assurance assessment, and performing immediate corrective actions.

6-38. Sample Performance Test—Survey Vessel Shuman (Philadelphia District). The Performance Test results shown below were done over a very flat anchorage area with depth variation of less than ±2 ft over a 200- x 200-ft test area. A reference surface was created by running two sets of four parallel lines, with line sets perpendicular to each other. The line spacing was approximate water depth (45 ft). After editing and application of tide and sound velocity corrections, the reference survey was gridded into 2- x 2-ft cells. The average of each cell (approximately 17 points per cell) was saved to an XYZ file. The results from comparison of the reference surface with two check lines (one in each direction) are shown in Table 6-2. This report was generated by the Beam Angle Test section of HYPACK/HYSWEEP multibeam processing program. (Additional Performance Test examples are shown in Appendix F.) The results of the above sample Performance Test indicate the multibeam system is providing reliable data out to a ± 75-deg beam width. However, the relatively large constant biases of + 0.1 ft between the two surveys might be questioned and further evaluated as to the cause. If this test had been performed for a payment survey on a rock cut project, then these large biases should have been investigated.

Table 6-2. S/V Shuman Performance Test results.

Beam Angle Limit	Max Outlier	Mean Difference
20	0.37	0.11
25	0.37	0.11
30	0.37	0.11
35	0.40	0.11
40	0.40	0.10
45	0.40	0.10
50	0.40	0.10
55	0.45	0.10
60	0.88	0.10
65	0.88	0.10
70	0.88	0.10
75	0.88	0.11

6-39. Fixed Calibration Barge (Louisville District). Figure 6-29 depicts a sunken barge on the Ohio River used to verify performance on Louisville District multibeam systems. This "reference surface" is in 40 ft of water. Star test patterns are run over the barge.

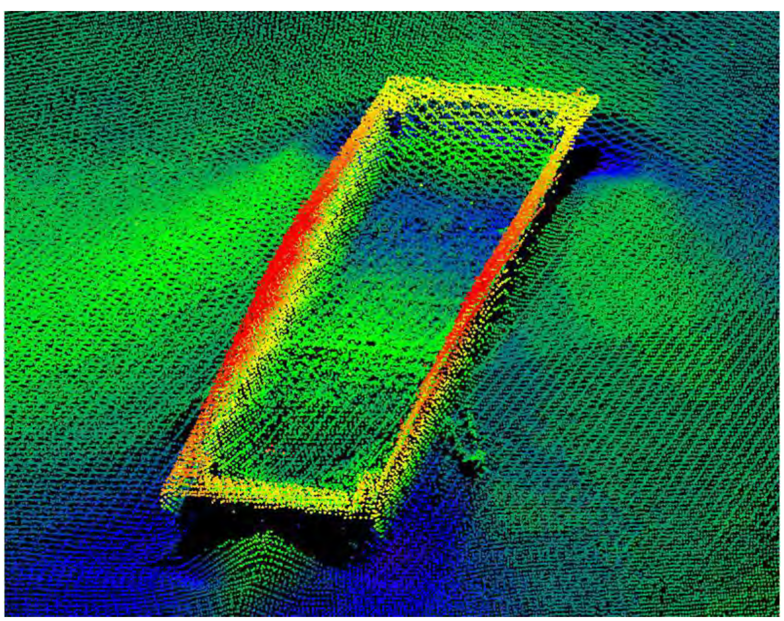

Figure 6-29. Louisville District calibration barge used as reference surface.

SECTION VII

Summary of Multibeam QC and QA Criteria.

Table 6-3. Recommended Quality Control and Quality Assurance Performance Criteria for Multibeam Surveys. (Refer also to Appendix F for additional guidance.)

Requirement	Recommended Frequency or Comment
Bar Check Calibration	Perform periodically (e.g., monthly or quarterly) recommended at start of new dredging project
Sound Velocity Calibration	Twice daily minimum, or more often in varying conditions (continuous velocity recording on some multibeam systems)
Horizontal Position Check	Daily on dredging projects (RTK v Code DGPS adequate)
Vertical Elevation Check (RTK)	Twice daily calibration at tide/staff gage.
System Alignment/Orientation Tests (e.g., Latency/Patch Test)	Perform periodically (e.g., quarterly) or as required. Recommended at start of new dredging project.
Vessel Squat/Settlement Test	Annually
Vertical Datum Verification	Refer to EM 1110-2-6056 for periodic requirements to ensure coastal tidal datums are consistent with NOAA reference datums; including periodic checks of tide/staff gages
Survey Coverage (Density)	100% coverage is recommended for maintenance dredging projects. 200% coverage is recommended for deep-draft projects with critical under keel clearances over rock.
Quality Assurance Performance Test	Periodically or as required based on project requirements. Recommended daily on critical dredging/clearance projects.
Object or Shoal Detection:	
Minimum object size	3 ft cube (periodically verify by independent detection test)
Minimum number of acoustic hits to confirm a shoal or strike above grade.	3 acoustic hits recommended. (successive passes over object)