# Chapter 11
# Acoustic Multibeam Survey Systems for Deep-Draft Navigation Projects

## 11-1. General Scope and Applications

This chapter provides USACE policy and guidance for acquisition, calibration, quality control, and quality assurance of multibeam survey systems used on deep-draft navigation, flood control, and charting projects. Instructions for operating specific multibeam systems, or the acquisition, processing, and editing of data from these systems, are found in manufacturer's operating manuals and software processing manuals specific to the systems employed.

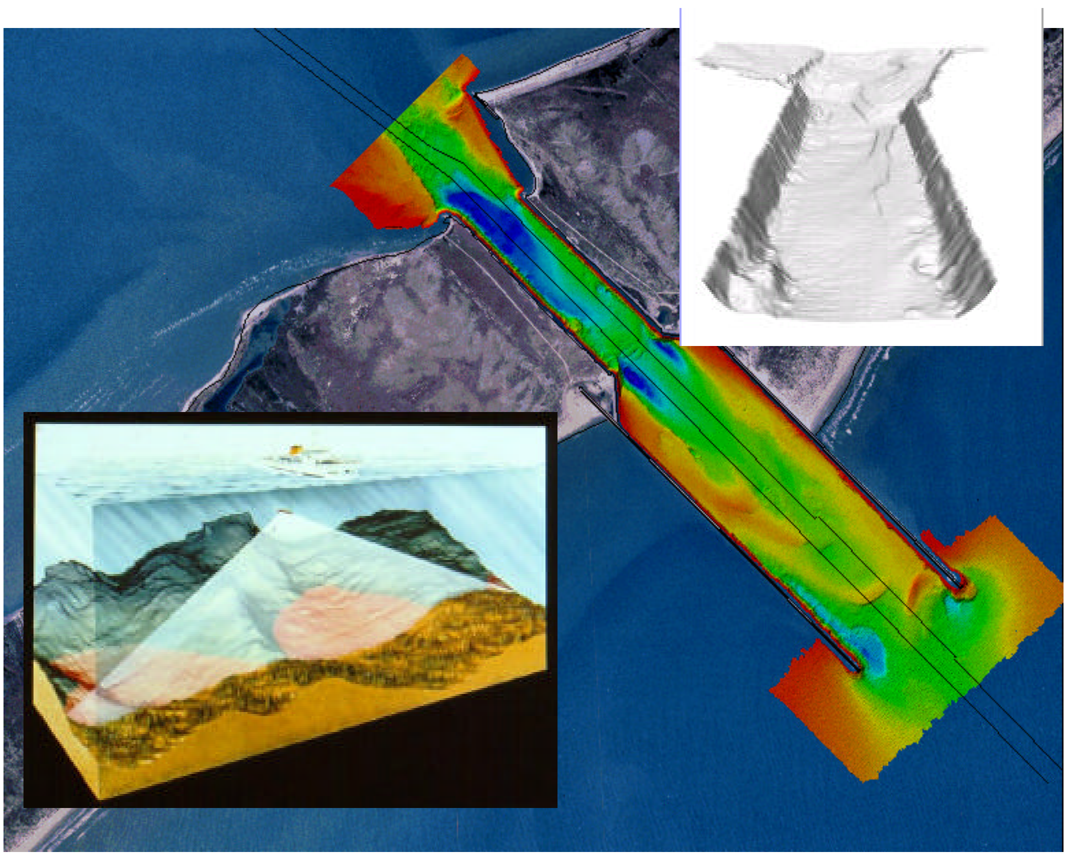

**Figure 11-1. Full-coverage multibeam survey of coastal inlet navigation project (Galveston District)**

## 11-2. Background

The US Navy developed multibeam swath survey technology in the early 1960s for deep-water bathymetric mapping. Only since the early 1990s has this technology been developed and marketed for shallow-water USACE applications, such as those illustrated in Figure 11-1. It is expected that use of multibeam systems will significantly increase over the next few years, and will gradually supplant single beam transducer survey systems in deep-draft navigation projects. Multibeam systems, when coupled with digital side-scan imaging systems, have the potential to become a primary strike detection method in USACE. Multibeam systems have technically advanced since their introduction in the early 1990's to the point that they now have a direct application to most Corps navigation project survey activities. When properly deployed and operated, the accuracy, coverage, and strike detection capabilities of multibeam systems now exceeds that of traditional vertical single beam echo sounding methods.

## 11-3. Principles of Operation

Multibeam sonar systems employ beamforming or interferometric (phased array) acoustic detection techniques from which detailed terrain cross-section (swath) data can be developed many times per second. A single transducer, or pair of transducers, form a fan array of narrow beams that result in acoustic travel-time 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--see Figure 11-2. Generating many sweeps per second (e.g., the Reson Seabat 8101 generates 30 profiles per second at 7.4 times water depth), multibeam systems can obtain 100% bottom coverage, and can provide high resolution footprints when narrowly focused beams are formed--e.g., < 1 deg. Multibeam systems can also be configured for waters-edge to waters-edge coverage (i.e., over 180 degree swath), allowing side-looking, full-coverage underwater topographic mapping of constricted channels, lock chambers, revetments, breakwaters, and other underwater structures. Some systems collect acoustic backscatter information which can produce digital side-scan imagery simultaneously with the swath mapping data, an advantage in locating underwater rock, hazards, shoals, or other objects (strike detection). Multibeam acoustic frequencies and signal processing methods may be adjusted to match the survey requirements--dredging measurement and payment, strike detection, structure mapping, 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 quantities can be completed in the field the same day the survey is performed.

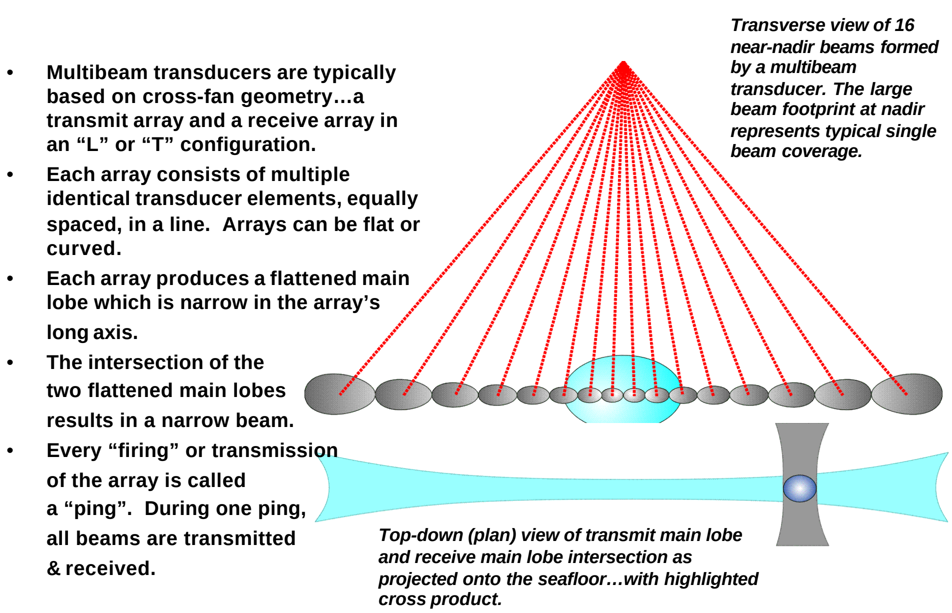


**Figure 11-2. Multibeam transducers and beam geometry (NOAA)**

*a*. *General.* All multibeam swath 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. Travel time estimates are converted into slant ranges, horizontal off-center distances, and then depth by applying beam angles and sound velocity profile data. The object is to convert two-way slope distance travel times to a vertical depth at points along the bottom. Slope distances are resolved using amplitude and/or phase detection methods. Amplitude detection relies on finding the time of beam bore site 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). The changeover point between amplitude and phase detection varies by design; methods include absolute cutoff, real-time analysis of each beam, and combination amplitude and phase. Depth accuracy can change at bottom detection transition points.

*b. Beam spacing.* Swath systems are typically designed with between a 0.5 deg and 3.0 deg beam spacing. Due to the physics involved, a half-degree beam spacing is about the best that can be achieved and still have a portable electronically beam-formed system. To increase resolution, interferometric phased array techniques are 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.

*c. Signal parameters.* Each individual bottom spot within the ensonifinied swath responds with an 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. The quality of the return signal is dependent upon the primary projector/receiver characteristics and the geometrical and reflective properites of the particular bottom spot. The hardware is a factor in the quality of the final data. In designs that rely totally on electronic beamforming, the transducer must be optimized for a particular application. 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 to determine the total sounding solution (i.e., X-Y-Z) relative to our Earth-fixed coordinate system. Most multibeam systems can also output the angle independent imagery--more commonly called pseudo side scan imagery.

*d. Vessel roll, pitch, and yaw effects.* Horizontal positioning accuracy is dependent upon the ability of the system to compensate for pointing errors caused by vessel roll, pitch, and yaw--Figure 11-3. Across-track location of each bottom point is critical. In wider swath systems, even a small degree of roll can cause large errors in the outer beams; thus restrictions are typically placed on use of outer beam data. These errors are compounded due to beam spreading.

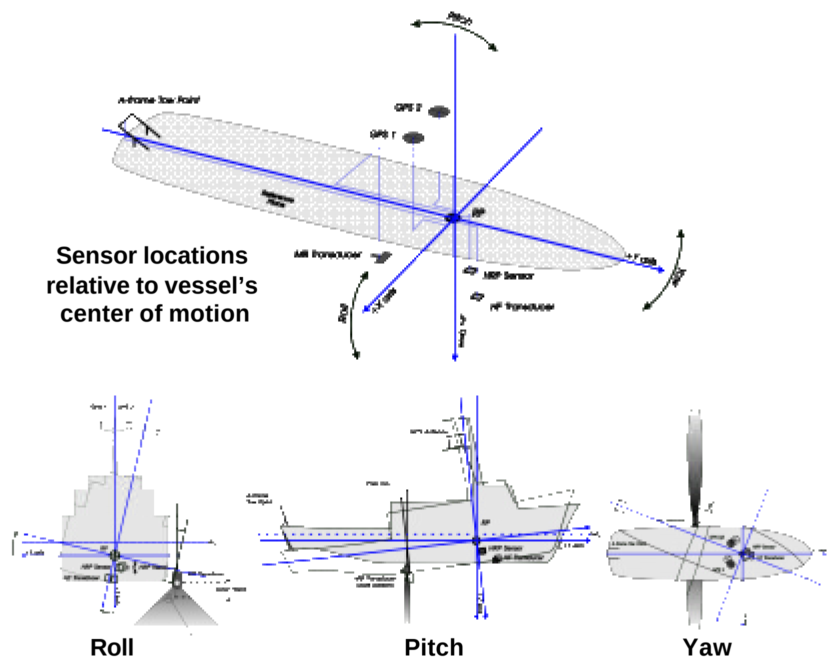


**Figure 11-3. Multibeam offsets, roll, pitch, and yaw (NOAA)**

*e. 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, restrictions are typically placed on use of outer beam data; which limits the amount of single pass coverage in multibeam surveys.

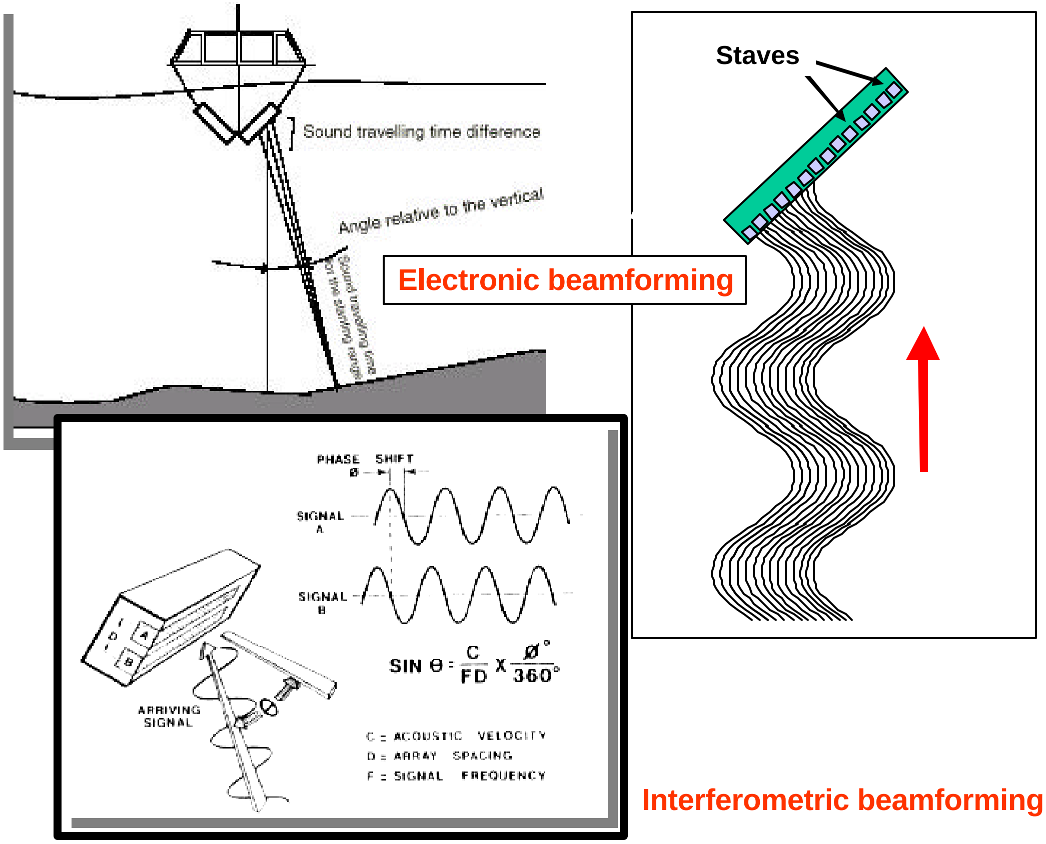


**Figure 11-4. Beam forming methods in multibeam systems (Odom Hydrographic Systems and University of New Brunswick)**

*f. Beamforming methods.* The following methods are used by various multibeam systems to determine slope distances and resultant depth from different directions in a beam array:

*(1) 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 multibeams estimate the slant range to each echo event point based on the strength of the signal relative to a threshold. Electronic beamforming provides a stable and robust range and bearing estimate for each individual channel, primarily in the inner beams. A disadvantage is that the resolution is limited by the geometric properties of the transducer array and the multiplexing rate of the electronics. Also, the transducer design dictates the resolution of the system. Because it would be impossible for the electronics box to contain a separate bank of filters for each channel, the electronics must be time-shared. Therefore, a multiplexer is required and it must sample each channel individually. All other channels are ignored during this sampling time. This results in a spatially truncated profile or "blocky" data set. All electronic beamformers also incur some degree of overlap between adjacent beams and inherent side lobe interference. Due to the mechanical design of an electronic beamforming transducer, it is almost impossible to avoid beam overlap at some point. Side lobe interference--something inherent in all electronic beamformers--causes unwanted returns that cannot always be removed in the filters. Side lobe interference also causes problems in the bottom detection process (especially where sharp bottom features are present) and false targets may be generated in the side

scan imagery. Electronic beamforming can be applied to either the transmit or receive cycles. To steer a beam downward, multiple staves (elements) are sequenced with a slight delay--see Figure 11-4. 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 all current electronic beamforming multibeams) is to apply this "phasing" principle to the receive signals. A fanbeam is projected across the swath and the received signals are processed (usually one iteration for each beam). Filters must be used to remove unwanted components from adjacent channels.

*(2) Physical beamforming.* The physically beamformed echo sounders use a common fanbeam projector and an array of polymer 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 polymer receive elements. Odom Hydrographic Systems ECHOSCAN uses a piezoelectric non-ceramic material, known as PVDF, that can be physically cut and shaped to produce the desired beam pattern that provides high sensitivity to weak signals, eliminates side lobe interference, and forms elliptical (pencil beam) patterns. Because it is not a "wide swath" multibeam, the ECHOSCAN can effectively apply the center-of-energy method of bottom detection and is not as prone to "ray bending." To offset the limited swath of 90 deg, the motion sensor is contained inside the transducer housing to allow tilting of the transducer to look up at structures or out to water's edge. The hydrodynamic shape to the transducer also allows for faster survey speeds. Also co-located are the side scan elements (traditional high-resolution, analog receive elements) to receive imagery simultaneously derived from the common 200 kHz projector. Advantages of physical beamforming include (1) very high signal-to-noise ratio, (2) negligable side lobe interference, (3) low percentage of "bad" data points, and (4) less expense. The only limitation to the physical beamforming approach is the compromise between swath width and transducer size.

*(3) Interferometry (Phased Array).* 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. The bottom spot direction is determined by differencing the acoustic arrival times (i.e., phasing). In Figure 11-4 the same signal arrives at element A slightly later than it does at B. 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 (boresight). 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. The term "beam" actually does not apply here in a physical sense. Consolidation into beams is more of a mathematical operation executed after the data is received and buffered. Interferometric techniques can provide extremely high resolutions and a large number of beams. There are distinct advantages to an interferometric multibeam system that cannot be achieved by other methods. Outer beam detection is more robust and stable and tends to be less noisy than in electronic beamforming methods. The beam angles are easily steered to compensate for vessel motion and can be adjusted to provide "equal footprint" ensonification to compensate for beam spreading. Depth resolution is limited only by the processing power of the electronics. The disadvantages of a purely interferometric multibeam echo sounder include: (1) phase tracking circuitry can become unstable and cause high data variations, and (2) resolution depends on the internal detection rate (i.e., sophistication of the processing system).

*(4) Combined electronic beamforming and interferometric (phased array) method.* The FANSWEEP Models 15 and 20 use a combination of electronic and interferometric techniques to process

multibeam data. This provides equal footprint spacing across the full array rather than variable footprint size from fixed beam width arrays. (See Figure 11-5). To accomplish this, the beam spacing angle must be variable from 1.5 deg at nadir to 0.12 deg on the outermost beams. The processing system must have full control of the beam spacing and direction--in real-time.

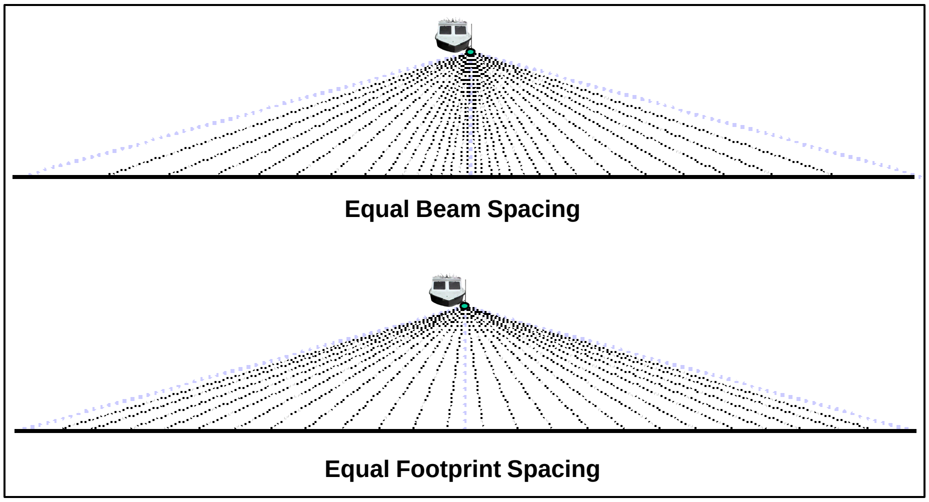


**Figure 11-5. Equal footprint spacing using electronic and interferometric beamforming (Odom Hydrographic Systems)**

Figure 11-6 depicts the design and configuration of the FANSWEEP 15/20 multibeam system mounted over-the-side on the 27 foot survey vessel. In this combined system, electronic beamforming techniques form four transmit beams and each transmit beam is at a slightly different frequency with the lower frequencies in the two outermost patterns to compensate for the longer ray paths. It configures 26 rows of elements into 2 groups for transmit beamforming, then into 10 groups for interferometric reception. The combination also allows for highly focused beams in the along-track direction. Individual beams in the across-plane follow an adaptive scheme which also allows for equal footprint ensonification over terrain that is not flat. All received raw echo samples are stored into an internal amplitude/phase memory. No beams are involved during the receive portion of the cycle; instead, all of the information is buffered simultaneously as it is received. This includes both phase and amplitude information. Independent, simultanous software processes emulate both the classical beamformer and the interferometer algorithms providing two independent depth estimates which are then resolved into 4096 bathymetry and side scan points across the swath. Based on the initial amplitude and phase estimates, a secondary correlation filter re-iterates the buffer to consolidate the points into groups of three or more (total of 1,440 at 12 times water depth). Data are grouped into the desired number of beams (bottom points). The number of beams (up to 1440) and the swath width (up to 12 times the water depth), and coverage restrictions to a small sector (port or starboard), are all operator selectable.

**A Combined Electronic Beamforming and Interferometric (Phased) Multibeam**

- **Square transducer array arranged in a "V"-shape aligned symmetrical to the ship's centerline**
- **Combined transmit/receive arrays including all necessary hydroacoustically active elements for transmission beamforming**
- **Each array consists of 26 rows of individual elements grouped into 2 sections for transmission and 10 sections for reception**
- **Each section provides identical, highly focussed beams in the for/aft direction**
- **Individual beams in the across plane follow an adaptive scheme**


**Over-The-Side Mount**
**M/V ECHOTRAC**
**(27-ft vessel)**

**Figure 11-6. FANSWEEP 20 combined electronic beamforming and interferometric multibeam (Odom Hydrographic Systems)**

*g*. *Other corrections.* The half round-trip travel time, i.e. each beam's slant range, is traced from the earth-fixed launch angle through the refracting water column, yielding the corrected along track, cross track, and depth relative to the sonar head. The along track and cross track distance for each beam are rotated with vessel attitude (roll, pitch, and heading) into geographical coordinates using offsets of the GPS navigation center and the sonar head.

*h. Multibeam sidescan imagery.* Multibeam imagery is generally not as good as towed side scan imagery. The high aspect of a hull mounted transducer results in high grazing angles. High grazing angles result in small shadows. The amplitude imagery (one of the sonar's data "triplets") is of limited hydrographic value. Each pixel represents the amplitude intensity of just one beam. The larger the beam footprint, the coarser the amplitude imagery. Each pixel is colored, or shaded, according to the beam's intensity. 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. Amplitude imagery is also called "backscatter intensity" and could be exploited for bottom classification. 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.

## 11-4. USACE Multibeam Policies, Procedures, and Applications

Multibeam systems are primarily deployed on deep-draft navigation projects where full-bottom coverage is required. Survey lines are run longitudinal with the channel 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 beam angle. Vessel speeds are typically slow in order to ensure multiple hits on potential hazards or shoals, or when collecting side scan imagery. At an update rate of some 30 profiles/sec, some 2,000 to 3,000 depths/elevations per second are generated; resulting in a large data base for the subsequent processing and other engineering applications. The tradeoffs to wide-swath, high-density data are increased editing and post processing time and the requirement for more sophisticated computer hardware.

*a. Dredging measurement and payment surveys.* Multibeam swath survey systems that provide complete bottom coverage are recommended for use in dredging measurement and payment surveys, i.e., plans and specifications surveys, pre-dredge surveys, post-dredge surveys, and final acceptance/clearance surveys. 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. Use of multibeam systems on dredging measurement, payment, and clearance work requires far more extensive quality control and assurance calibration and attention to bottom type with respect to frequency as this may impact significantly upon volume computations. Multibeam systems are not recommended for payment or clearance use on shallow-draft projects.

*b. Project condition surveys.* Multibeam survey systems may optionally be used for project condition surveys of channels, revetments, and other underwater structures where complete bottom coverage is desired to fully delineate the feature or structure. Multibeam sensors can be configured to detail pipelines, bulkheads, flood walls, lockwalls, 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.

*c. Shoal or strike detection.* 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 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.

*d. 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.

*e. Other channel sweeping methods.* Multiple-transducer, boom-mounted, channel sweep systems are generally preferred for use over multibeam survey systems in shallow-draft (<15 to 20 feet), sand/silt-bottomed navigation channels. Multi-transducer systems will also provide 100% bottom coverage on navigation channels, as will mechanical, or manual, channel sweeping techniques and towed side scan sonar devices. Mechanical bar sweeps remain an effective dredging quality control technique when rock is encountered.

*f. Volume computations.* Measurement and payment surveys performed using either multibeam or multiple transducer boom systems shall compute pay quantities using the full, densely populated, data digital terrain models (DTM) generated by swath survey data. Data sets should be thinned to a gridded or binned to a digital elevation model (DEM) only when multiple or duplicate points within a specified bin size exist; the representative depth selected within a fixed bin should not be biased or overly smoothed. The bin (or DEM post) size should not exceed either the estimated positional accuracy or the acoustic beam footprint size. The algorithms used for data thinning routines must be thoroughly tested to verify that thinned volume quantities do not differ from raw data set quantities. In effect, data thinning shall be kept to an absolute minimum. Actual dredged quantities should be computed from either the raw DTM or the gridded DEM relative to the applicable payment template using standard CADD software routines. (For sparse data sets, such as traditional single-beam cross-section surveys, dredged volumes may be computed using traditional average end area routines or from triangulated irregular network (TIN) models).

*g. Dredging contract specifications.* Measurement and payment provisions in dredging contract specifications shall clearly stipulate the type of 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.

*h. 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) Coastal Oceanographics, Inc., (3) Triton Elics International, (4) Odom Hydrographic Systems, Inc., (5) University of New Hampshire-NOAA Joint Hydrographic Center, or (6) The Hydrographic Society of America seminars. Multibeam manufacturers may also offer specialized training sessions. In addition, the operator should have completed a manufacturer or Corps PROSPECT course associated with the differential GPS system, inertial compensating system, and CADD processing/editing system employed. For contracted multibeam survey services, the Architect-Engineer (A-E) contract solicitations shall require that proposals identify the experience and training of system operators in Block 7 of the SF 255.

*i. Plant utilization and justification.* Multibeam surveys may be obtained using hired-labor forces or through A-E service contracts. Commands proposing to purchase multibeam systems shall obtain advance approval from HQUSACE (ATTN: CECW-OD). This approval is necessary to ensure effective and efficient utilization of floating plant, given the $200 K to $500 K investment for a complete system. Justifications shall indicate the (1) proposed 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.

*j. Calibration and quality control.* Field 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. Accuracy performance tests are essential in order to 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. 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.

*k. Multibeam installation on Corps floating plant.* Multibeam systems are mounted on a variety of vessels, ranging from 22-ft up to 65-ft vessels. Multibeam systems are normally more cost-effectively utilized on small, mobile (trailerable) survey vessels up to 26 feet in length, with the transducer assembly externally mounted over the side (bow, port, or starboard). This allows the system to be rapidly deployed on remote projects. Permanent placement on large, non-trailerable, 30- to 65-ft survey vessels is generally recommended in areas where such a vessel is permanently deployed on a major navigation project. Following are examples of multibeam installations aboard a 65-ft and 23-ft vessel, taken from representative Corps districts.

(1) 65-Foot Survey Vessel Adams II, Norfolk District. In 1998 the Norfolk District installed a RESON "HydroBat 200 Multi-beam Sonar Integrated Hydrographic Survey System" (SeaBat 8101 with Option 037) on their 65-ft survey boat. Option 037 is the titanium sonar head in lieu of the standard aluminum sonar head. Figure 11-7 shows the location of the transducer. The SeaBat 6042 data acquisition system is interfaced with an Ashtech Z-12 DGPS positioning system, a gyro heading sensor (Anschütz –Standard 20), motion sensor (TSS–DMS–05), and the SeaBat 8101 sonar processor. Project defined real-time navigation capability is provided by HYPACK software. Calibration, playback, editing, and binning is handled with HYPACK/HYSWEEP software. Additionally, velocity profile information is collected with an AML (SV-Plus) velocity profiler and manually input in HYPACK file format.


**Figure 11-7. RESON SeaBat 8101 installation on Survey Vessel Adams II (Norfolk District)**

(2) 23-Foot Survey Boat, Buffalo District. In 1998, the Buffalo District installed a multi-beam sonar system for use on its navigation projects on Lake Ontario and Lake Erie. Following is a brief description from Buffalo District reports as to why a multibeam system was purchased, the equipment installed, and the rationale behind the installation particulars.

(a) The Buffalo District decided that a multi-beam was needed for several reasons. The first of which was to provide for better surveys of the District's channels. The multi-beam would provide 100% coverage of the channel resulting in a more accurate description of the bottom of the project. For dredging purposes, a more complete volume computation could be obtained using a full-model method of computation--i.e., TIN--rather than the approximate "average end area" method. The multibeam system will provide information between the normal cross-sections and a TIN volume computation method takes into account the whole area: thus providing a better ‘picture’ of what the channel looks like. The second reason the District needed a multi-beam system was to survey the various breakwaters within the Buffalo District to check for needed repairs. The multi-beam would be able to show areas where the stone was falling away and needed to be replaced.

(b) The components of the multibeam system installed were 1) Reson SeaBat 8101 with 210 deg array coverage and with sonar display, 2) TSS POS\MV Model 320 motion sensor, and 3) Triton-Elics Isis computer and data logging software. Also on the Triton-Elics computer is HYPACK software used for navigation purposes. The TSS POS/MV was chosen because is provides the motion data [heave, pitch, roll], heading, and position all in one processor, with a small inertial block, making it easier to install on a small boat. An Innerspace Model 449 dual-frequency (vertical beam) depth sounder was already being used and would also be part of the new system for quality control purposes. In addition, an Innerspace velocity profiler that was already being used within the Buffalo District was also part of the installation. A major concern is how to get the data from the boat to the office. Since the office personnel already had computers with PCMCIA slots, it was decided that the data would be put on a PCMCIA card and sent to the office. Since the computers in the District Office have a Windows NT operating system, software from SystemSoft (called ‘Card Wizard’), a “hot swap” of PCMCIA cards is possible without shutting down the computer.

(c) The Buffalo District installed the system on a 23-foot SeaArk launch. This meant space was limited within the cabin and weight distribution was a major concern. As with most smaller survey vessels, the launch operator sits on the starboard side and the equipment operator sits on the port side of the boat, at the back of the cabin. Without changing that balance, the processors for all new and existing equipment would be rack-mounted on the starboard side, behind the launch operator. This will allow for the equipment operator to have them within easy reach. The only equipment in front of the operator are two monitors, one for the computer doing the data recording and a second monitor for the operator to see what the launch operator sees. This is achieved with a video splitter. Because the computer doing the data recording has a virtual screen, this allows for the navigation display to be sent to a flat panel screen for the launch operator, negating the need for a second computer for navigation. Next choice was where to install the sonar head. Since the multibeam has coverage of 210 degrees, if the sonar head were mounted through the hull, it would have to be mounted deep enough for the outer beams to get past the outer edges of the hull. This was not practical since the boat is transported by trailer. The other option, which was eventually chosen, was to mount it over the side. It was mounted on the port side to aid in proper weight distribution. It is attached to a pipe that can be rotated to bring the sonar out of the water for putting the boat on a trailer. The next decision was how deep to have the sonar in the water. Because of the typical hazards that are in the Buffalo District, i.e., submerged pilings, and allowing for the ability to survey in rougher sea conditions, it was mounted deep enough to ensure that the sonar head was shallow enough to remain out of danger of obstacles and deep enough to remain in the water during rough seas (heave, pitch and roll). The effect of this is that the sonar head is in the water deep enough to get only approximately 95 degrees from nadir on the starboard side, not the full 105 degrees. This only presents a problem for doing the above mentioned breakwater surveys. To get the best coverage, the boat will always survey with the port side of the boat towards the breakwater.

(3) 45-Foot Survey Launch Vollert, Galveston District. Figure 11-8 depicts the installation of an Odom multibeam system aboard the Vollert. The Vollert is a 45-foot length vessel with twin diesels, a 12-foot beam, and 3-foot draft. This vessel is normally used to conduct extensive hydrographic surveys 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.

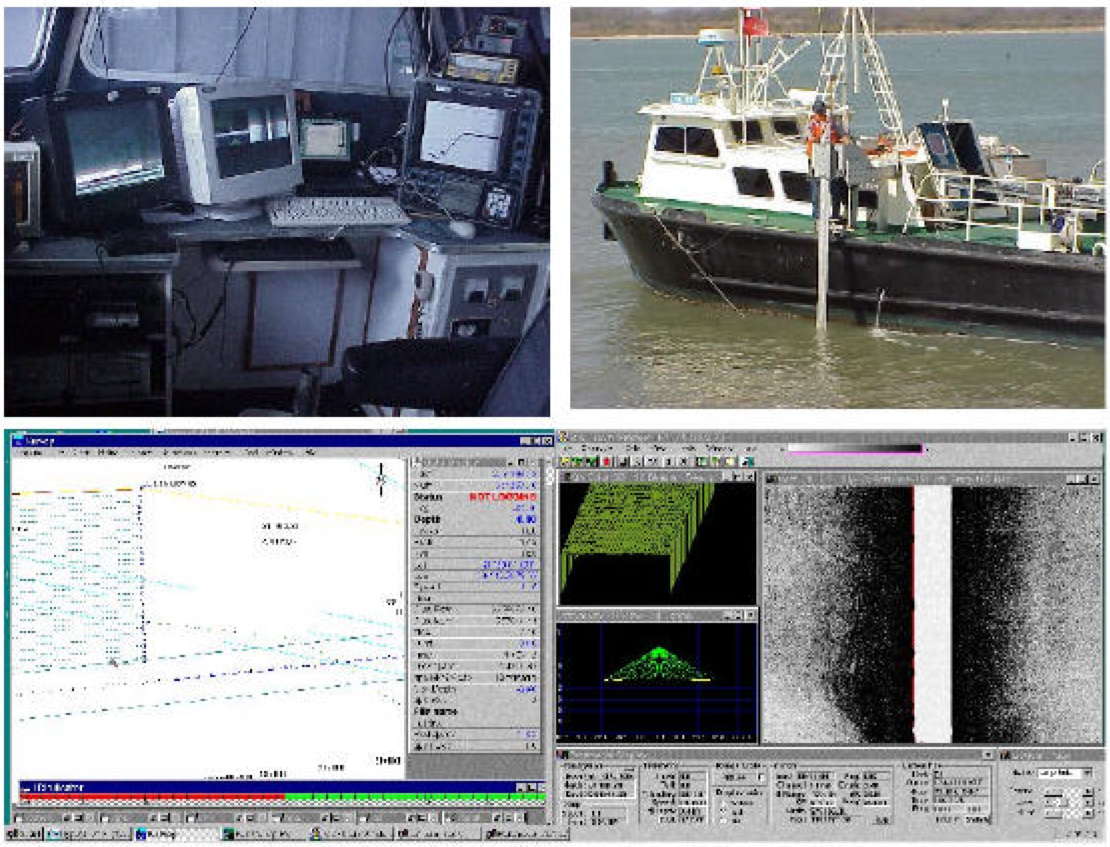

**Figure 11-8. Surveyboat Vollert Odom Multibeam installation (Galveston District)**

*l. Data collection hardware/software.* Navigation, data collection, and data processing software employed with multibeam systems shall have real-time guidance, display, and quality assurance assessment capabilities. The software shall also be capable of applying all calibrations and corrections in the field such that data can be collected, edited, and processed in near real-time in order to effectively support dredging contract administration. Software shall also be capable of performing near real-time statistical quality assurance assessments between comparative accuracy performance test models. Strike detection systems may require more high-end PC-based or CADD work stations in order to adequately display and replay 3D imagery in real-time. CADD data thinning or binning routines shall be rigorously tested to ensure data integrity is not adversely modified. This may be accomplished by comparing quantities between raw and thinned data sets. Figure 11-9 shows the instrumentation and equipment requirements for a typical multibeam system.

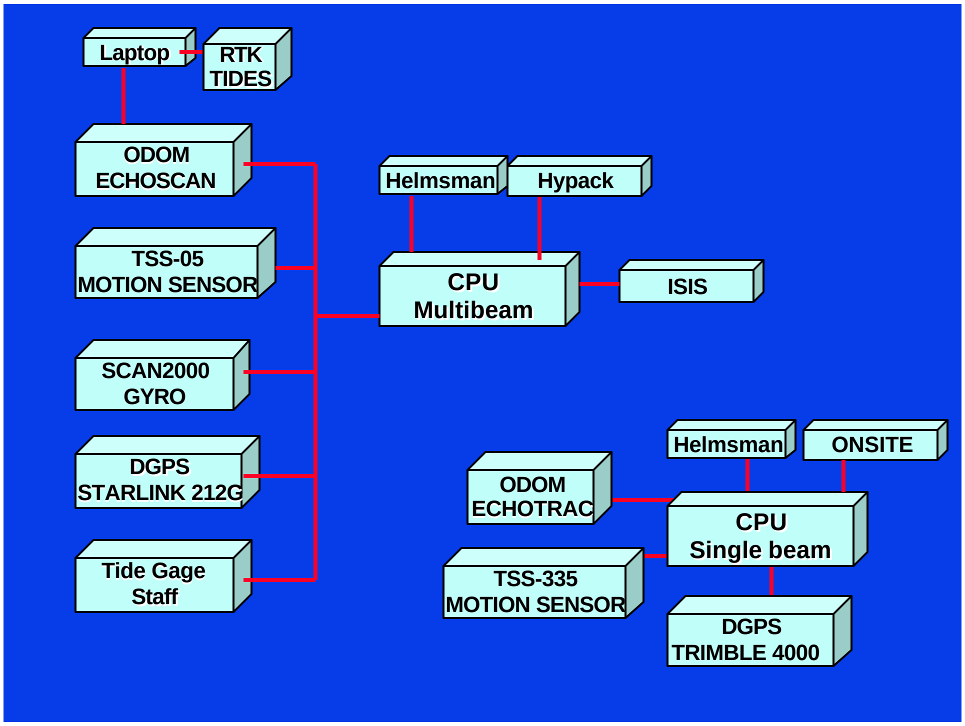


**Figure 11-9. Multibeam system configuration (Surveyboat Vollert, Galveston District)**

A number of multibeam data acquisition software packages are used by Corps districts. The more common packages include: HYPACK/HYSWEEP MAX (Coastal Oceanographics), Bathy Pro Real Time (Triton Elics), and 6042 Version 7 (Reson, Inc.). Data acquisition packages must support all navigation peripheral devices, such as those shown in Figure 11-9. They must also provide the QC and QA calibration and testing requirements indicated in Table 11-2 at the end of this chapter. Other software packages (e.g., Caris) are tailored to post-processing of multibeam data. Both data acquisition and processing packages must be capable of editing and processing data to meet engineering and construction purposes, as opposed to nautical charting functions. If the software packages do not meet these criteria, then multibeam data may have to be processed using standard engineering CADD packages such as AutoCad or MicroStation.

*m. Vessel positioning requirements*. In general, code-phase, meter-level US Coast Guard differential GPS radio beacons will provide sufficient accuracy for most project surveying applications. It also ensures Corps projects are referenced relative to the National Spatial Reference System (NSRS). Where required, translations from NAD 83 to NAD 27 should be performed real-time by the hydrographic data acquisition software. In offshore coastal areas where traditional tidal modeling is deficient, carrier-phase kinematic DGPS (i.e., RTK) may be needed to enhance vertical accuracy of measured depths. When the multibeam is deployed horizontally to map underwater structures, RTK carrier-phase DGPS may be needed to maintain decimeter-level horizontal accuracy.

## 11-5. Quality Control and Quality Assurance Procedures for Multibeam Systems

*a. Purpose.* The following sections provide recommended technical guidance for performing quality control calibrations and quality assurance tests of multibeam sonar systems used on Corps dredging and navigation projects.

*b. Background.* Field calibration requirements for multibeam systems are significantly more difficult and demanding than those required for single beam echo sounders. Periodic, precise calibration is absolutely essential in order to assure multibeam derived elevations meet the prescribed accuracy tolerances for the project--especially in the case of wide-swath multibeams near the outer beams of the array where refractive ray bending and vessel alignment and motion variations can significantly degrade the data quality. In addition, velocity profile data is critical to correct for outer beam refraction and must be taken several times per day. Sound velocity varies spatially and temporally. Improper or inadequate determination of sound velocity can render multibeam data unusable. A characteristic of inadequate refraction correction is the "smile" or "frown" of a multibeam profile. Multibeam system sensor alignments and measurement corrections must be periodically aligned, calibrated, tested, and monitored in order to ensure data quality. A calibration determines navigation time latency, roll bias, pitch bias, and heading bias for the integrated suite of equipment. Pitch, roll, and yaw alignment sensors must have the capability of sensing angular changes of 0.1 to 0.05 deg. Comparative performance QA tests must be performed on independent swath runs made over the same area. The test results should be checked against the prescribed statistical criteria. Procedures for performing these calibration and quality control processes are detailed in the manuals provided with the individual sensors making up a multibeam survey system. It should be strongly emphasized that the software and procedures for calibrating, editing, and thinning multibeam data are still being refined and will undergo modifications as new data is acquired and performance is validated. Likewise, the overall accuracy and object detection performance capabilities of multibeam systems are still being assessed. Therefore, any recommended procedures outlined in this manual must be considered as interim.

## 11-6. Multibeam Calibration Requirements

There are distinct calibration procedures that must be performed in order to operate a multibeam 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 sensor calibration (roll, pitch, yaw, and heave sensors), and various other vessel alignment and coordinate/datum corrections. 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. A summary of measurement and calibration requirements is contained in the tables at the end of this chapter. These calibration requirements are mandatory--failure to perform adequate calibration may render a survey invalid.

*a. Sensor alignment and offset measurements*. Alignment and offset parameters must be measured for the various sensors making up the multibeam system, e.g., gyro alignment/offsets, transducer mounting angles/offsets, DGPS antenna offsets, static and dynamic drafts, vessel settlement/squat, and estimated latencies. These measurements are made upon initial installation or upon replacement, removal & reinstallation of a sensor. Alignment and offset corrections are typically entered in the software system setup modules--e.g., HYPACK Device Setup.

*b. Patch Tests/residual bias calibration.* Patch tests are performed after initial installation, and periodically thereafter if sensors are modified, to quantify any residual biases from the initial system alignment. During this calibration series, four separate tests are performed to determine residual alignment biases for:

- Position Time Delay (Latency)
- Pitch Offset
- Roll Offset
- Yaw/Azimuthal Offset

The above parameters are tested, quantified, and updated using commercial software Patch test routines.

*c. Barchecks.* Traditional bar checks under the center beam must be performed to quantify any draft or index errors in the system. Galveston District has developed techniques for bar checking the outer beams of their multibeam systems, and not just those within the range of the bar check below the boat (Figure 11-10). See also reference 11-14 c.

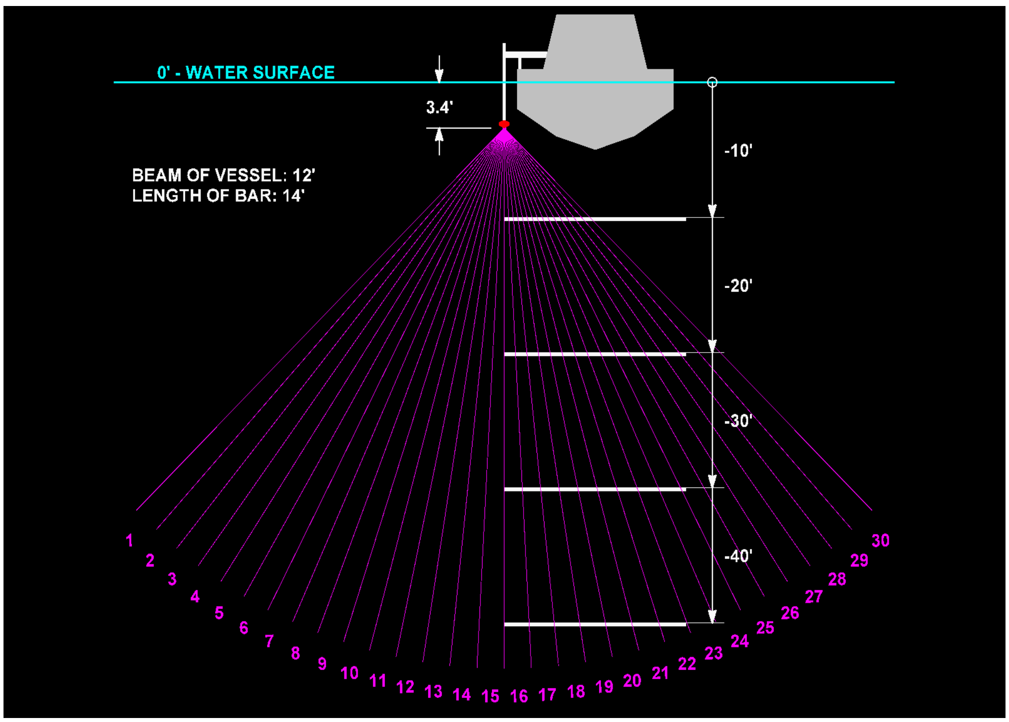


**Figure 11-10. Bar check of multibeam system (Galveston District)**

*d. Velocity profile corrections.* Sound velocity profile calibrations are critical--in particular for the outer portion of the beam array. Velocity calibrations shall be performed periodically during the day, and no less than twice per day, and at more frequent intervals or locations in a project if physical changes in the water column (e.g., temperature, salinity) are impacting data quality. The quality of velocity data may be subsequently assessed through use of the "Performance Test" which compares overlapping survey data models. Beam angles shall be reduced below the maximum limits specified in Table 11-2 if velocity data and/or performance tests indicate uncertainty in outer beam depth measurements. Velocity profile data is entered into the system such as under the HYPACK MAX Sound Velocity Program section.

*e. Quality assurance performance test*. A performance test is a quasi-independent test used to assess the quality of data being collected, and to verify conformance with the prescribed accuracy specification or object detection requirements for the project. A performance test typically compares overlapping data sets from two different multibeam surveys. This test could also be performed by comparing multibeam data with that collected by another single beam echo sounder. Other 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 should also be verified by sweeping over simulated objects of known size; placed either in open water or controlled lock chambers. These tests should be periodically performed as a QA check on the overall system performance. A performance test failure indicates the system parameter alignments, offsets, or velocity profiles are invalid, and must be retested. Performance data reduction, processing, and statistical analysis should be performed in near real-time--preferably on board the survey boat. They should be conducted before a critical dredging measurement and payment survey project; however, they are not needed prior to individual surveys in that project. See Table 11-2 for recommended allowable tolerances. For non-navigation surveys, performance tests may be required weekly, monthly, quarterly, or less frequently, depending on the long-term stability of the results, variations in different project areas, etc.

*f. 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, 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. An alternative quality control assessment is a traditional bar check of individual beams--see reference 11-14 c.

*g. Criteria.* Table 11-2 contains recommended minimum requirements and tolerances for each of the above tests. Since many of the alignment and offset parameters are interrelated, failures at one level of test may require recalibration and/or retesting prior levels. The remaining sections in this section provide more detail on technical procedures for performing the individual tests. The referenced publications or manufacturer's operation manuals should be consulted for more details.

*h. Coverage 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 manufacturer. 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. Due to the increased density of soundings with multibeam systems, it is possible, with proper calibration and adjustments, to detect and resolve smaller objects on the bottom relative to single beam systems. However, this detection capability may be reduced due to larger footprints in the outer beams.

## 11-7. Error Sources in Multibeam Systems

Several sources of errors and biases exist in multibeam surveying which are not found in single beam surveying. With improved resolution and coverage comes the need for much greater control and calibration to ensure that the sounding is recorded from the correct position on the sea floor. This is accomplished by using a high accuracy differential GPS system, heave-pitch-roll (HPR) sensor, and 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 these various components which make up the total system. Some of the more significant error components include:

*a. Static offsets of the sensors.* These are the distances between the sensors and the reference point of the vessel or the positioning antenna.

*b. Transducer draft.* This is the depth of the transducer head below the waterline of the vessel. As in single beam systems, standard bar checks are performed to measure static and dynamic draft variations.

*c. Time delay between the positioning system, sonar measurement, and HPR sensor.* This delay or latency must be accurately known and accounted for in the processing of the hydrographic data.

*d. Sound velocity measurements.* The velocity of sound in the water column must be accurately known so the correct depth can be measured.

*e. Acceleration and translation measurements of the HPR sensor.* These measurements are critical for corrections to the vessel's roll and pitch.

*f. Quality control criteria.* These parameters must be measured and corrected in the multibeam sonar system. These corrections must be performed in the field, not in a post-processing environment. Commercially available software is designed to process and accommodate these inputs, offsets, and corrections.

## 11-8. Initial Installation Alignment and Static Offset Measurements

This is the process of physical measurement and alignment of the vessel platform, transducers, gyrocompass, and HPR sensor. This measurement should be performed with the vessel stabilized on a trailer or on blocks where more exact measurements can be made. This will minimize errors in positioning of the sensors and, with the proper offsets applied, the static corrections will be reduced. The sensors should be measured from a reference point in the vessel. 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, the y-axis abeam the keel, and the vertical (z-axis) positive up. 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 of the sensor or can be accurately measured with a survey tape. It is common for the acoustic and physical centers to be in different places (e.g., Simrad EM 3000). The magnitude and direction of the measurement should be verified and recorded.

*a. HPR Sensor*. If possible, the HPR 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. (Some HPR devices allow heave high pass filtering at a remote location). If possible, use the same mount angles as used for the transducer. The x-axis of the HPR should match the x-axis of the transducer. Azimuthal misalignment of the HPR will result in the depth measurements being in error proportional to the water depth. Misalignment of the HPR sensor in yaw causes a roll error when pitching, and a pitch error while rolling. (If the transducer and HPR are collocated (e.g., Odom Echoscan), many alignment corrections become far less critical).

*b. Transducer.* The multibeam transducer should be installed as near as possible to the centerline of the vessel and level about the roll axis. It should also be aligned with the azimuth of the vessel. This alignment is critical if there is no electronic beam steering in the multibeam system.

(1) Most multibeam transducers used on smaller USACE vessels are mounted over-the-side on a shaft and boom device. (Norfolk and New York Districts 65-foot vessels have hull-mounted transducers). The smaller survey vessel in the New York District is outfitted with a bow-mounted Odom ECHOSCAN. With the over-the-side type of mount, it is imperative that the azimuthal alignment between the transducer and keel be as accurate as possible. This can be accomplished with the vessel on a trailer or blocks on land and using standard surveying and leveling techniques. Since this boom-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 correct alignment. The frequency with which it is checked will depend on what type of surveying is performed and under what conditions. Hull mounted transducers are generally fixed in place and will not need to be checked as frequently.

(2) The angle of the transducer mount must be determined and recorded, unless the HPR is collocated. Since most vessels underway will be lower in the stern, the transducer will generally need to be rotated aft to compensate for this angle. The patch test will also check for the transducer angle. The resulting beam should then project normal to the sea floor while conducting surveying operations.

*c. Gyro.* The gyro 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 1deg at the 95% confidence level, realign the gyro with the centerline and repeat the observations. If less than 1deg, apply the correction to the gyro output. This procedure can also be performed using three GPS receivers instead of the total station. The processing may take longer than with the total station.

*d. Squat/Settlement measurement using transit/theodolite.* 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 the HPR will not measure the long-term change in elevation. The sensor will record the sudden change in elevation but the measured heave will drift back to zero. The settlement can be measured with a transit on shore and a 2- meter level rod or stadia board on the vessel positioned over the HPR sensor (i.e., the point where the heave data are low pass filtered). 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. Be sure the correct sign is applied when entering the correction in the software.

*e. Squat/Settlement measurement using RTK DGPS*. An alternate method for determining squat/settlement makes use of carrier-phase differential GPS elevation difference measurement.

(1) Position the DGPS antenna near the center of the vessel and measure the vertical and horizontal distance from the antenna to the vessel's reference point with steel tape.

(2) Use data from a nearby tide gauge to provide a datum from which to measure the elevation. The gauge should be in the survey area and if the area is large, two gauges should be used.

(3) Run the same survey line at different speeds. Also run the line under different loading conditions.

(4) Record the GPS positions, heave, pitch, roll, vessel speed and water levels at common times. The sampling rate should be at the highest for GPS and HPR sensors (10Hz and 100Hz, respectively) while the water levels can be recorded at approximately 5-10 minute intervals.

(5) Record the antenna height while stationary.

(6) All data should be synchronized and interpolated if necessary.

(7) Use the GPS antenna offsets and attitude data to compute the roll and heave and correct the antenna elevations. Subtract water level data and heave data from GPS antenna elevation.

(8) With these corrections for motion and water levels, compute the average speed in the water and the average antenna elevation with respect to the ellipsoid. Produce a look up table for the transducer draft correction.

(9) RTK DGPS may be used to directly reference the absolute vertical position of the multibeam transducer, thus eliminating the need for tide/stage data, squat, dynamic draft, etc. If RTK DGPS is used only to determine the tide/stage level, then squat and draft measurements must be input to the processor.

*f. HPR sensor time delay*. Time delay in the attitude sensor will result in roll errors, which greatly affect reduced elevations at the outer beams. In addition, horizontal accelerations in cornering can also affect the HPR measurements, which will also result in errors in the depth measurements. Basically, the principle to detect roll errors is to observe, from the bathymetric data, short period changes in the across track slope of the sea floor when surveying flat and smooth areas. Coastal Oceanographic's HYPACK MAX and TEI's Isis/Bathy Pro programs can be used to check the time delay. HYPACK MAX will process the timing in post-time while the TEI Isis/Bathy Pro displays a real-time confidence check. The Canadian Hydrographic Service and University of New Brunswick have developed UNIX based software to assess time delay in multibeam data.

*g. 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.

## 11-9. Patch Test (Residual Bias Calibration)

Patch tests are periodically performed to quantify any residual biases in the initial alignment measurements described previously. This test (actually a series of reciprocal lines run at varying speeds, depths, and bottom terrain--see Figure 11-11) must be performed carefully to ensure that subsequent data collected when surveying is accurate and reliable. The Patch test determines (and provide correctors for) the following potential biases: (1) residual pitch offset, (2) residual roll offset, (3) residual positioning time delay, and (4) residual azimuthal (yaw) offset. The determined offsets and delays will be used to correct the initial misalignments and calibrate the system. Each of these bias tests is described below and is summarized in Table 11-1 at the end of this section.

*a. Data acquisition.* Survey quality DGPS positioning instruments must be used when conducting the Patch tests--especially in shallow draft projects. The weather should be calm to ensure good bottom detection and minimal vessel motions. Since most of the lines to be run will be reciprocal lines, it is important to have capable vessel steering and handling. The lines should be run in water depths comparable to the typical project depths encountered. The order the lines are run is not important although it is recommended that at least two (2) sets of reciprocal lines be run for redundancy. Although the outer beams of multibeam sonar are subject to a smaller grazing angle, these beams should provide good data provided the appropriate corrections are applied from the patch test. Vessel speed should be regulated such that 50% forward overlap is obtained. The maximum speed may be calculated by the following equation:

$$v = S \cdot d \cdot \tan (b/2) \tag{Eq 11-1}$$

where:

$v$ = maximum velocity (m/s)
$S$ = sounder sampling rate per second (1/t)
$d$ = depth
$b$ = fore-and-aft beamwidth angle

*b. Positioning time delay test and pitch bias test.* Two or more 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 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° to 20°, 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. Pitch is determined from the runs made over the same lines at the same speed in opposite directions.

*c. 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.

*d. Azimuthal (Yaw) offset test.* 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 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.

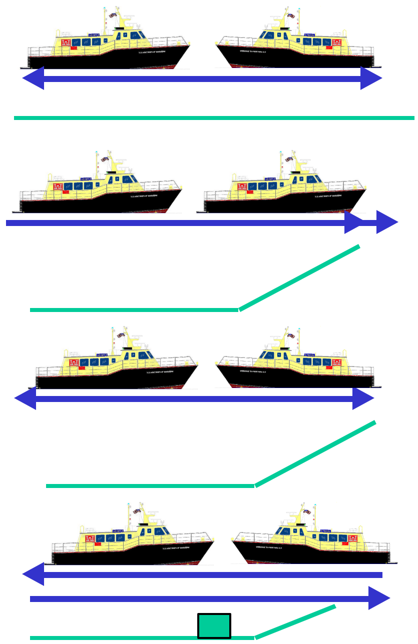


**Figure 11-11. Summary of patch test runs**

## 11-10. Patch Test Data Processing and Adjustment

Commercial patch test routines automatically calculate system latencies, roll, pitch, and yaw biases in multibeam data. The adjustment procedure outlined below uses the entire data set collected from the patch test lines without thinning (i.e., gridding or binning). Visualization of the bathymetric 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 not necessary since individual soundings will not be adjusted but rather clusters of data points will be analyzed. The procedures to process the patch test data should follow the CHS/UNB sequence recommended below. Note that this differs from the sequence recommended by Coastal Oceanographics: roll-latency-pitch-yaw. Future software packages are expected to fully automate the sequential process described below, using imagery enhancing and model fitting technology. Such a process would be far more accurate than the current sequential process.

*a. 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 so as to avoid the effect of pitch offset errors. The equation to compute time delay is:

$$TD = d_a / (v_h - v_l) \qquad \text{(Eq 11-2)}$$

where:

$TD$ = time delay in seconds
$d_a$ = along-track displacement
$v_h$ = higher vessel speed
$v_l$ = lower vessel speed

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.

*b. 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. The pitch offset can be computed using the following equation:

$$a = \tan^{-1} [( d_a / 2 ) / (depth) ]$$

where:

| | | |
|---|---|---|
| $a$ | = | pitch offset |
| $d_a$ | = | along-track displacement |
| *depth* | = | water depth |

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. It should be noted that unless kinematic GPS (i.e., RTK DGPS) positioning is employed, determining $d_a$ to a reasonable level of accuracy is difficult in shallow water.

*c. Azimuthal (Yaw) offset bias.* Parallel lines run normal to a bathymetric feature will be used for the measurement of the azimuthal offset. One pair of adjacent lines run in opposite directions is processed at a time to remove any potential roll offset. The azimuthal offset can be obtained from the following equation:

$$y = \sin^{-1} [ ( d_a /2 ) / X_I ] \qquad \text{(Eq 11-3)}$$

where:

| | | |
|---|---|---|
| $y$ | = | azimuthal offset |
| $d_a$ | = | along-track displacement |
| $X$ | = | relative across track distance for beam i |

The survey lines are processed with only the positioning time delay and pitch offset corrections and static sensor offsets. The azimuthal offset is averaged by several measurements of the displacement $d_a$ over the feature and knowing the across-track distance $X$ at the location of the measurements. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

*d. 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. For small angles of less than 3 deg the roll offset can be estimated by the following equation:

$$r = \tan^{-1} [ ( d_z / d_a ) / 2 ] \qquad \text{(Eq 11-4)}$$

where:

| | | |
|---|---|---|
| $r$ | = | roll offset |
| $d_z$ | = | depth difference |
| $d_a$ | = | across-track distance |

The survey lines are processed while applying the positioning time delay, pitch offset, gyro offset corrections, and static sensor offsets. The roll offset is averaged by several measurements of the across track displacement $d_a$ along the test swaths. This process is performed iteratively until the profiles and contours match or achieve a minimum difference.

**Table 11-1. Summary of Patch Test Procedures and Computations**

| | Latency Delay | Pitch Offset | Azimuth/Yaw Offset | Roll Offset |
|---|---|---|---|---|
| LINES REQUIRED | Two (2) on same heading over slope or shoal; different speeds | Two (2) pairs on reciprocal headings at 2 speeds | Two (2) pairs over bathymetric feature at equal speed | Two reciprocal lines over flat area; equal speed |
| PRIOR CORRECTIONS APPLIED | None--other than static offsets | Positioning time delay | Position time delay and pitch | Position time delay, pitch, & gyro |
| COMPUTATION METHOD | Average of displacements in <u>along</u> track direction | Average of displacements in <u>along</u> track direction | Average of displace in <u>across</u> track direction | Average of displacements <u>in across</u> track direction |
| VISUAL METHOD | Match profiles and contours | Match profiles and contours | Match profiles and contours | Match profiles and contours |

*e. Automated Patch Test.* Figure 11-12 depicts screen displays of automated Patch Test bias computations. The results are input directly into the real-time processing system.

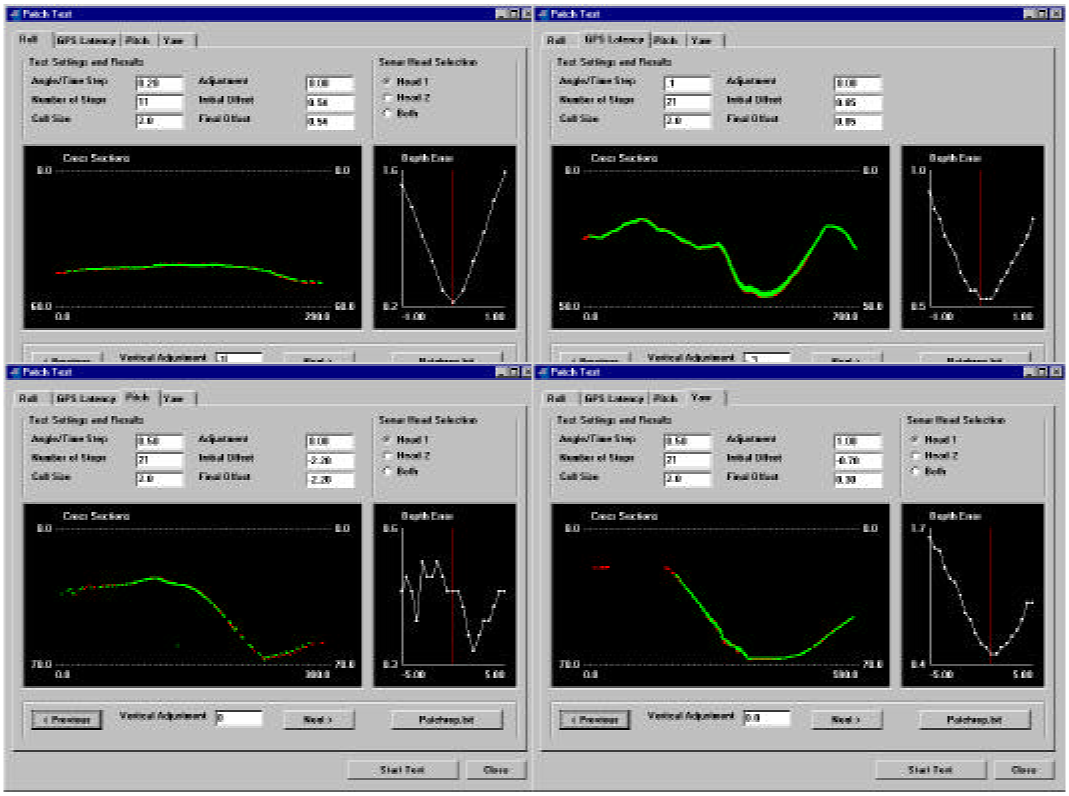

**Figure 11-12. Automated Patch Test parameter computations--roll, latency, pitch and yaw. (Coastal Oceanographics, Inc.)**

## 11-11. Quality Assurance Performance Test (Overlapping Models)

Quality assurance performance tests are conducted upon equipment installation or modification or at the beginning of major projects. This test partially checks the parameters and biases that were measured and computed during the above calibrations. The procedure described below compares a check line swath beam with a reference surface model complied from narrowly spaced multibeam data using only near-center beam data. In some cases, the "reference surface" is derived from independent vertical single beam data. This is adequate provided a fairly dense single beam model is obtained. These QA tests are not truly independent but are an assessment indicator. Failure of the performance test survey to meet the recommended tolerances in Table 3-1 and Table 11-2 requires corrective action--i.e., remeasurement, recalibration, patch testing, etc.

*a. Reference surface.* This is essentially a small survey run over a flat area in water depths of not more than 100 ft. It represents the "baseline" area. The beams outside about 45-60 deg swath width should be removed prior to editing. Four parallel lines are run with at least 150% bottom overlap--i.e., 25% sidelap. One should ensure that the inner beams overlap enough to give redundant data. 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.

*b. Check lines.* Multibeam "check lines" will be run such that the full beam array can be tested against the Reference Surface. A pair of parallel multibeam swath lines should be run inside the reference surface. Overlap as described above is not needed. The vessel speed is the same as for the reference surface.

*c. Data processing and analysis.* Performance test data processing should follow the general rules outlined below.

(1) The reference surface should be cleaned of outliers. This should be performed manually and adjustment of positions, attitude and bathymetry be made to ensure clean data. Smoothing, thinning, or binning of data must not be made.

(2) A digital terrain model (DTM) of the reference surface is created from the cleaned data. Then use an averaging gridding algorithm to smooth the data. The gridding size should be no larger than the average footprint of the inner beams or the estimated positional accuracy, whichever is greater. Using large vertical exaggeration, the DTM should be observed on 3D-visualization software.

(3) The check lines are then processed individually and each beam depth throughout the entire array is compared to the reference surface. A difference surface between the reference DTM surface and the check lines is then created and contoured and statistics computed to assess overall performance. From these differences the corrections to the system can be checked against the criteria recommended in Table 11-2.

(4) Statistical parameters to be computed and evaluated include:

- *Outliers*. Depth differences between the check and reference surfaces are computed at each beam point along the check line array. Maximum outliers should not exceed the values recommended in Table 11-2. Presence of excessive outliers in the outermost portions of the array indicates calibration/velocity problems, and requires correction and/or restricted beam widths.

- *Mean difference or bias.* The difference, or bias, between the reference and check surfaces should not exceed the recommended allowable bias value in Table 11-2. This is the most critical quality assurance check on the data in that a bias error will adversely skew depths and related quantity computations. Excessive surface bias errors require immediate assessment and correction. They could indicate problems with the multibeam data or vertical tide/stage corrections. The confidence of the computed bias can be estimated by computing the standard error of the mean, as demonstrated in chapter 4. Given thousands of comparative data points on multibeam surveys, the standard error of the mean should be small.

- *Standard deviation.* The standard deviation of the differences between the reference and check surfaces should not exceed the limit shown in Table 11-2--i.e., the prescribed performance accuracy standard for depths given in Table 3-1. Software programs typically output one-sigma standard deviations. These must be converted to the 95% confidence level--i.e., multiply by 1.96. 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. In order to assess resultant accuracy as a function of swath width, it may be necessary to isolate sections of the beam swath.

*d. Testing outer beam quality*. The data quality for the outer beams may be tested by running two perpendicular swaths as shown in Figure 11-13. Either swath is selected as the "reference surface" and data from the central portion of the beam is used to compare data from the outer portions of the other swath.

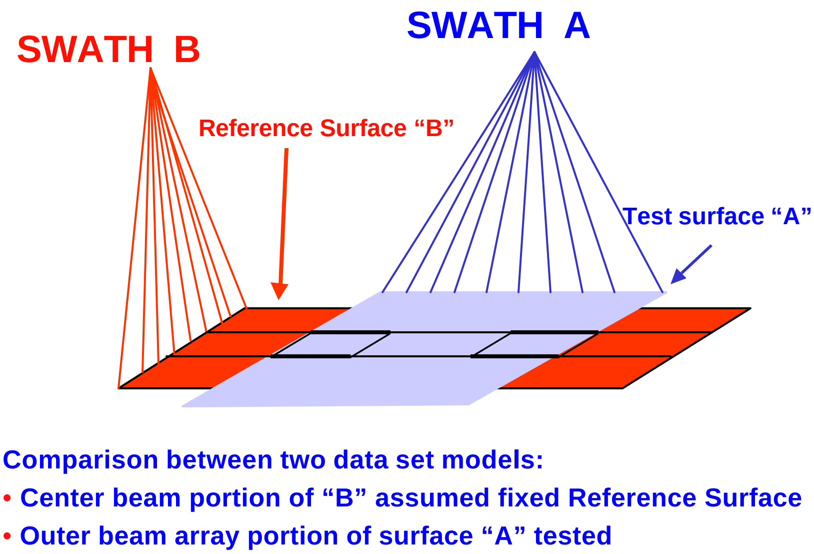


**Figure 11-13. Comparison of two perpendicular swaths**

*e. Calibration, QC, and QA documentation.* Project or contract files must contain documentary evidence that all calibration tests were performed. This would include a written log (or equivalent digital record) of sensor offset and alignment measurements, patch test calibration results, sound velocity measurements, tide/stage observations, performance test results, and other quality assurance observations, such as bar checks. Original records of such calibrations should be retained in a permanent, bound surveyor's field book aboard the boat.

*f. Sample performance test calibration--Philadelphia District (SB Shuman).* The performance test was 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, line sets perpendicular to each other with spacing equal to the 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) is saved to an XYZ file. The results from comparison of the reference surface with two check lines (one in each direction) are shown in the tables and histogram below.

| Statistical Quantity | Shuman Result | Maximum Allowed |
|---|---|---|
| Maximum Outlier | 0.40 ft | 1.0 ft OK |
| Mean Difference (Reference surface – Check line) | + 0.10 ft | < 0.2 ft OK |
| Depth Standard Deviation (1-σ) | ± 0.07 ft | ------- |
| at 95% Confidence (per Table 3-1) | ± 0.15 ft | NTE ± 2.0 ft OK |

Results of the comparison of the multibeam check lines to the reference surface. This report is generated by the Beam Angle Test section of HYSWEEP multibeam processing program MB Max (Figure 11-14).

| ± Beam Angle Limit | Max Outlier | Mean Diff | Std Dev | 95% Confidence |
|---|---|---|---|---|
| 20 | 0.37 | 0.11 | 0.08 | 0.16 |
| 25 | 0.37 | 0.11 | 0.08 | 0.16 |
| 30 | 0.37 | 0.11 | 0.08 | 0.15 |
| 35 | 0.40 | 0.11 | 0.08 | 0.15 |
| 40 | 0.40 | 0.10 | 0.08 | 0.15 |
| 45 | 0.40 | 0.10 | 0.07 | 0.15 |
| 50 | 0.40 | 0.10 | 0.07 | 0.15 |
| 55 | 0.45 | 0.10 | 0.07 | 0.15 |
| 60 | 0.88 | 0.10 | 0.08 | 0.15 |
| 65 | 0.88 | 0.10 | 0.08 | 0.16 |
| 70 | 0.88 | 0.10 | 0.08 | 0.16 |
| 75 | 0.88 | 0.11 | 0.08 | 0.16 |

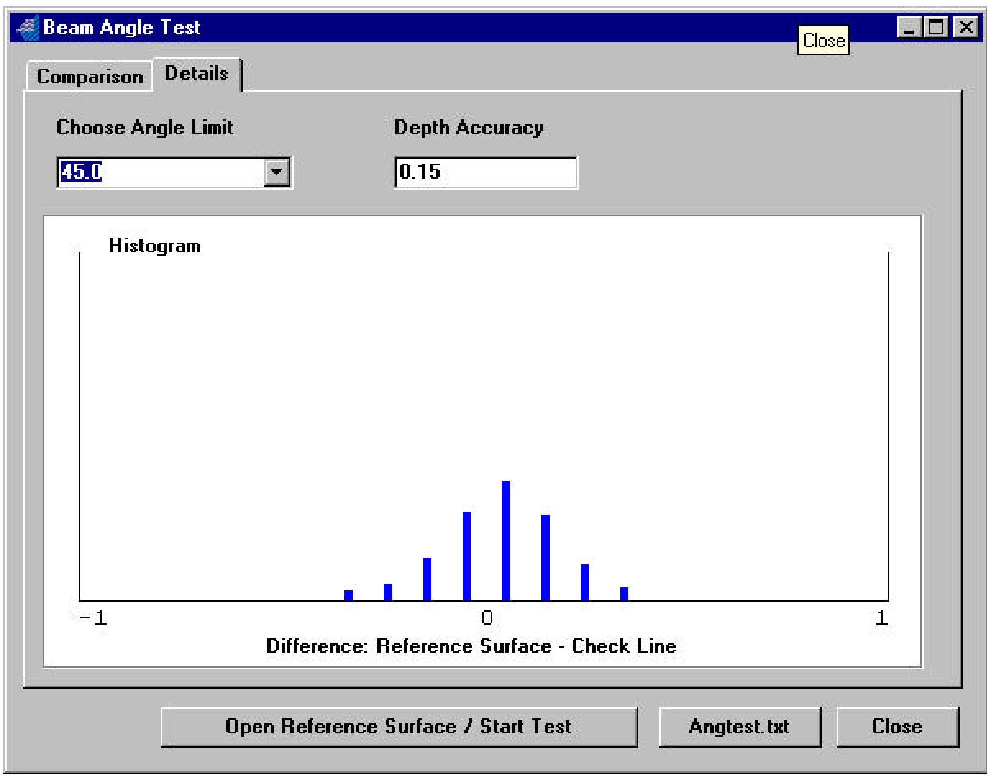


**Figure 11-14. Histogram showing dispersions of performance test against reference surface--at beam angle of 45 deg (Coastal Oceanographics, Inc.)**

## 11-12. Multibeam Data Editing and Processing

Multibeam data is processed and edited on a variety of commercial platforms and software packages--e.g., HYPACK MAX Sweep Editor. Data processing software has now progressed to the point that multibeam data may be filtered, edited, thinned, and binned in real-time; thus eliminating much of the post-processing editing work previously associated with large multibeam datasets. Procedures and guidance in software manuals should be consulted. The procedures used for such data thinning/binning could adversely corrupt or erroneously warp the reduced model, and could impact dredged volume computations. Automated filtering for data spikes must be closely monitored. Data thinning routines must be intelligent in order to maintain the integrity of the topography. Averaging data into bins must also ensure that the basic topography is not compromised. If bin sizes are too large, data may be overly smoothed. Topographic data corruption can also occur if shoal biasing or averaging is used to form bins or cells in a digital terrain model (DTM) or digital elevation model (DEM)--such biasing processes should be avoided. Many of these procedures, and related intelligent data thinning software routines, are being continually updated as new algorithms and performance test techniques become validated.

*a. Data filtering and editing.* Multibeam data typically contains many 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 editing could be performed by viewing each cross-sections and editing out spikes from individual beams. At 40 cross-sections/sec, this is not practical. More commonly, the entire dataset is viewed in 3-D form and data spikes are edited out manually in the 3-D model. This is likewise a labor-intensive process. Spike or data anomaly filtering can also be performed during data acquisition or during post-processing. Such "intelligent" filtering is usually based on setting up maximum data quality or magnitude changes. During this process, data can also be automatically thinned and binned. Final 3-D model review and editing is still recommended. Given the increasing densities of collected multibeam data, coupled with requirements for minimum bin sizes (e.g., 20 cm), automated filtering and editing is the only practical way to process these large datasets.

*b. Binning or gridded depth reduction.* Binning or gridding routines (e.g., HYPACK MAPPER) display a depth in a selected grid cell of a size to prevent overplotting adjacent depths. Although designed for reducing the size of multibeam data, these binning routines may also be used for single beam data as well. Various depth outputs are possible with binned data:

(1) Minimum depth within the cell (e.g., shoal biasing)
(2) Maximum depth within the cell
(3) Average of all depths recorded within the cell
(4) Shot depth closest to the cell center

The shot depth closest to the cell center should be used rather than minimum, maximum, or average options. The "shot" depth option is recommended for USACE navigation and dredging surveys. The average depth over the series can overly smooth the data; however, this may be desirable in some instances. It is not desirable on excavated slopes since the average depth does not correlate with the position. Visual interpolation of analog depth records basically averages the depths nearest the fix event mark and interpolated intermediate points. If averaged depths are recorded, the system software must tag a position with the center of the depth series. This requires some form of on-line position interpolation.

*c. Shoal biased or minimum depth.* The minimum depth recorded within a bin area may be used for some strike detection purposes. However, such biased depths shall not be used for dredging payment surveys, and should be used with caution on navigation project condition surveys. This is due to the relatively high variance in acoustic depth data--see discussion on data accuracy and confidence intervals in Chapter 4. Use of minimum shoal-biased depths can adversely skew dredge quantity computations and erroneously portray clearance data. Shoal biasing can also skew minimum clearance computations on channel condition surveys. Shoals above grade must be assessed based on multiple hits over successive passes--the least depth recorded in a bin is not necessarily the absolute elevation over an object.

*d. Maximum bin size.* Table 11-2 specifies that bin sizes should not exceed 1 meter or 5 meters, depending on the type of bottom. In irregular topography, 5 meters may be too large, and a smaller bin size would be recommended. Bin sizes as small as 20 cm are used for applications where maximum detail is required--e.g., underwater structure surveys.

## 11-13. Summary or Multibeam QC and QA Criteria

Table 11-2 below summarizes criteria for using multibeam systems. The measurement, alignment, calibration tests, and quality assurance procedures and criteria standards are based on procedures currently followed by a variety of government and commercial sources. Multibeam component calibrations and accuracy performance tests must be performed and documented for all surveys. QC and QA performance tests are recommended at beginning of all critical dredging projects, or occasionally on surveys within a project where high quality assurance is required. Depending on documented stability of system, frequency of QC calibrations and QA performance tests may be locally modified from the indicated intervals. Much of the following criteria duplicate single-beam or multiple transducer criteria, so explanations for these items are covered in these previous chapters.

*a. Maximum beam angle.* Beam/swath width should generally not exceed the indicated values, unless independent QA performance test results indicate depth accuracies can be achieved with wider arrays. The beam angle should be reduced for critical object detection or should QA performance test results indicate poor correlation in the outermost portion of the array. Larger beam widths must be recorded to compensate for roll. Excessive footprint size should be avoided by reducing beam width.

*b. Beam overlap*. In navigation projects a 50% side overlap (i.e., 200% bottom coverage) is strongly recommended when sweeping for rock shards or other hazardous objects remaining above project grade. Beam angle should not generally exceed 90 degrees in strike detection work--due to expansion and poorer return from outer beams.

*c. Velocity and bar check calibrations.* Velocity casts should be taken at the indicated intervals. They shall be taken directly in the work area and at a density such that the water column is adequately modeled. A QC Bar Check should be made under the center beam, if feasible. Bar check procedures should follow those prescribed for single- and multiple-transducer systems.

*d. System alignment and patch test calibrations.* Multibeam system alignment checks and Patch tests are performed on an as needed basis; usually when mandatory QA Performance Tests indicate data is not meeting standards. The time interval required between Patch tests is dependent on QA test results -- no specific interval is mandated.

*e. QA performance tests.* Performance tests on multibeam data are absolutely essential and are mandatory. They should be performed at the beginning of each new project, and periodically during a project. The time interval needed between QA performance tests will depend on the consistency of test results. The maximum mean bias computed between two data sets should not exceed the indicated tolerances. The allowable standard deviation is a function of the project depth, as indicated in Table 3-1.

*f. Minimum depth.* Multibeam systems should not be used for dredge measurement, payment, and acceptance purposes in project depths less than those shown in Table 11-2. Exceptions should be requested from HQUSACE (ATTN: CECW-OD).

*g. Maximum survey speed.* Recommended maximum velocities are prescribed to ensure data integrity. Further limitations may be required for multibeam or side-scan systems to ensure 100% or greater forward (along-track) coverage or object detection.

**Table 11-2. Critical Quality Control and Quality Assurance Criteria for Multibeam Surveys**

| | PROJECT CLASSIFICATION | | |
|---|---|---|---|
| | Navigation & Dredging Support Surveys | | Other General Surveys & Studies |
| | Bottom Material Classification | | |
| | Hard | Soft | |
| MULTIBEAM QUALITY CONTROL | | | |
| Maximum beam angle | 90-degrees | 120-degrees | Unlimited |
| Beam overlap | 10%-50% | 10% | N/A |
| Bar check (center) | 1/day | 1/day | optional |
| Alignment calibrations | as reqd | as reqd | as reqd |
| Patch test calibrations | periodic | periodic | periodic |
| MINIMUM PROJECT DEPTH | | | |
| Dredging surveys | > 15 ft | > 15 ft | N/A |
| Condition surveys | > 20 ft | > 20 ft | any depth |
| MAXIMUM SURVEY SPEED | 2-5 knots | 5-10 knots | Unlimited |
| ACOUSTIC FREQUENCY (± 20%) | 200 kHz | 200 kHz | 200 kHz |
| VELOCITY PROBE CALIBRATIONS | | | |
| Perform velocity calibration | > 2/day | 2/day | 2/day |
| Record velocity to nearest | 1 fps | 1 fps | 1 fps |
| Record velocities at maximum every | 5 ft | 5 ft | 5 ft |
| Reject tolerance between checks | 5 fps | 5 fps | 5 fps |
| Location of calibration | At project site | Near project site | Vicinity |
| Perform internal calibration | Weekly | Weekly | Monthly |
| MISCELLANEOUS CHECKS | | | |
| Squat test calibration performed | Annually | Annually | Annually |
| Check vessel draft variations | 2/day | 2/day | 2/day |
| QA PERFORMANCE TEST | | | |
| Requirement | 1/project | 1/project | 3 mos |
| Maximum Outliers | 1 ft | 1 ft | 2 ft |
| Maximum allowable mean bias | < 0.1 ft | < 0.2 ft | N/A |
| Standard deviation (95%) | [ per Table 3-1 ] | | N/A |
| RECORDED DEPTH | | | |
| Dredge payment quantities | Full density shot | Full density shot | N/A |
| B/D or A/D plot | Selected shot | Selected shot | N/A |
| Project condition plot (thinned/binned) | Centroid shot | Shot or minimum | Optional |
| Maximum bin size (quantities) | 1 m | 5 m | as req'd |
| Record depth to nearest | 0.1 ft | 0.1 ft | 0.1 ft |
| ARCHIVED ANALOG DEPTH RECORDS | | | |
| Contracted construction | [ Write-once disc ] | | |
| Project condition surveys | Digital | Digital | Optional |

**Table 11-2. Critical Quality Control and Quality Assurance Criteria for Multibeam Surveys (Contd)**

| | Frequency of Measurement (Minimum) [1] | Calibration Procedure | Allowable Tolerance (95%) | Corrective Action |
|---|---|---|---|---|
| SENSOR ALIGNMENT AND OFFSET MEASUREMENTS: | | | | |
| Transducer | Initial installation | Leveling/Tot Station | 0.5 degrees | Remount |
| Gyro | Initial installation | Self calibration | Manufacturer's specification | Replace |
| Heave/Pitch/Roll | Start of project | Self calibration | 0.1 degree | Remount |
| GPS Antenna | Initial installation | Leveling | 0.1 foot | Remount |
| Squat | Annually | Transit/level/DGPS | 0.1 foot | None |
| Dynamic Draft | As required | Fixed vessel marks | 0.1 foot | None |
| PATCH TEST (RESIDUAL BIAS CALIBRATION): | | | | |
| Pitch | Init Install or Mod | 2 pairs or reciprocal lines on slope | 0.2 feet | apply corr'n in software |
| Roll | Init Install or Mod | 1 pair of reciprocal lines over flat area | 0.2 feet | apply corr'n in software |
| Time Delay (latency) | Init Install or Mod | 2 pairs of reciprocal lines on slope | 0.2 feet | apply corr'n in software |
| Azimuth/Yaw | Init Install or Mod | 2 pairs of adjacent lines over shoal | 0.2 feet | apply corr'n in software |

1. Calibration frequency indicated should not be considered absolute as it is subject to local conditions, such as stability of project area, stability between repeated tests, nature of project, etc.

*h. Acoustic frequency*. The 200 kHz frequency is recommended for most USACE navigation projects; however, different frequency systems may optionally be used if needed for better beam definition or to penetrate suspended sediments in a particular project area. Frequency is not considered as a mandatory criteria.

*i. Velocity calibrations.* Velocity probe calibrations are critical to obtaining high quality multibeam data--especially if beam width is extended. More frequent calibrations may be needed in conditions where temperature or salinity is variable.

*j. Squat tests.* Squat tests should be performed at the intervals indicated.

*k. Recorded depths.* For dredge payment applications, the full multibeam dataset is recommended for clearance and volume computations. Since many newer multibeam systems record far more data than can be plotted or is needed for volume computations, it may optionally be thinned down into rectangular bins (or grids) using standard commercial software routines. The maximum bin size will depend on the application. For dredging measurement, payment, or acceptance, the bin size should be kept as small as possible--typically less than 1 to 5 m is recommended. The shot point depth nearest the bin centroid shall be used; not average or minimum, or shoal-biased depths. Bin size may be increased for smooth, soft bottoms.

## 11-14. References

*a*. Field Procedures for the Calibration of Shallow Water Multibeam Echo-Sounding Systems, André Godin, Canadian Hydrographic Service, February 1996.

*b*. HYPACK MAX User's Manual, Coastal Oceanographics, Inc., Middlefield, CT., www.coastalo.com, May 2000.

*c*. Multibeam Surveying Workshop Proceedings, U.S. Army Corps of Engineers and NOAA Surveying, Mapping, and Remote Sensing Conference, St. Louis, MO, 19 Aug 1997.

*d*. Trimble HYDROpro Navigation Software Manual, Trimble Navigation Limited, Sunnyvale, CA, http://www.trimble.com

*e*. American Congress on Surveying and Mapping (ACSM), ACSM-ASPS-MAPS-MARLS 2000 Workshop Program, Hydrographic Surveying, Little Rock, AR, 21 March 2000 (Shallow Water Multibeam Systems for NOAA Hydrographic Surveys)

## 11-15. Mandatory Requirements

The policy outlined in paragraph 11-4 (USACE Multibeam Policies, Procedures, and Applications) is considered mandatory. All calibration, QC, and QA criteria summarized in Table 11-2 are mandatory.