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.

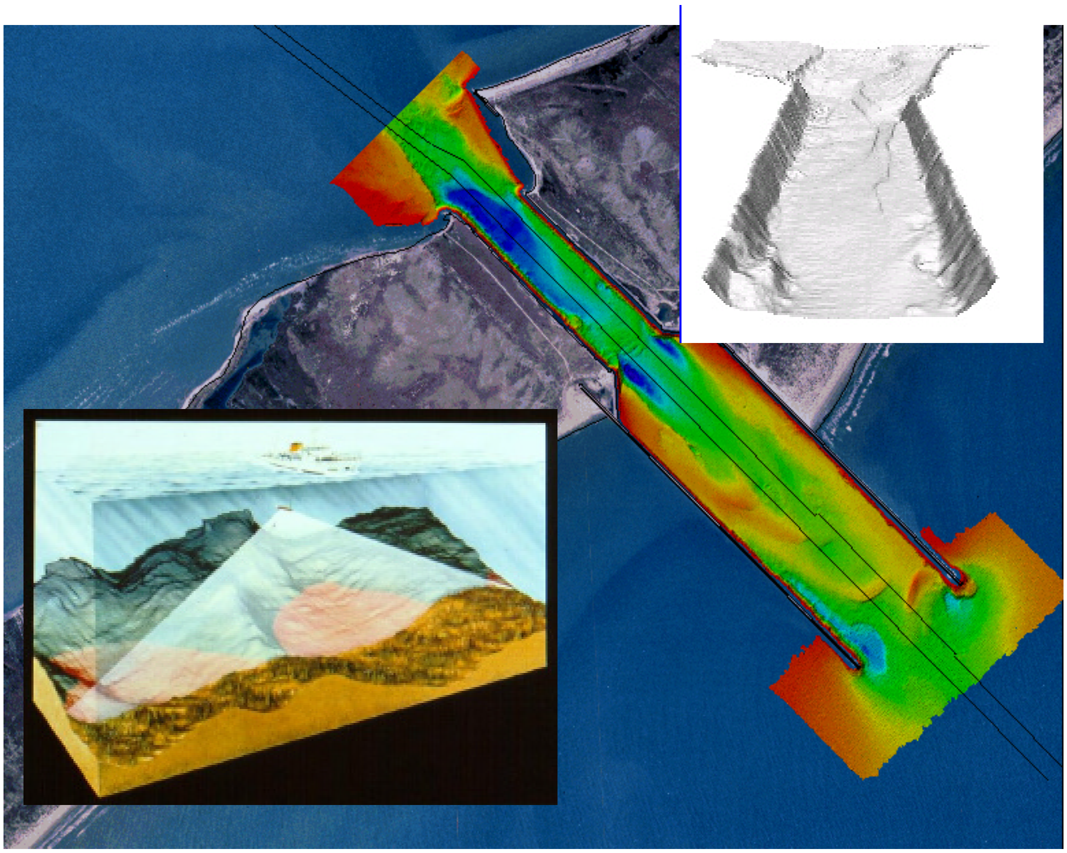


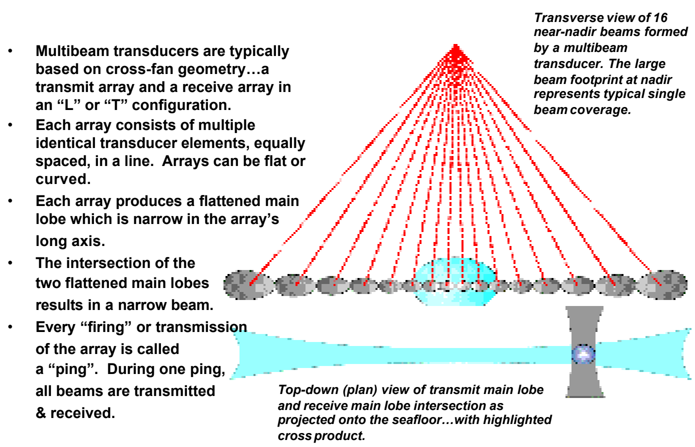
Figure 11-1. Full-coverage multibeam survey of coastal inlet navigation project (Galveston District)

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 the 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, forms 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 that 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.



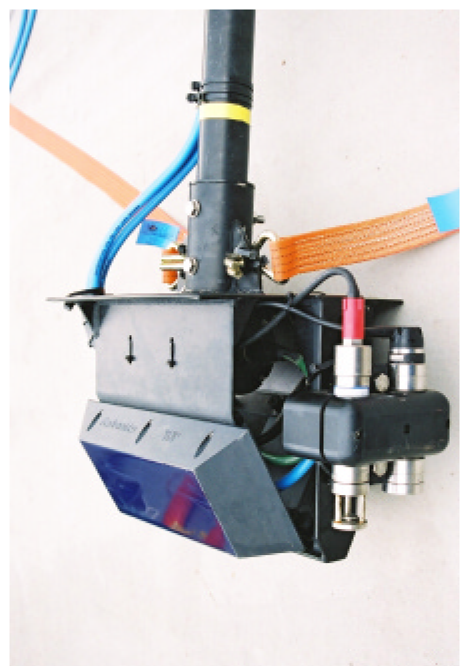


Figure 11-2. Multibeam geometry (NOAA) and typical transducer array configuration (GeoAcoustics, Inc.)

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.

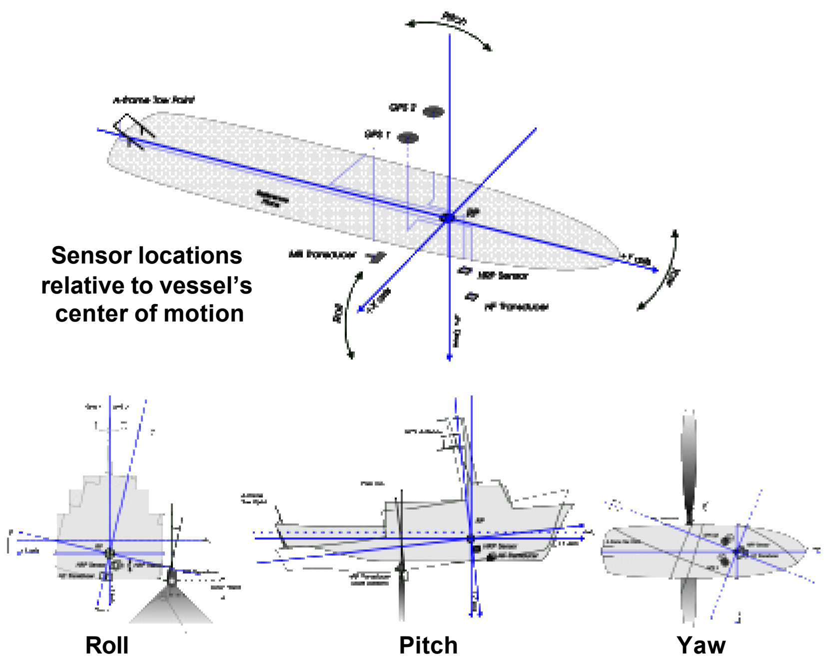


Figure 11-3. Multibeam offsets, roll, pitch, and yaw (NOAA)

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.

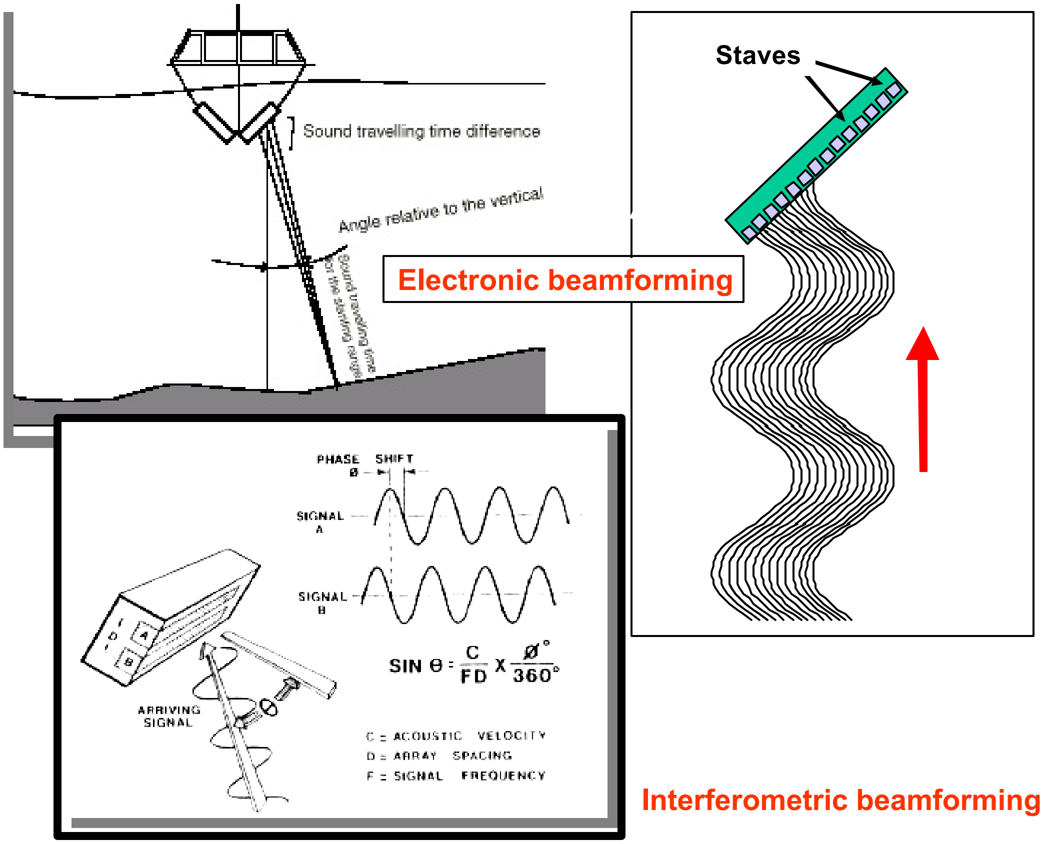


Figure 11-4. Beam forming methods in multibeam systems (Odom Hydrographic Systems and University of New Brunswick)

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 multibeam systems 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 System's 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.

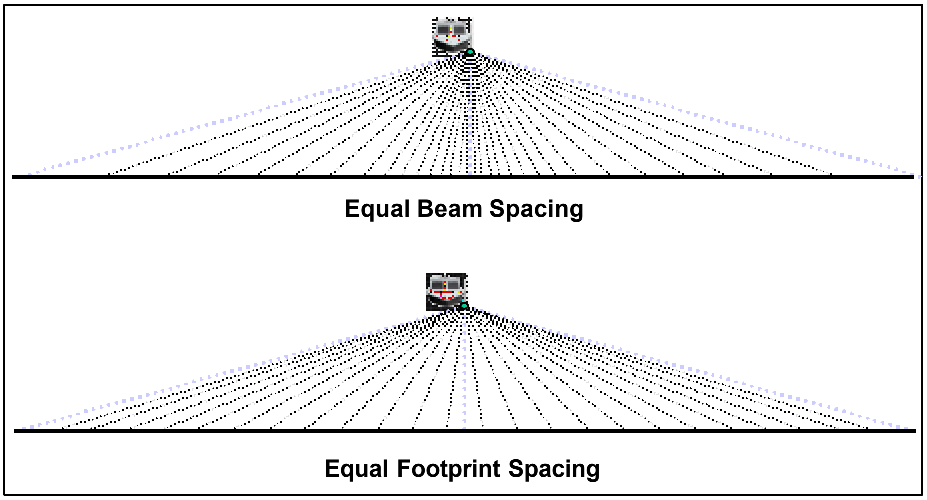


Figure 11-5. Equal footprint spacing using electronic and interferometric beamforming (Odom Hydrographic Systems)

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 (4) 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 two 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 30 profiles/sec, some 2,000 to 3,000 depths/elevations per second are generated; resulting in a large database 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 and coastal engineering 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 delineate the feature or structure. Multibeam sensors can be configured to detail pipelines, bulkheads, floodwalls, lock walls, revetments, breakwater riprap, and other similar underwater structures. Systems can be configured (or the transducer rotated) to provide up to 190-deg coverage, which would provide "water's-edge to waters-edge" coverage to both port and starboard. In some narrow projects, a single swath pass may provide full coverage.

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 should compute pay quantities using the densely populated digital terrain models (DTM) generated by swath survey data. Data sets should be thinned 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 generally 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 and/or binned volume quantities do not differ from raw data set quantities. In effect, data thinning should be kept to an absolute minimum. Actual dredged quantities should be computed from the binned 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 should 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 should 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 considering procurement of multibeam systems should internally determine that such a system represents an effective and efficient utilization of floating plant, given the $200 K to $500 K investment for a complete system. Some factors that should be evaluated include: (1) proposed multibeam vessel, (2) system configuration (hardware and software), (3) estimated annual utilization (time and location), (4) FTE allocations, (4) system operator qualifications, (5) field data processing, editing, and plotting, and turnaround capabilities, (6) estimated daily plant and survey crew rental rate, and (7) comparative analyses between hired-labor and contract costs.

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 are 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 multibeam 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 multibeam was needed for several reasons. The first of which was to provide for better surveys of the District's channels. The multibeam 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--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 multibeam system was to survey the various breakwaters within the Buffalo District to check for needed repairs. The multibeam 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 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 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 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.

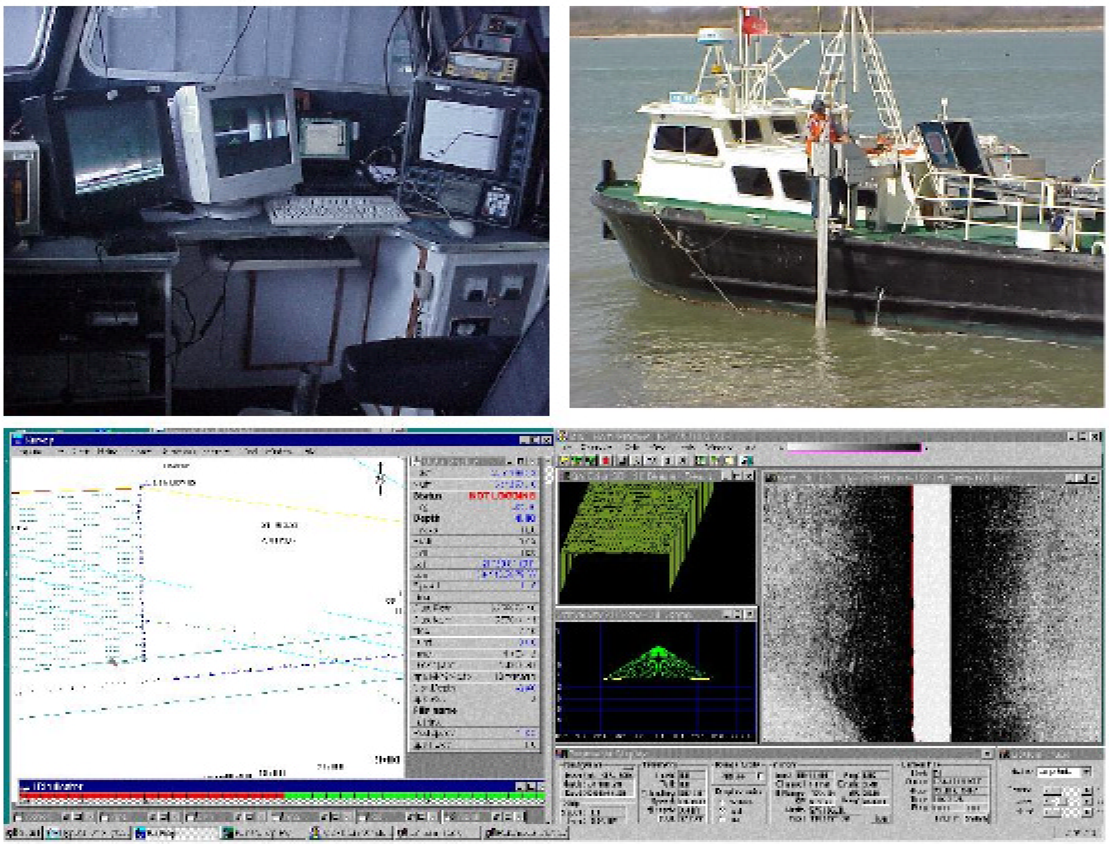


Figure 11-8. Surveyboat Vollert Odom Multibeam installation and typical real-time display (Galveston District)

l. Data collection hardware/software. Navigation, data collection, and data processing software employed with multibeam systems should have real-time guidance, display, and quality assurance assessment capabilities. The software should 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 support dredging contract administration. Software should 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 workstations in order to adequately display and replay 3D imagery in real-time. CADD data thinning or binning routines should 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.

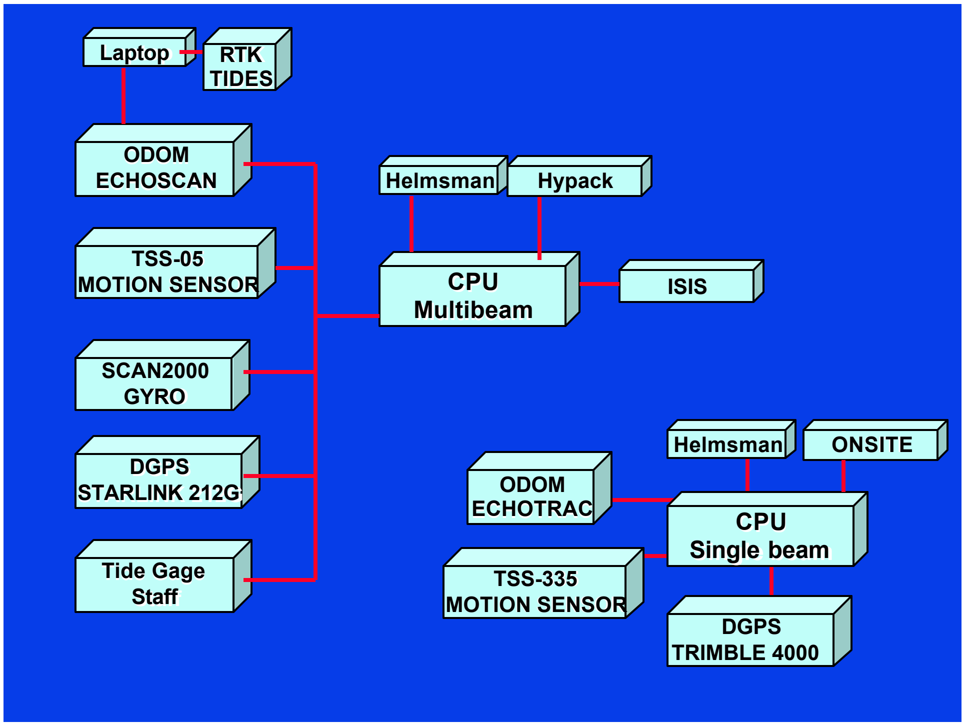


Figure 11-9. Multibeam system configuration (Surveyboat Vollert, Galveston District)

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. General. The following sections in this chapter provide recommended technical guidance for performing system alignments, quality control calibrations, and quality assurance tests of multibeam sonar systems used on Corps dredging and navigation projects.

b. Background. Field alignment and calibration requirements for multibeam systems are similar to those required for single beam systems described in Chapter 9. However, some calibration and quality control procedures for multibeam systems are more critical and demanding than those required for single beam echo sounders. Periodic, precise calibration and verification testing is absolutely essential in order to assure multibeam derived elevations meet the prescribed accuracy tolerances for the project--especially near the outer beams of the array where refractive ray bending and vessel alignment and motion variations can significantly degrade the data quality. With improved resolution and increased beam coverage, there is a greater need for accurate sensors to ensure that the recorded sounding is reduced to its correct position on the sea floor. This is accomplished by interfacing the multibeam system with position and attitude sensors, such as: (1) a high accuracy differential GPS system (including heading and attitude RTK systems), (2) inertial motion reference units (MRU) to monitor changes in position, velocity, acceleration, heave, pitch, and roll, and/or (3) a gyrocompass. In addition, the time synchronization for all these components is critical. For this reason, the system accuracy is comprised not only of the multibeam sonar accuracy but also the various components that make up the total system.

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

(2) Quality assurance performance tests are periodically performed to compare independently surveyed multibeam swaths and/or single beam runs made over the same area. A performance test will provide a statistical estimate of the data accuracy (or "repeatability" if the comparative surveys are not truly independent). The test results should be checked against the prescribed statistical accuracy criteria in Table 3-1.

c. QC and QA requirements. Procedures for performing these calibration and quality assurance tests are outlined in the following sections of this chapter and are more fully detailed in the manuals provided with the individual sensors making up a multibeam survey system. These include acoustic refraction measurements (i.e., velocity casts and bar checks), system latency calibrations (time variances between positioning, depth, and motion sensors), vessel motion and heading sensor calibration (roll, pitch, yaw, and heave sensors), and various other vessel alignment and coordinate/datum corrections. A summary of recommended measurement and calibration requirements is contained in Table 11-2 at the end of this chapter. Some of these calibration requirements are critical--failure to perform adequate calibration may render a survey invalid. Since many of the alignment and offset parameters are interrelated, failures at one level of test may require recalibration and/or retesting prior levels. Some calibrations are performed during initial equipment installation on the vessel; however, others must be performed on a more frequent basis--especially when dredging measurement and payment surveys are involved. It should be strongly emphasized that the software and procedures for calibrating, processing, editing, and thinning multibeam data are still being refined and will undergo modifications as new systems are acquired and performance is validated. Likewise, the overall accuracy and object detection performance capabilities of multibeam systems are still being assessed.

11-6. Initial Installation Alignment and Static Offset Measurements

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

a. Static offsets of the sensors. These are the distances between the various sensors and a designated reference point on the vessel. This entails physical measurement on the vessel platform--locating the relative X-Y-Z coordinates of the multibeam transducer, GPS antenna(s), gyrocompass, MRU sensor, POS/MV system, etc. These measurements should be performed with the vessel stabilized on a trailer or on blocks where more exact, stable measurements can be made. A total station and/or tape are used to obtain the measurements. The sensors should be measured from a reference point in the vessel. 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 for 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.

b. MRU Sensor. If possible, the inertial MRU sensor should be placed on the centerline of the vessel as close as possible to the center of gravity or the intersection of the roll and pitch axes of the vessel. (Some MRU 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 MRU should match the x-axis of the transducer. Azimuthal misalignment of the MRU will result in the depth measurements being in error proportional to the water depth. Misalignment of the MRU sensor in yaw causes a roll error when pitching, and a pitch error while rolling. (If the transducer and MRU are collocated (e.g., Odom Echoscan), many alignment corrections become far less critical).

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

(1) Most multibeam transducers used on smaller (e.g., less than 30 foot) USACE vessels are mounted over-the-side on a shaft and boom device. Most Corps 65-foot vessels have permanent hull-mounted transducers. Other larger vessels have retractable transducers. Some smaller survey vessels are outfitted with retractable bow-mounted transducers. 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 MRU 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.

d. Gyroscope. The electronic gyroscope should be aligned with the x-axis of the vessel using an electronic total station and geodetic control points. This can be done with the vessel on a trailer or secured tightly against a pier where there is minimal wave action. The gyro should be warmed up and, if necessary, the proper corrections for latitude applied. Locate two points on the centerline of the vessel and position a target on each of them. Observe the two targets with the total station and synchronize the readings with the gyro readings. Several readings will be needed for redundancy. Compute the vessel's azimuth and compare with the gyro readings. Compute the mean and standard deviation of the readings. If the offset is more than 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.

e. MRU 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 MRU 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 Oceanographics' 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.

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

11-7. Vessel Squat/Settlement and Draft Variations

a. *Squat/Settlement measurement*. The combined squat and settlement of the vessel should be measured at several speeds and a look-up table produced for correcting the transducer draft. (Refer to procedures outlined in Chapter 9). This measurement is essential since a MRU will not measure the long-term change in elevation. A MRU heave sensor will record the sudden change in elevation but the measured heave will drift back to zero. The settlement can be measured with a transit on shore and a 2-meter level rod or stadia board on the vessel positioned over the MRU 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.

b. *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 MRU sensors (10 Hz and 100 Hz, 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.

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

d. *Short term draft measurements.* Changes in vessel draft due to fuel or loading changes should be monitored throughout the day, and depth corrections applied if trim variations are significant. These procedures are identical to those described for single beam surveys (Chapter 9). Heave corrections output from RTK and/or MRU systems must be monitored to ensure long-term sea swells or vessel turns do not bias the data.

11-8. 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 11-10) must be performed carefully to ensure that subsequent survey data collected is accurate and reliable. The Patch test determines (and provides correctors for) the following residual biases:

- pitch offset
- roll offset
- positioning time delay (latency)
- 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.

a. Data acquisition. Survey quality code or (preferably) carrier phase DGPS positioning 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. In practice, multiple runs should be made to average (and assess the long-term repeatability) of the computed bias parameters. 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:

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

where:

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

b. Positioning time delay test and pitch bias test. Two pairs of reciprocal lines are run at different speeds to check for biases in both positioning time delay (latency) and pitch bias. Latency is determined from runs made over the same line in the same direction, but at differing speeds. (Both 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. The greater the difference in velocity, the more accurate the test. Pitch is determined from the runs made over the same lines at the same speed in opposite directions.

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. At least two adjacent parallel pairs of reciprocal lines shall be run normal to a prominent bathymetric feature such as a shoal or channel side slope, in shallow water. Do not use a feature with sharp edges such as wrecks since there is more ambiguity in the interpretation. The adjacent lines 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.

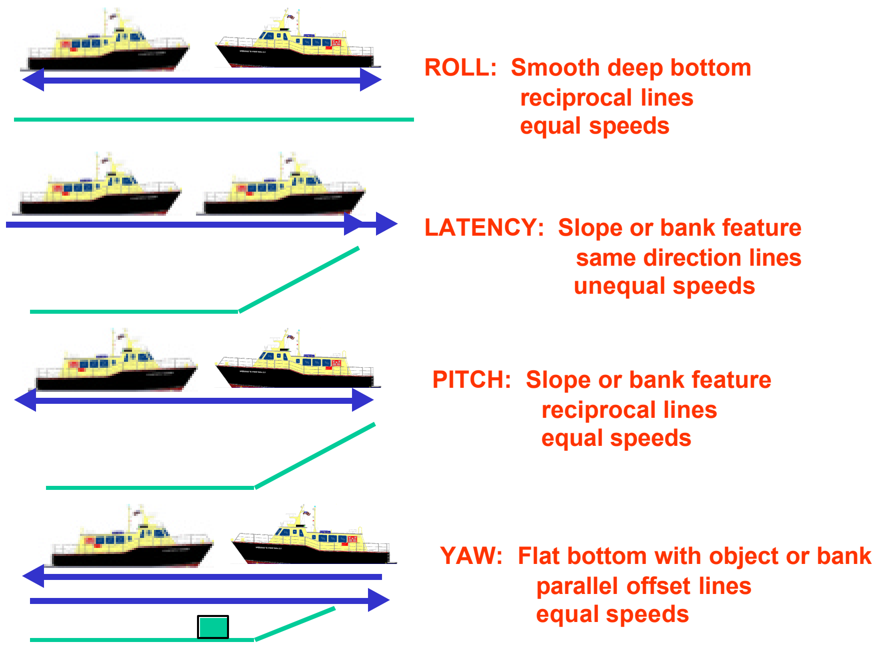


Figure 11-10. Summary of patch test runs

e. 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 sequence recommended below. Note that this differs from the sequence recommended by Coastal Oceanographics: roll-latency-pitch-yaw. Since a single run Patch Test may contain internal inaccuracies due to positioning, inadequate depth, poor feature recognition, etc, it is recommended that the test be performed over different conditions and times in order to arrive at an average, longer term, correction. 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.

(1) Positioning time delay (latency) bias. This delay is computed by measuring the along-track displacement of soundings from the pair of coincident lines run at different speeds over the steep slope or other prominent topographic feature. Lines run in the same direction should be used to avoid the effect of pitch offset errors. The equation to compute time delay is:

$$TD = d_a / (v_h - v_l)$$

(Eq 11-2)

where:

- TD = time delay in seconds
- d_a = along-track displacement (ft)
- v_h = higher vessel speed (ft/sec)
- v_l = lower vessel speed (ft/sec)

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.

(2) 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 (in degrees) can be computed using the following equation:

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

where:

- a = pitch offset (bias angle)
- 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.

(3) 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 (in degrees) can be obtained from the following equation:

$$y = sin^{-1} [(d_a /2) / X_I]$$

(Eq 11-3)

where:

- y = azimuthal offset (deg)
- d_a = along-track displacement (ft)
- X = relative across track distance for beam i (ft)

The survey lines are processed with only the positioning time delay, 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.

(4) Roll offset bias. Roll bias is computed using the pairs of reciprocal lines run over a flat, deep area. Generally, this offset is the most critical in deeper water and should be carefully measured. For small angles of less than three (3) deg, the roll offset can be estimated by the following equation:

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

where:

r = roll offset (deg)
d_z = depth difference (ft)
d_a = across-track distance (ft)

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 along track direction	Average of displacements in along track direction	Average of displace in across track direction	Average of displacements in across track direction
VISUAL METHOD	Match profiles and contours	Match profiles and contours	Match profiles and contours	Match profiles and contours

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

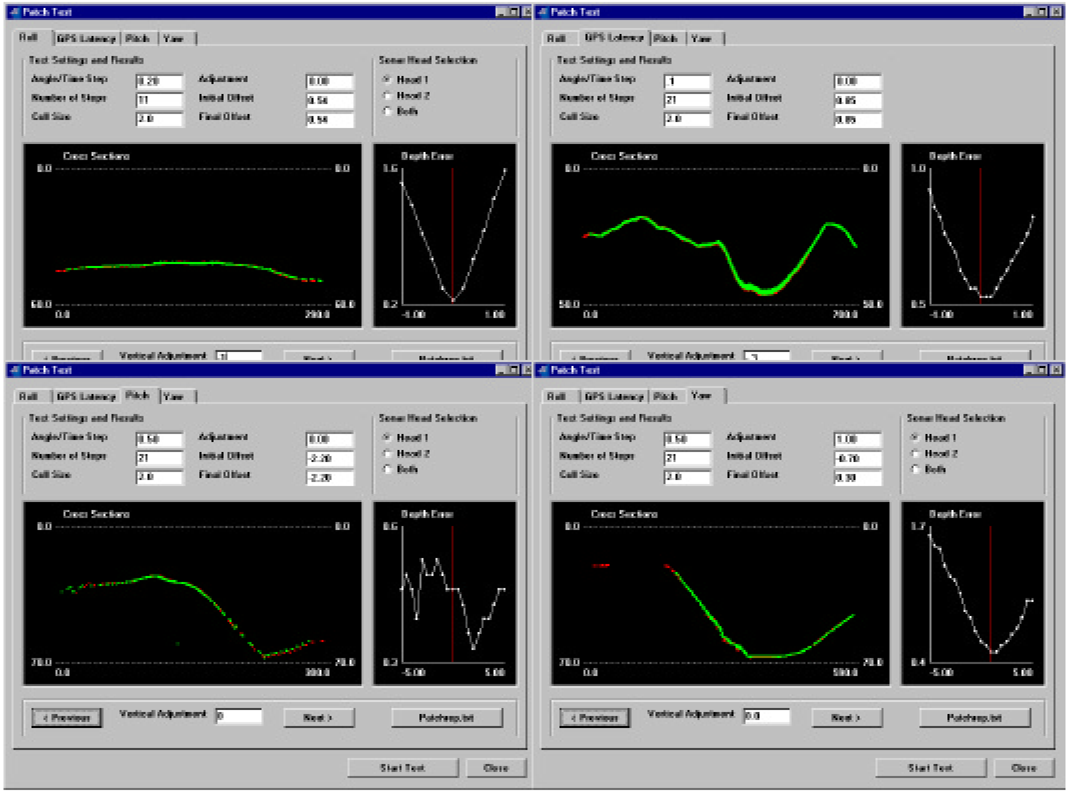


Figure 11-11. Automated Patch Test parameter computations--roll, latency, pitch, and yaw. (Coastal Oceanographics, Inc.)

11-9. Velocity Measurements

As in single beam systems, the velocity of sound in the water column must be accurately known so the correct depth can be measured. However, in multibeam systems, velocity measurements are more critical due to the effects of refraction ("ray bending") in the outer beams. Since sound velocity in the water column can vary spatially and temporally, improper or inadequate determination of sound velocity corrections can render multibeam data unusable. Velocity calibrations should be performed periodically during the day, and no less than twice per day, and at more frequent intervals or locations if physical changes in the water column (e.g., temperature, salinity) are affecting data quality. Some multibeam systems (e.g., GeoAcoustics, Inc. GeoSwath System) incorporate continuous near-surface velocity meters in the transducer head—see Figure 11-2). The quality of velocity data may be subsequently assessed through use of the "Performance Test" which compares overlapping survey data models. Beam angles should be reduced 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.

11-10. Vessel Draft and Index Measurements (Bar Checks)

As in single beam systems, a bar check represents the "reference standard" by which multibeam echo soundings are calibrated. Upon initial installation, and periodically thereafter, a traditional bar check should be performed to calibrate the multibeam draft and index corrections and verify velocity corrections (from velocity meter casts) are accurate. The frequency of this calibration is a function of the results, the stability of the system, and the nature of the survey. If periodic bar checks verify the draft/index corrections are holding constant, then less frequent checks are needed--perhaps every few months. Multibeam bar checks are performed similarly to single beam bar checks. The check bar may likewise be coated with foamed material to more nearly simulate actual bottom conditions (reflectivity).

a. Nadir beam bar checks. Bar checks are performed under the center beams to quantify any draft or index errors in the system. As stated above, these need only be done on an infrequent basis, depending on the long-term stability of the results. This calibration is identical to that performed for single beam transducers (Chapter 9). Figure 11-12 depicts a typical bar check over a portion of the multibeam array. See also reference 11-14 c.

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

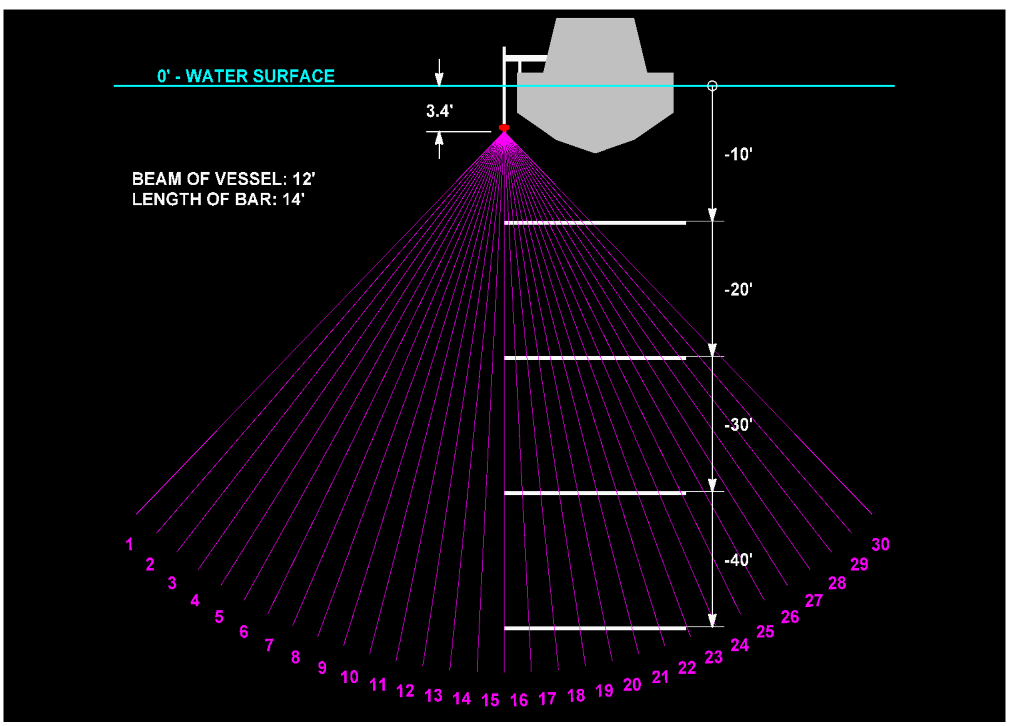


Figure 11-12. Standard bar check of a multibeam system (Galveston District)

11-11. Beam Width Restrictions on Multibeam Systems

The coverage of multibeam systems is a function of swath width and water depth. Most systems provide coverage of two to approximately seven times the water depth. The number of individual beams (and footprint size) within the swath array varies with the 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. Thus, the recommended maximum beam limits in Table 11-2 are contingent upon some type of quality performance check to verify the adequacy of the entire array. Depending on various factors, primarily velocity and bottom reflectivity variations, it may be necessary to restrict beam widths to less than the recommended limits shown in Table 11-2. (There are known cases where multibeam arrays had to be restricted to ± 22.5 deg due to poor data quality outside these limits).

11-12. Quality Assurance Performance Test (Overlapping Models)

A performance test is used to evaluate the quality and confidence of multibeam data being collected. This test typically compares overlapping data sets from two different multibeam surveys--performed either by the same vessel or by different vessels. This test may also be performed by comparing multibeam data with that collected by another single beam or multiple transducer echo sounder--obtained by either the same vessel or different vessels. Other comparison test methods are also used, such as matching multibeam bathymetry of a flooded Corps lock chamber against topographic data measured in the same lock chamber during a dewatered state. Object detection capabilities may also be verified by sweeping over simulated objects of known size; placed either in open water or in controlled lock chambers.

a. Purpose. The purpose of a performance test is to obtain an <u>estimate</u> of the accuracy (or repeatability) of a multibeam system throughout its entire swath. These accuracy estimates can then be compared with the minimum standards in Table 3-1. This test also partially checks the parameters and biases that were measured and computed during the previously described QC calibrations (velocity profile calibrations, Patch Test bias parameters, etc). If performed over different tidal phases, it may also detect poor tidal modeling in the survey area.

b. Frequency of performance tests. Tests should be conducted before a critical dredging measurement and payment survey project; however, they are not needed prior to individual surveys in that project. For non-navigation surveys, performance tests may be conducted weekly, monthly, quarterly, or less frequently, depending on the long-term stability of the results, known variations in different project areas, etc. Performance tests should also be conducted upon equipment installation or modification. Performance test data reduction, processing, and statistical analysis should be performed in near real-time--i.e. on board the survey boat.

c. Undetected biases. Performance tests conducted by the same vessel, the same multibeam system, and over a short tidal time period, are not truly independent but are only an assessment indicator--a constant bias in the system could go undetected. A more truly independent performance test is obtained when comparison surveys are run at different tidal phases, using different multibeam and single beam systems, by different vessels, in different locations, and differing sea state conditions. However, this type of ideal test is not practical in actual Corps practice--typically, a performance test is done at the beginning of the day before the pre/post dredge survey is run. In this case, the test more properly indicates a level of "repeatability" in the data--see Chapter 4. Some of the biases that may not be detected when the same vessel and multibeam system is used in a performance test include:

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

(2) Draft errors due to undetected loading variations.

(3) Tide/stage modeling errors. When the comparison test is performed at the same time (tidal phase), errors in the tidal model will not be detected. However, performing the test at the same time will indicate the multibeam system is outputting quality data, independent of any tidal modeling errors. Performing the comparison tests at both the same and different tidal phases is strongly recommended, in that the independent quality of the multibeam system can be checked separately from any biases in the tidal model. As was discussed in Chapter 4, errors in the tidal model can represent the major portion of an error budget for an individual depth measurement, and can easily mask the errors in the multibeam system. If performance test biases are small (< 0.05 ft) when run at the same tide phase, and large when tested over different times/phases, then a tidal modeling problem is indicated. No amount of multibeam QC calibration or QA testing will rectify this modeling error--the only practical solutions are to correct the tidal model or utilize RTK direct elevation solutions (which also require appropriate geoidal and tidal modeling corrections).

(4) Bottom reflectivity. A constant depth error due to signal processing biases may be detected by comparing different portions of the array, multibeam systems, frequencies, etc. Variations can also occur in the outer beams due to differences in amplitude and phase detection processing. In addition, any index variations due to reflectivity differences between the bar check and actual bottom will not be detected.

Given the above, obtaining an absolute performance confidence test on a multibeam system is not a simple task. However, since use of the same vessel (and survey system) is recommended for all USACE measurement and payment surveys on a project, the performance test will yield a good estimate of the data repeatability and confidence, and indirectly the accuracy of any pay yardage derived from a survey. This presumes any undetected biases are constant (and hopefully small) for both pre and post dredge surveys.

d. Reference and Check Surface development. The procedure described below compares a "check line" multibeam dataset with a "reference surface" dataset complied from narrowly spaced multibeam data using only near-center beam data. The "reference surface" derived from independent vertical single beam data could also have been used, provided a reasonably dense single beam model is obtained. Failure of the performance test survey to meet the recommended tolerances in Table 3-1 and Table 11-2 requires corrective action--i.e., remeasurement, recalibration, patch testing, etc.

(1) Reference surface (Figure 11-13). This is essentially a small survey run over an extremely flat area (less than 1 ft gradient) in water depths of not more than 100 ft. A flat bottom area minimizes the effect of positional errors on the test. It represents the "baseline" area. Four or five parallel lines are run with at least 150% bottom overlap--i.e., 25% sidelap. The line spacing must be close enough to ensure that the inner beams overlap enough to give redundant data. The beams outside a 45-60 deg swath width should be removed prior to editing. After these lines are run, four or five parallel lines are run perpendicular to the previously run lines with the same swath and overlap. The speed over the ground should be the same on both sets of lines. A velocity cast should be made in this area and the corrections applied. All the edited data in the Reference Surface are then binned at 1 ft x 1 ft cell sizes. The data in each cell are then thinned using the average depth of all the depths in a cell.

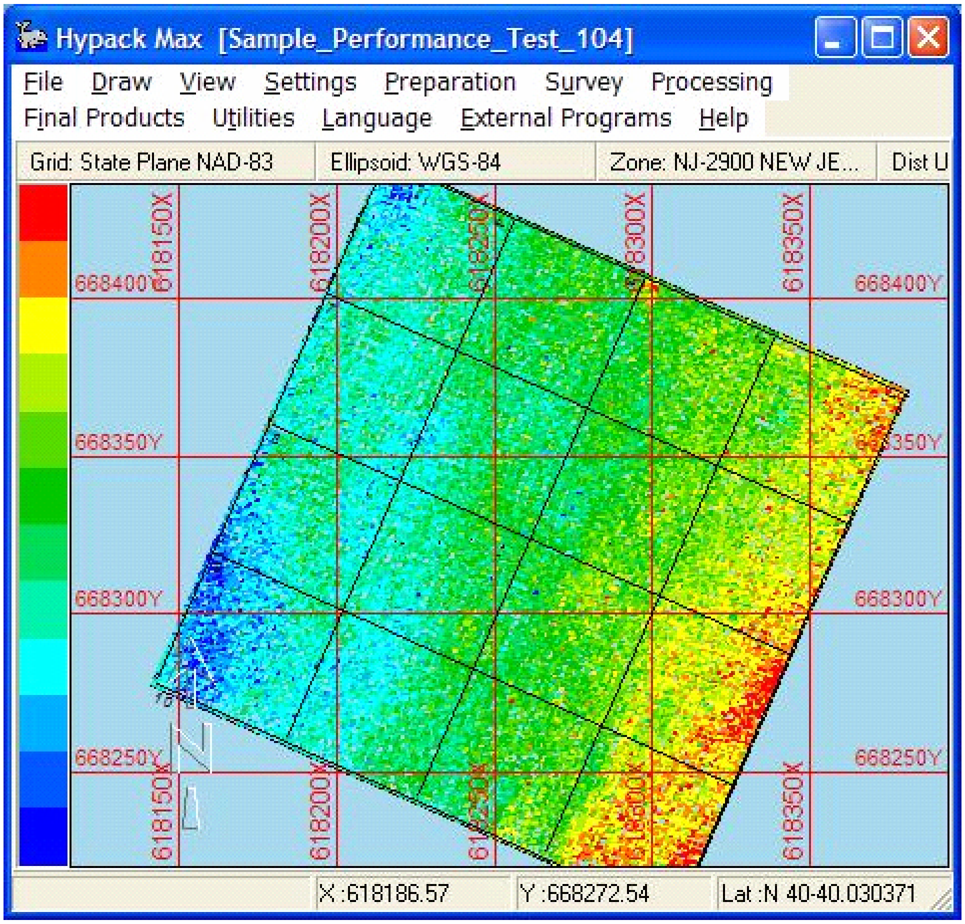


Figure 11-13. Color-coded Reference Surface binned into 1 ft x 1 ft cells. Five multibeam lines were run in each direction and combined to make up the Reference Surface (Coastal Oceanographics, Inc.)

(2) Check lines. Multibeam "Check Lines" will be run such that the full beam array can be tested against the Reference Surface. At least two perpendicular multibeam swath lines should be run inside the reference surface. The vessel speed is the same as for the reference surface. Ideally, a more independent test is obtained when the Check Lines are additionally surveyed at a different time and tidal phase from that of the Reference Surface survey; however, this is not always feasible in practice. (Another alternative is to run single beam Check Lines--either from the same vessel or another vessel-- to compare with the multibeam Reference Surface). The beam width of the Check Lines is not restricted so that the data quality in the outer parts of the array can be assessed. A difference surface between the Reference Surface and the Check Line surface can also be created and statistics computed to assess overall performance. From these differences, the corrections to the system can be checked against the criteria recommended in Table 3-1 (and Table 11-2). Software vendors have developed programs that will automatically perform these statistical assessments.

e. Data processing and analysis. Performance test data processing and analysis should include assessment of the following statistical parameters:

- *Outliers.* Depth differences between the Check Line surface and Reference Surface are computed at each beam point along the Check Line array. They can be visually displayed in a histogram as shown in Figure 11-14. 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 maximum allowable bias value in Table 11-2 (and mandated in Table 3-1). 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 (e.g., MRU alignment) or vertical tide/stage corrections (see paragraph c above). 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; typically well less than 0.05 ft, and well within the relatively liberal 0.1 ft and 0.2 ft allowable tolerances in Table 11-2 (Table 3-1) which factor in assumed uncertainties in the tidal model. The example test in Figure 11-15 shows biases computed at various beam angle widths. This type of plot should be used to determine the maximum beam width that should reliably be used.

- *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. Some 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, as is shown in Figure 11-15.

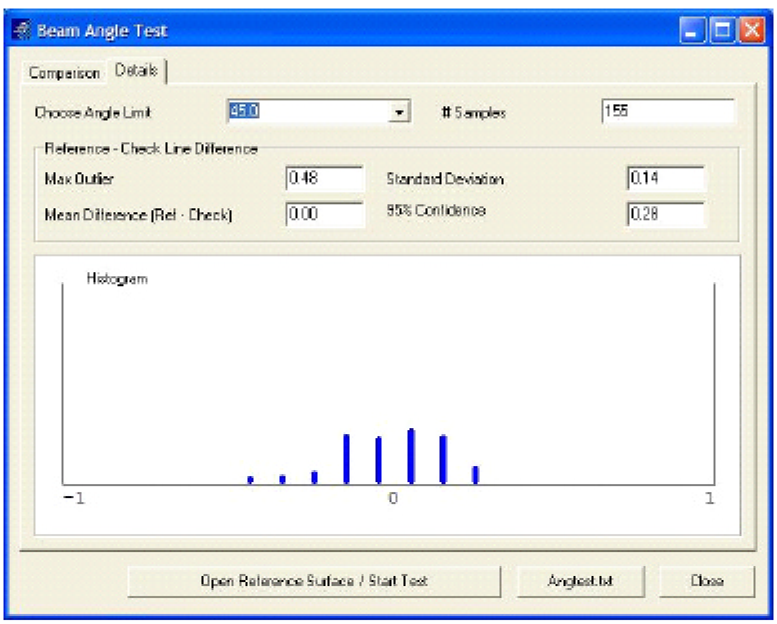


Figure 11-14. Statistical results of a Performance Test with Check Line beam angle width of ± 45 deg. Histogram shows dispersions and outliers (- 0.48 ft maximum). No bias was present and the 95% confidence was ± 0.28 ft. (Coastal Oceanographics, Inc.)

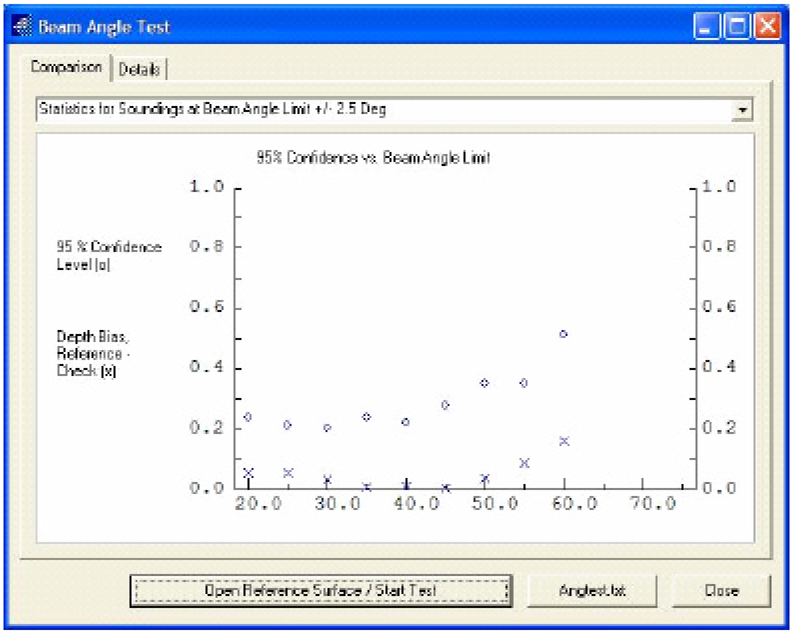


Figure 11-15. Plot of statistical bias and confidence results at various beam angles widths. Note that bias and confidence degrades beyond ± 45 deg, indicating data should not be used outside a full 90 deg swath width. (Coastal Oceanographics, Inc.)

f. Sample performance test calibration--Philadelphia District (Surveyboat 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 following tables.

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 can also be tabulated as shown below. This report is generated by the Beam Angle Test section of HYSWEEP multibeam processing program MB Max.

± 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

The results of the above sample Performance Test indicate the multibeam system is providing reliable data out to a ± 75 deg beam width. However, the relatively large constant biases of + 0.1 ft between the two surveys might be questioned and further evaluated as to the cause. If this test had been performed for a payment survey on a rock cut project, then these large biases would have exceeded the 0.1 ft allowable tolerance in Table 11-2.

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

11-13. Multibeam Data Processing--Editing, Filtering, Thinning, and Binning

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. It is important that data filtering, thinning, and binning processes do not adversely corrupt or erroneously warp the reduced model, potentially biasing 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 matrixed 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 is used to form bins (or cells) in a digital terrain model (DTM) or digital elevation model (DEM)--any such biasing processes should be used with caution. 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. Editing and filtering data. Multibeam data typically contains many noise spikes that must be edited out of the database. Filtering and editing can be done in real-time, in post-processing, or in combination. Manual editing could be performed by viewing each cross-section and editing out spikes from individual beams. At 40 cross-sections/sec, this is not practical. More commonly, the entire dataset is viewed in 3D form and data spikes are edited out manually in the 3D 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 3D model review and editing is still recommended. Given the increasing densities of collected multibeam data, coupled with requirements for small bin sizes, smart use of automated filtering and editing has become a practical way to process these large datasets.

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

11-14. Depth Selection Options

Once raw data points are collected within their given positional cell, the multiple depths within each cell may be thinned to a single representative depth for that cell. Binning or gridding routines (e.g., HYPACK MAPPER) provide options to thin multiple depths within a cell. Although designed for reducing the size of multibeam data, these binning routines may also be used for single beam data as well. Various representative depth outputs are possible with binned data:

- Minimum depth within the cell (e.g., "shoal biasing")
- Maximum depth within the cell
- Average (or mean) of all depths recorded within the cell
- Median of all depths recorded within the cell
- Shot depth closest to the cell center

Each of the above depth selection options has advantages and disadvantages. On dredge measurement and payment surveys where multiple passes are made, a small (e.g., 5 ft x 5 ft) cell could contain, say, 5 to 50 data points, from which a single representative (i.e. "thinned") depth must be selected. One of these points could be a noise "spike" that passed the processing filter described above. The average of 50 depths within the cell may not be representative if the cell is too large and shoaler depths within the cell are obscured by the average. Likewise, the shot depth nearest the cell center (centroid) may not be representative. Therefore, selecting a bin size and representative thinned depth for a given project is a complex task and should be based on experience with specific project applications. Recommended maximum bin sizes and depth selection options are given in Table 11-2 for this purpose. In addition, for most surveys, the X-Y coordinate origin of the grid matrix must be specified so that different processors will obtain the same results from a given dataset.

a. Shot Depth. For most applications, the "shot depth" closest to the cell center is used to best represent the terrain. This is because some of the other options can significantly bias the terrain representation if the cell sizes are too large, resulting in a false depiction of the true bottom condition (and dredged quantities). Statistically, a shot depth selection represents the best option for depicting datasets in that no inherent biases are produced in thinning the data. (Use of an unthinned raw dataset is, in effect, nearly unbiased; however, the size of the raw dataset may be too large for efficient quantity computations). The position of the shot depth is typically shifted to the X-Y coordinates of the center of the cell.

b. Average (mean) depth. The "average depth" option can overly smooth the data if cell sizes are too large; however, this may be desirable in some instances. If cell sizes are kept relatively small, then the average depth can be a good representation of the bottom condition; and will represent a consistent, equitable payment method in dredging surveys. "Average" depths within a small, fixed bin size are recommended for computing dredged quantities--see Table 11-2. If bin sizes are set too large, then averaged depths may not be desirable on excavated slopes. (Visual interpolation of analog depth records on single beam surveys, in effect, averages the depths nearest the fix event mark. If single beam averaged depths are recorded, the system software must tag a position with the center of the depth series--requiring some form of on-line position interpolation).

c. Median depth. The median depth of all depths in a cell will generally be nearly equal to the average depth when a large number of depths fall within the cell. When only one or two depths are contained within a cell, the median depth is identical to the average depth. The median depth may be superior to the average depth if noise spikes have not been adequately filtered out. For example, in a cell containing three depths (6 ft, 7, ft, and 17 ft), the median depth would be 7 ft but the average depth (10 ft) is biased due to the 17 ft spike.

d. Shoal-biased or minimum depth. The minimum depth recorded within a given area has often been used for strike detection, dredge clearance, and controlling channel depth purposes. NOAA uses these minimum recorded or "shoal-biased" depths on nautical charts as a form of safety factor. Shoal-biased depths for Corps construction applications should be used with caution unless multiple "confirmed hits" are recorded within a bin, and/or between adjacent bins over a given area. Use of minimum shoal-biased depths can adversely skew dredge quantity computations and erroneously portray clearance depth data. Raw shoal biasing can also skew minimum clearance computations on Channel Condition Surveys or on tabular Channel Condition Reports. Shoals above project 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. This is due to the relatively high variance in acoustic depth data--see discussion on data accuracy and confidence levels of assessing multiple hits in Chapter 4. Automated software has been developed to perform this "multiple hit" analysis within each bin, and output bins containing depths with "confirmed" hits above a specified grade.

e. Maximum depth. There are few USACE applications for processing maximum depths in a project.

11-15. Plotting Representative Depths in Plan

When individual depths are plotted on a traditional plan drawing at some fixed scale (e.g., 1 in = 200 ft), the method by which a particular depth is selected from a dense multibeam dataset is a difficult process. This was not a problem with older lead line or single beam survey methods--data were recorded at 25 ft or 50 ft intervals and could be easily plotted on a 1 in = 100 ft or 1 in = 200 ft drawing scale (without any need for thinning or binning). With multibeam data points being collected at 1 ft sq or smaller densities, it is impossible to portray the data at any reasonable or realistic two-dimensional hard copy drawing scale. The entire raw or binned dataset of individual depths, or equivalent three-dimensional terrain models, can be easily viewed on computer displays. However, as long as traditional hard copy drawings of plotted depths are required, then standardized procedures must be developed for plotting representative depths from the large multibeam database.

a. Selecting representative depths. Selecting a representative depth to depict on a plan drawing entails selecting a plot cell size that is large enough to prevent overlapping plots but small enough to represent the condition and still be readable at the plot scale. For example, at a scale of 1 in = 200 ft, a minimum cell size would be roughly 40 x 40 ft square to 50 x 50 ft square in order to avoid overlapping depth plots. Such a large cell size could contain hundreds of multibeam data points; thus the single representative depth that is selected for the plot may not be representative of the overall cell and may represent less than 1% of the total data points that were collected. For this reason, plan drawings of representative depths should not be used for dredge clearance or volume computations--far smaller bin sizes are needed for such purposes. Plan drawings used in contract plans and specifications, dredging as-built surveys, disseminated project condition surveys, etc., should clearly indicate the depth selection option used, and whether or not this is a biased selection.

b. Contour or color-coded plots. As an alternative to traditional 2D plan view plots of individual depths, contour or color-coded point 2D plots or 3D models may be used to better depict project conditions. This allows use of the entire edited (or binned) dataset. Any of the above depth selection options may be used, depending on the purpose of the survey. Thus, even at a 1 in = 200 ft plan scale, nearly all data points can be adequately represented by point color or contour plot.

11-16. Recommended Bin Sizes and Depth Selection for USACE Navigation Surveys

The following paragraphs contain guidance on maximum bin size and depth selection for all types of navigation surveys as defined in Chapter 3, to include: dredging measurement & payment surveys, dredge clearance/acceptance surveys, plans and specifications surveys, project condition surveys, and other related navigation surveys. This guidance is based on over five years of collective multibeam data processing experience by the Districts within the North Atlantic Division, and some other USACE Districts. These recommended standards may be included, either directly or by reference to this manual, in dredging contract specifications. The intent of this guidance is to provide a consistent standard throughout USACE for processing multibeam data and computing dredge payment. These same criteria may also be applied, with some modification, to multiple transducer boom sweep systems and single-beam systems. The recommended bin and depth selection standards in the following subparagraphs are summarized in Table 11-2 at the end of this chapter, under the section "Recommended Depth Selection and Data Processing/Thinning Bin Matrix Limits" at the end of the table.

[Note that "selected representative shot, average, or minimum depths" referred to in the following sections are derived from the entire <u>edited</u> multibeam dataset. This implies that extraneous noise spikes have been filtered or manually edited out of the raw dataset before binning is performed.]

a. Recommended Maximum Bin Size. For a "hard" bottom material classification (as defined in Chapter 3), a 3 ft x 3 ft cell size is specified. For a "soft" bottom material classification, a 5 ft x 5 ft cell size is specified. Evenly spaced 3 ft or 5 ft grid matrices shall be generated over the full dataset relative to a fixed origin point to ensure that different individuals (or software) processing the same edited dataset will obtain identical results--e.g., dredged quantities.

b. Depth Selection Method for Dredging Volume Computations. The "average depth" of all depths within each 3 x 3 ft or 5 x 5 ft cell should be used as the representative depth for the cell. The horizontal location of the representative average depth is the cell center or centroid. The representative average depths are used to generate rectangular digital terrain models (DTM) or trapezoidal triangulated irregular network (TIN) models from which dredge volume computations are computed in CADD routines using all the bins in the edited dataset matrix. If optional average end area volume (AEA) computations are performed in soft material by generating simulated cross sections through the full DTM or TIN model, cross sectional spacing shall be kept small so that AEA approximation errors are minimized. For example, a 5-ft cross-section spacing is far more accurate than a 100-ft spacing, and will better approximate the volume derived from a full TIN model computed using CADD differencing routines.

c. Plotting Selected Depths on Dredging and Navigation Surveys. For generalized plan drawing portrayals of a project condition, plans & specifications, or dredging progress survey, a "shot" depth taken from randomly selected bins provides the most unbiased representation of the pre- or post-dredged bottom condition. Shot depths are randomly selected from the edited 3 x 3 ft or 5 x 5 ft bins. As outlined in Section 11-15 above, only a small percentage of the depths in the dataset matrix can be shown on typical plan drawing scales used in USACE (e.g.,, 1 in = 100 ft). Plan drawing CADD note block layers/levels should clearly state that the generalized plotted depths are not representative of the full dataset, and that the plotted depths shown should not be used for channel clearance or volume computations; and also noting that the original binned dataset should be (or was) used for such purposes.

d. Contour or Color-coded Plots of Dredging and Navigation Surveys. Use all "shot" depths in the edited dataset matrix to generate contour or color-coded plots.

e. Navigation Surveys--Strike Detection or Minimum Channel Clearance. For strike detection or dredge clearance/acceptance purposes, multiple "hits" on strikes or shoals above a specified grade are required. Typically, the specified grade is the "Required Grade" although an overdepth grade or supergrade could also be used. Multiple confirmation sweep passes are always recommended for channel clearance surveys in that strikes above grade detected from different sweep aspects helps to minimize the possibility of noise spikes creating false strikes on a single pass. The representative "shoalest depths" are used to generate "strike plots" depicting project areas remaining above grade, and the possible need for additional excavation.

(1) Confirmed hits. The multiple "hits" may be obtained on a single sweep pass or from multiple sweep passes over a suspected shoal/strike area. A recommended USACE standard of three (3) hits is specified to represent a "confirmed" hit. The "hits" above grade are determined by assessing "minimum" edited depths recorded in a cell, or from a series of adjacent cells. Three confirmed hits within either 3 x 3 ft or 5 x 5 ft cell sizes are used; however, adjacent cells may need to be assessed if only sporadic hits occur in a single bin.

(2) Strike Plots--plotting minimum hits above grade in plan. If many shoals/strikes exist in bins over a small area, then the processing software will have to select the most representative (e.g., highest/shoalest) confirmed strike to plot for this area--to avoid overplotting depths at the plot scale. If contour or color-coded depth plots are generated, then all the minimum confirmed hits can be easily represented in plan or 3D format.

f. Reports of channel conditions (EP 1130-2-520--ENG Forms 4020-R and 4021-R). Tabular reports of controlling minimum depths in a channel reach are, in effect, large bins encompassing a wide breadth of the channel over its entire length. Reducing hundreds of thousands of recorded multibeam depths in this "bin" down to a single representative "minimum controlling" depth requires some type of standardized process. For example, in a 400 ft x 5,000 ft channel reach, the minimum depth shown for each channel quarter represents a 100 ft x 5,000 ft bin, or a 500,000 sf area. A "shoal biased" depth selection option is typically selected to represent the minimum depth over such a large reach. Unless the dataset is evaluated based on a "confirmed hit" type of analysis, a single anomalous and unrepresentative noise spike could end up being the falsely reported controlling depth for the entire channel reach. Reported controlling minimum depths should be truncated to the nearest whole foot, as shown in EP 1130-2-520. Channel Condition Reports are intended to report a minimum (safe) clearance depth based on the latest survey (Post dredge, Project Condition, etc.). If an additional clearance "safety factor" is desired, then the representative depth could be rounded up to the nearest whole foot using the NOAA 0.7 ft truncation rule.

(1) Standards for Reports of Channel Conditions. For assessing minimum clearances over an entire project reach (e.g., Channel Condition Reports), "minimum confirmed" depths above grade should be used. Tabular reports of channel conditions should be generated similarly to Strike or Clearance detection above. Depths are binned from the edited dataset using either 3 x 3 ft (hard material) or 5 x 5 ft (soft material) cell sizes. The "shoalest depth" of all depths in the cell is used as the representative depth for the cell; provided that there are a minimum of three (3) confirmed hits above project grade in the cell; or in an area between adjacent cells when the cells themselves are sparsely populated. The controlling minimum depth within a channel reach is then selected by analyzing all the cells in the given reach and selecting the individual cell with the minimum "confirmed" depth above grade. Automated software has been developed to perform this analysis over a channel reach.

(2) Plotting or tabulating only selected "minimum confirmed" depths (or worse, "unconfirmed" minimum recorded depths) on a Project Condition Survey that accompanies a tabular Channel Condition Report is a biased representation of the true project condition. Survey plots depicting only minimum (shoal-biased) depths should never be used for dredging plans and specifications since significant constant biases may be present. Plan drawings (or CADD files) of Project Condition Surveys should clearly note the depth selection option used.

g. Other General Surveys and Studies. There is no specified maximum bin size or depth selection method for other types of non-navigation surveys that are defined in Chapter 3. Bin sizes may be varied depending on the type of bottom or purpose of the project (e.g., beach sand transport studies, hydraulic studies). In smooth, flat areas, bin sizes may be expanded to any level that will adequately depict the terrain. Bin sizes as small as 1 ft sq may be used for applications where maximum detail is required--e.g., underwater structure surveys. Instead of binning, more efficient data thinning methods may be used to generate a TIN model for 3D analysis. Any of the representative depth selection options may be used, although the "shot" depth is recommended for most applications to avoid biasing the data.

11-17. Contract Specifications for Multibeam Measurement and Payment

The following contract clauses are recommended when multibeam systems are used on dredge payment or acceptance surveys. This version was developed by the North Atlantic Division Multibeam User's Group (Reference 11-18f).

> Measurement and Payment. The total amount of material removed and to be paid for under the contract, will be measured by the cubic yard in place. Measurement of the number of cubic yards in place will be made by computing the volume between the bottom surface shown by soundings of the last survey made before dredging and the bottom surface shown by the soundings of surveys made as soon as practicable after the work specified in each acceptance section has been completed. The volume for measurement will include the material within the limits described in the Paragraph entitled: "OVERDEPTH AND SIDE SLOPES', less any deductions that may be required for misplaced material described in the Paragraph entitled: "DISPOSAL OF EXCAVATED MATERIAL" of this section. The volume of material removed will be generated by using either the Average End Area Method or by the TIN (Triangulated Irregular Network) computation, as outlined in the Hydrographic Surveying Manual EM 1110-2-1003, dated 1 January 2002, and subsequent changes/revisions issued by HQUSACE. All depths obtained from single beam surveys will be utilized for volume computation purposes. If multiple vertical transducer sweep systems or multibeam survey technology is used, a 5-foot by 5-foot matrix using the average depth of all depths recorded in a cell will be generated from the edited multibeam data to perform the TIN volume computations, following the procedures outlined in EM 1110-2-1003. Any corresponding plotted plan view sounding sheets depicting representative depths over a dredging project will be generated using a cell size that is plot-scale dependent, utilizing a

randomly selected sounding that is closest to cell center (shot depth) shifted to the center of the cell from the edited multi-beam data, as described in EM 1110-2-1003. If the material to be dredged in the contract is categorized to be hard bottom, the matrix used for the volume computations will be reduced to a 3 foot by 3-foot matrix and an average of the soundings in the cell will be used. Shoal or strike plots depicting material above the required dredging grade will be generated using confirmed minimum depths in accordance with the data processing procedures outlined in EM 1110-2-1003. All raw survey data and edited/processed binned data used for volume computations shall be available to the Contractor upon request.

Hydrographic Survey Equipment. Hydrographic surveys will be conducted to meet USACE minimum accuracy standards defined in Table 3-1 of EM 1110-2-1003 (Hydrographic Surveying). Surveys will be performed by single vertical beam transducer, or multiple vertical beam transducer sweep, or multibeam sweep methods. When vertical single beam or multiple sweep beam transducers are employed, an acoustic frequency of [200 kHz (± 20%)] *[*or insert alternate frequency*]* will be used. When utilizing multibeam technology, the operating acoustic frequency will range from [180 kHz to 250 kHz] *[*or insert alternate frequency*]*. All depth measurement devices will be calibrated following the procedures outlined in EM 1110-2-1003.

11-18. Multibeam Technical References

The following publications provide additional technical information on the use and calibration of multibeam systems.

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

b. HYPACK MAX User's Manual and Annual HYPACK Conference Training Notes, Coastal Oceanographics, Inc., Middlefield, CT., www.coastalo.com, (latest edition).

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).

f. US Army Corps of Engineers, North Atlantic Division Multibeam User's Group Conference Reports, 2002 (New York District) and 2003 (Philadelphia District).

g. GeoAcoustics, Inc. GeoSwath Product Information Bulletin, November 2002, Cypress TX.

11-19. Mandatory Requirements

All calibration, QC, and QA criteria summarized in Table 11-2 are recommended unless otherwise indicated as being mandatory. These updated criteria supersede QC, QA, and procedural criteria in other chapters of this manual.

11-20. Summary or Multibeam QC and QA Criteria

Table 11-2 below summarizes criteria for conducting multibeam surveys. The measurement, alignment, calibration, quality assurance, and data processing criteria are based on procedures currently followed by a variety of government and commercial sources; and especially from actual USACE experience on dredging projects (Reference 11-18f). For some criteria, references are provided to their applicable sections in this chapter. Since some of the criteria in Table 11-2 duplicate single-beam criteria, explanations for these items are referenced to sections in Chapter 9.

a. Frequency of tests and checks. QC and QA checks, calibrations, and other tests are recommended at beginning of all critical dredging projects, and on all surveys where high quality assurance is required (e.g., a project clearance survey in dispute). Depending on documented stability of a system, and user experience and confidence, the frequency of calibrations and performance tests may be locally modified from the indicated intervals.

b. Calibration, QC, and QA documentation. Project or contract files must contain documentary evidence that all calibration and performance 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, bar checks, squat calibrations, tide/stage observations, performance test results, etc. Original records of such calibrations should be retained in a permanent, bound surveyor's field book aboard the boat.

c. Other Surveys and Studies. Specific criteria for multibeam surveys outside navigation projects are not listed in Table 11-2. It is recommended that the general QC and QA procedures for dredging surveys be followed. For general underwater topographic surveys, many of these requirements can be significantly relaxed based on user experience with a particular system. This would include unlimited beam width restrictions and far less frequent calibrations. However, for detailed underwater structural investigations, more demanding criteria than that shown in Table 11-2 might be warranted.

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys

Criteria		PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	Soft	Section Reference and Notes
QUALITY ASSURANCE PERFORMANCE TEST				Mandatory Calibration (Table 3-1) Reference Section 11-12
Perform Calibration		1/project	1/project	Test should be performed at the beginning of each new project (e.g., a pre or post dredge survey), and periodically during a longer-term project, such as a Project Condition Survey. The time interval needed between QA Performance Tests will depend on the consistency of test results.
Perform comparison with different vessel multibeam and/ or single beam		Periodically	Periodically	
Location of test		at project site	at project site	
Perform tests over same and different tidal phases		Recommended	Recommended	Tests should be conducted over same and different tidal phases to check for tidal model biases. Reference 11-12c (3).
Maximum outliers between data set comparison points		1 ft	1 ft	
Maximum bin size for comparison data sets		1 ft sq	1 ft sq	Use averaged depth in bin for Reference Surface
Maximum allowable mean bias between data sets		< 0.1 ft	< 0.2 ft	The maximum mean bias computed between two data sets should not exceed the indicated tolerances (repeated from Table 3-1). Reference 11-12e.
Resultant Elevation/Depth Accuracy	Depth (d)			
	(d<15 ft)	± 0.5 ft	± 0.5 ft	Standard Deviation (at 95%)--computed from Performance Test results (repeated from Table 3-1). Reference 11-12e and Chapter 4.
	(15>d<40 ft)	± 1.0 ft	± 1.0 ft	
	(d>40 ft)	± 1.0 ft	± 2.0 ft	
POSITION QUALITY ASSURANCE CHECK		1/day	1/project	Mandatory Calibration (Table 3-1) Check different DGPS beacons, known point, etc. Reference Chapter 7, Table 7-1

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Continued)

Criteria	PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	 Soft	Section Reference and Notes
SOUND VELOCITY CALIBRATION			Mandatory Calibration (Table 3-1) Reference Section 11-9 and Chapter 9, Section 9-10
Perform velocity probe calibration	> 2/day	2/day	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. More frequent calibrations may be needed in conditions where temperature or salinity are variable, or where Performance Test data indicates large variances are present.
Location of calibration	In project site	In project site	
Record velocity to nearest	1 fps	1 fps	
Record velocities in water column every	5 ft	5 ft	
Perform internal (distilled water) probe calibration	Weekly	Monthly	Reference Section 9-10.
BAR or BALL CHECK ON CENTER (NADIR) BEAM	Quarterly	Quarterly	Mandatory Calibration A QC Bar Check should be made as near to the nadir beam as possible. This periodic check shall be used to verify/calibrate any index or draft error in the system. Reference procedures outlined in Sections 9-7, 9-8, and 9-9.
SQUAT TEST CALIBRATION PERFORMED	Annually	Annually	Mandatory Calibration Reference procedures in Sections 9-11 and 11-7.
PLATE CHECK ON OUTER BEAMS	Daily	Daily	Perform before each survey as QA "blunder" check Reference Section 11-10b.
RECORD SHORT TERM VESSEL DRAFT VARIATIONS	2/day	2/day	Reference procedure in Sections 11-7d and 9-12

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Continued)

Criteria	PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	 Soft	Section Reference and Notes
OBJECT DETECTION CONFIDENCE CHECK (for specialized search surveys)	Daily	Daily	Reference procedures in Chapter 12 Similar to side scan confidence check Verify hits on multiple passes over object
MAXIMUM BEAM ANGLE	90-deg	90-deg Meas & Pay Surveys 120-deg Proj Cond Surveys	Reference Section 11-11 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 may be further reduced for critical object detection--due to footprint expansion and poorer return from outer beams--or should QA performance test results indicate poor correlation in the outermost portion of the array.
BEAM OVERLAP	50%	10%	Reference Sec. 6-7 (Density of Data & Line Spacing) 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. Two or more overlapping passes on different aspects of the beam are recommended in shoal areas--to confirm hits above grade.
MAXIMUM SURVEY SPEED	2-5 kts	5-10 kts	Recommended maximum velocities are prescribed to ensure data integrity and minimize latency errors. 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. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Continued)

Criteria		PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	 Soft	Section Reference and Notes
INSTRUMENT ALIGNMENT/OFFSET MEASUREMENTS				Reference procedures in Section 11-6
Measure Antenna-Transducer-Inertial system relative coordinates to nearest		0.05 ft	0.05 ft	Alignment measurements are performed on installation or change of equipment.
PATCH TEST BIAS CALIBRATIONS				Reference procedures in Section 11-8
Perform test		periodically	periodically	The time interval required between Patch tests is dependent on Quality Assurance Performance Test results -- usually when mandatory QA Performance Tests indicate data is not meeting standards . No specific interval is mandated.
Patch Test Bias Resolution				Based on user experience, patch test bias corrections may be averaged over a long series of Patch Tests, rather than using the results from a single test. See Section 11-8e.
	Roll	0.1 deg	0.1 deg	
	Pitch	1 deg	1 deg	
	Yaw	1 deg	1 deg	
	Latency	0.1 sec	0.1 sec	
HEAVE CORRECTIONS (MRU)				
Measure heave to accuracy of		0.2 ft	0.2 ft	or 5% of heave amplitude, whichever is less
MRU/RTK update rate at least		20 Hz	20 Hz	

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Continued)

Criteria		PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	 Soft	Section Reference and Notes
MISCELLANEOUS CRITERIA				[Refer also to applicable single-beam criteria in Section 9-12]
MINIMUM PROJECT DEPTH (Dredging Surveys)		> 15 ft	> 15 ft	Reference Section 11-4a. Multibeam systems are recommended for dredge measurement, payment, and acceptance purposes in project depths greater than those shown.
ACOUSTIC FREQUENCY (+ 20%)	Nominal	200 kHz	200 kHz	Reference Section 9-3d (200 kHz standard frequency)
	Project Option	[< 20 KHz to > 500 KHz]		The nominal 200 kHz frequency is recommended for most USACE navigation projects; however, different frequency systems may optionally be used if needed for better beam definition on objects (e.g., 450 KHz) or to penetrate suspended sediments in a particular project area (e.g., 24 KHz). The same frequency should be consistently used for a specific project and specified in dredging contracts. See Section 9-3d.
ARCHIVED DIGITAL AND/OR ANALOG DEPTH RECORDS				
Contracted construction		[Write-once disc]		Reference Section 9-4d. Entire raw data file should be retained similarly to single-beam requirements. Retention of side scan data also recommended.
Project condition surveys		Digital	Digital	

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Continued)

Criteria	PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	Soft	Section Reference and Notes
RECOMMENDED DEPTH SELECTION AND DATA PROCESSING/THINNING BIN MATRIX LIMITS			*[Reference Sections 11-13 through 11-16]*
Dredging Measurement & Payment Surveys and Project Condition Surveys (including those used for contract Plans & Specifications)			
Bin/Cell size--Recommended maximum	3 ft sq	5 ft sq	The X-Y coordinate origin of the matrix must be specified. Reference Section 11-16a.
Depth Selection--Method used to select representative depth from multiple depths in a cell for use in volume computations	Average of all depths in 3x3 cell	Average of all depths in 5x5 cell	Average depth is truncated to nearest 0.1 ft and located at the cell centroid X-Y coordinate. Reference Sections 11-16b.
Volume computation method	Full DTM/TIN binned matrix	Full DTM/TIN binned matrix AEA optional	Volumes should be computed using the selected representative depths from the entire 3 x 3 or 5x 5 ft sq dataset matrix. AEA cross section spacing should be kept as small as possible. Reference Sections 11-16b.
Depth Plot (Plan)--Method used to select depths from cell matrix for a generalized hard copy display of individual depths/elevations	Randomly selected 3x3 ft cells containing representative shot depth	Randomly selected 5x5 ft cells containing representative shot depth	Density of plotted data dependent on output drawing scale. Plotted depths are generalized representations of the full multibeam dataset and should not be used for quantity computations. Shot depth may be shifted to center of 3x3 or 5x5 ft cell. Reference Section 11-16c.
Contour or Color-Coded Plot-- Method used to select depths from a cell matrix for generating contours or DTM color-coded plots	Use all 3x3 cells containing representative shot depth	Use all 5x5 cells containing representative shot depth	Full edited database used. Reference Section 11-16d.

Table 11-2. Recommended Minimum Quality Control and Quality Assurance Criteria for Multibeam Surveys (Concluded)

Criteria	PROJECT CLASSIFICATION Navigation & Dredging Surveys Bottom Material Classification Hard	 Soft	Section Reference and Notes
RECOMMENDED DEPTH SELECTION AND DATA PROCESSING/THINNING BIN MATRIX LIMITS (Continued)			*[Reference Sections 11-13 through 11-16]*
Dredge Clearance & Acceptance Surveys (Shoal/Strike detection) and Minimum Channel Clearance Condition Reports			*Surveys using “minimum” or “shoal biased” depths shall NOT be used for Plans & Specs or volume computations.*
Depth Selection--Method used to select representative “shoalest” depth from multiple depths in a cell	Shoalest of 3 confirmed depth hits above project grade in 3x3 cell	Shoalest of 3 confirmed depth hits above project grade in 5x5 cell	Individual cells must be assessed to determine multiple hits above grade. Reference Section 11-16e.
Number of confirmed "hits" above grade required per cell	3 hits	3 hits	Based on a single pass or multiple passes. Hits on multiple passes provide better confidence. Reference Section 11-16e(1).
Depth Plot (Plan)--Method used to select plotted depths from cell matrix for a generalized hard copy display of the shoalest individual depths above grade	Selected 3x3 ft cells containing representative shoalest confirmed depth	Selected 5x5 ft cells containing representative shoalest confirmed depth	Density of selected cells that can be plotted dependent on output drawing scale. Reference Section 11-16e(2).
Contour or Color-Coded Plot-- Method used to select depths from cell matrix for generating contours or DTM color plots	Use all 3x3 cells containing representative shoalest depth	Use all 5x5 cells containing representative shoalest depth	Full edited database matrix used. Reference Section 11-16e(2).
Tabular Report of Channel Conditions (ENG Form 4020/4021) Method used to select minimum controlling depth for channel reach	Least recorded depth in 3x3 ft cells containing representative shoalest confirmed depth	Least recorded depth in 5x5 ft cells containing representative shoalest confirmed depth	Select least controlling depth from all the cells contained over a given channel reach. Selected controlling depth should be shown on plan of condition survey if submitted. Reference Section 11-16f.
Record minimum controlling depth to nearest	1 ft	1 ft	Reference EP 1130-2-520 (Chapter 2)