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Field Calibration Procedures for Multibeam Sonar Systems

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Multibeam sonar systems are the latest advancement in hydrographic surveying technology. These systems consist of a transducer, motion sensor, gyrocompass, and navigation system. Reliable data can only be acquired after proper calibration has been performed on the system as a whole. This calibration begins with the alignment and static offsets of the sensors referenced to the centerline of the vessel and the transducer. The alignment will reduce the static corrections of each sensor and can be performed with either GPS receivers or a total station geodetic instrument. After the static offsets are determined, a patch test is performed. This test is designed to reveal the following residual biases: pitch offset, roll offset, positioning time delay, and azimuthal offset. The test consists of a small survey of several lines that are evaluated for inconsistencies and then corrected using software designed for multibeam surveys. There are several mathematical equations developed for analyzing these biases that are incorporated into the processing software for the patch test. The performance test is the final check of the offsets and biases to verify whether the data meet accuracy requirements for the survey. This test is a series of parallel and cross lines with significant overlap to give redundant data.

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PREFACE

This work was performed under the Surveying and Mapping Program, Work Unit 32996 "Applications of Acoustic Multibeam Sonar Systems for Construction, Dredging, Surveying and Geotechnical Investigation."

This work was performed during the period October 1995 to September 1997 under the supervision of Messrs. Anthony Niles, Team Leader, Peter Cervarich, Chief, Geodetic Applications Division and Richard Herrmann, Director, Topographic Applications Laboratory.

Dr. William E. Roper was the Director and COL Robert F. Kirby was the Commander and Deputy Director of the U. S. Army Topographic Engineering Center at the time of publication of this report.

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FIELD CALIBRATION PROCEDURES FOR MULTIBEAM SONAR SYSTEMS

INTRODUCTION

There have been many recent advances in the methods of bathymetric data acquisition that are being employed by the U.S. Army Corps of Engineers (USACE). These improvements include multibeam sonar transducers, light detection and ranging (LIDAR) surveys, acoustic seafloor classification systems, sub-bottom profilers, and digital sidescan sonar transducers. These systems can be operated from small boats, thus are ideal for the type of operations in which USACE is involved. This report will focus on acoustic multibeam sonar systems that many USACE districts are acquiring for their dredging and condition surveys.

Types of Echo Sounding Systems. Three basic types of echo sounding systems are used today for hydrographic surveys. The standard ***single beam*** echo sounder produces one narrow sonar beam directly beneath the transducer and receives a return from the closest point at which it intersects. This single beam echo sounder has been the typical method for collecting hydrographic survey data for USACE. A ***sweep system*** is characterized by several transducers mounted on a boom, which is then operated parallel to the water's surface and orthogonal to the vessel's direction of travel. The transducers are equally spaced to yield sonar bottom coverage of a constant width independent of water depth. These systems are generally used in shallow water where full or close to full coverage is required. The ***swath*** or ***multibeam sonar*** system has a single transducer, or pair of transducers, that continually transmit numerous sonar beams in a swath or fan-shaped signal pattern. They are ideal systems for mapping large areas rapidly, with essentially 100 percent bottom coverage. Multibeam signal backscatter information can be used to generate sidescan data for imaging bottom features and targets in a wide variety of water depths.

Coverage of Multibeam Echo Sounding Systems. The coverage area of these systems is a direct function of water depth. Most systems provide coverage ranging from two to approximately seven times the water depth. The number of beams also varies with the manufacturer and ranges from 30 to more than 120; however, the outer beams on each side of the swath are subject to more errors and may not be useful. Because of the increased density of soundings with multibeam systems, it is possible, with proper calibration and adjustments, to detect and resolve smaller objects on the bottom relative to single beam systems.

Use of Technology. The USACE recently introduced multibeam sonar technology for use in channel and harbor surveys. Multibeam sonar systems were recommended for construction dredging measurement and payment surveys in these shallow waters, where the accuracy requirements can be the most critical and the need for correct and thorough calibration becomes essential. At present, USACE districts have acquired two different types of multibeam transducers from different manufacturers - the Reson Seabat and the Odom Echoscan multibeam systems. In addition, the navigation and acquisition software used by all USACE districts is HYPACK and HYSWEEP, produced by Coastal Oceanographics, Inc. This report will cover the calibration procedures for these multibeam systems using software in conjunction with methods used by the Canadian Hydrographic Service (CHS). Other systems, such as Simrad EM3000, EM950, and Elac Bottomchart Compact, may need other calibration procedures. The software and procedures for calibrating multibeam sonars are still being developed and will undergo modifications and updating as new data are acquired and performance is validated.

Need for Calibration. With this improved resolution and coverage comes the need for much greater control and calibration to ensure that the sounding is recorded from the correct position on the seafloor (geo-positioning). This geo-positioning is accomplished by using a high accuracy differential global positioning system (DGPS), heave-pitch-roll (HPR) sensor and a gyrocompass. In addition, the time synchronization for all these components is critical. For this reason, the system accuracy is comprised not only of the multibeam sonar accuracy, but also of the various components that make up the total system. This overall quality control assessment must be performed in the field because empirical data are necessary for validation.

Sources of Errors. Several sources of errors and biases exist in multibeam surveying that are not found in single beam surveying.

- *Static offsets of the sensors* are the distances between the sensors and the reference point of the vessel or the positioning antenna.
- *Transducer draft* is the depth of the transducer head below the waterline of the vessel.
- *Time delay between the positioning system, sonar measurement, and HPR sensor* is the delay or latency that must be accurately known and compensated for in the processing of the hydrographic data.
- *Sound velocity measurement* is the velocity of sound in the water column that must be accurately known so the correct depth can be measured.
- *Acceleration and translation measurements of the HPR* are critical for corrections to the vessel's roll and pitch.

These parameters must be measured and corrected in the multibeam sonar system. It is assumed that the software used in the processing will accommodate these inputs and that the correct sign is used when entering the offsets and corrections.

Single Beam Transducers. Single beam transducers are calibrated with a bar check coupled with a velocity cast. With the bar lowered to a given depth, the depth recorder signal output can be adjusted to match the known bar depth. The velocity cast gives the speed of sound in the water column, and the proper speed can be applied to the echo sounder. With multibeam sonars, the bar check is not feasible because of the fan-shaped array of the pulse and the difficulty of measuring the outer beams; however, the vertical beams can be checked using the bar. The velocity cast is still critical and must be recorded for each survey and when there are significant water characteristic changes.

Calibration Measurements. The field procedures necessary for proper calibration are the alignment of each sensor, the patch test, and the performance test. These measurements are discussed in the next sections.

ALIGNMENT AND STATIC OFFSETS

The process of physical alignment of the vessel platform, transducers, gyrocompass, and HPR sensor is referred to as static offsets. This process ideally will take place with the vessel stabilized on a trailer or on blocks where more exact measurements can be made. This stability will minimize errors in the positioning of the sensors and, with the proper offsets applied, the static corrections will be determined. The sensors should be measured from a reference point in the vessel that 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, thus must be chosen to represent the typical conditions expected while surveying. This information can be obtained from the blueprints of the vessel. The reference point should be a place that is easily accessible and from where measurements to the sensors will be made.

The sensor offsets are measured distances from the reference point to the center of the sensor. The center of the sensor can be found in the manufacturer's schematic of the sensor, or can be accurately measured with a survey tape. The magnitude and direction of the measurement should be verified and recorded.

HPR Sensor. If possible, the HPR sensor should be placed on the centerline of the vessel as close as possible to the center of gravity or the intersection of the pitch and roll axes of the vessel (Figure 1), with the same mount angles used for the transducer. The x-axis of the HPR should match the x-axis of the transducer (x-axis is defined as the bow-stern axis of the vessel while the y-axis is the beam axis of the vessel). Azimuthal misalignment of the HPR sensor will result in the depth measurements being in error proportional to the water depth.

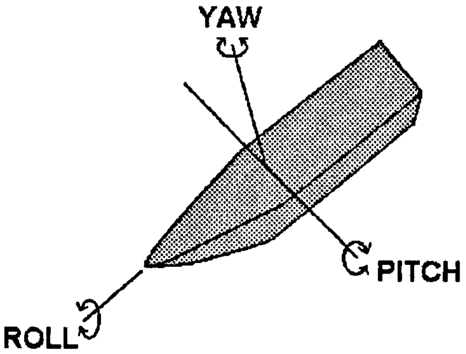

Figure 1. Rotation axes of vessel.

Transducer. The transducer should be installed as near as possible to the centerline of the vessel and level about the roll axis. It should be aligned with the azimuth of the vessel (Figure 2). This alignment is critical as there is no beam steering with either the Reson Seabat or Odom Echoscan. There is, however, beam steering with the Simrad transducers about the y-axis. Most of the multibeam transducers used on USACE vessels are mounted over-the-side on a shaft and boom device. With this type of mount, it is imperative that the azimuthal alignment between the transducer and keel be as accurate as possible. This alignment can be accomplished with the vessel on a trailer, or blocks on land, using standard surveying and leveling techniques. The 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, therefore 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 (e.g. different accuracy requirements, weather conditions, vessel draft). Hull mounted transducers are generally fixed in place and will not need to be checked as frequently. The angle of the transducer mount must be determined and recorded. Since most vessels underway will be lower in the stern, the transducer will generally need to be rotated aft along the centerline axis to compensate for this angle. The patch test will be used to check the transducer angle for the pitch offset. After alignment, the resulting beam should then project normal to the sea floor while conducting surveying operations.

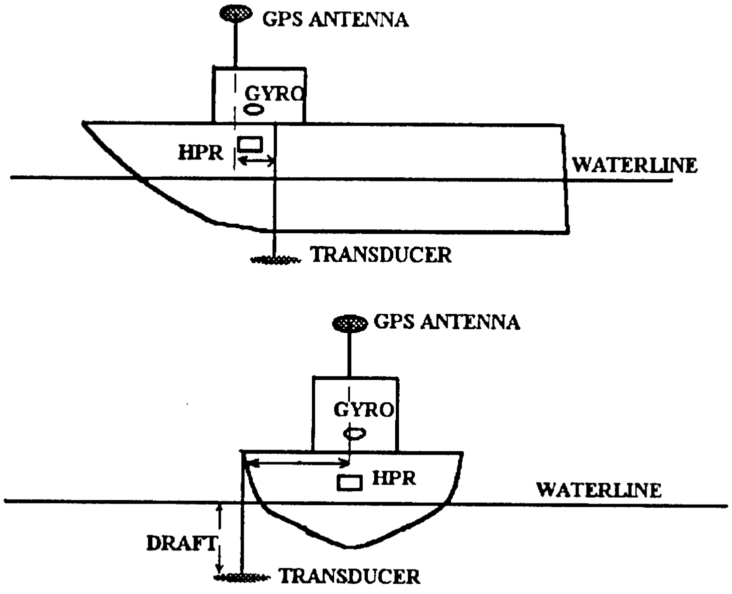

Figure 2. Offset locations of sensors.

Gyro. The gyro should be aligned with the x-axis of the vessel using a total station and geodetic control points. This alignment 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. By locating two (2) points on the centerline of the vessel and placing a target on each, the two targets can be observed with the total station, which enables synchronization of the readings with the gyro readings. Several readings are needed for redundancy. The vessel's azimuth is computed and compared with the gyro readings. Following analysis of the mean and standard deviation, if the offset is more than 1 degree at the 95 percent confidence level, the gyro must be realigned with the centerline and the observations repeated. If less than 1 degree, the correction is within the specified tolerance and can be applied to the gyro output. This procedure also can be performed using three GPS receivers instead of the total station, however, the data processing may take longer than using the total station.

Settlement Measurement Using Transit. The settlement of the vessel is the magnitude of the increase in the draft and should be measured at several speeds and a look-up table produced to correct the transducer draft. This measurement is essential since the HPR will not measure the low frequency change in elevation. The sensor will record the sudden change in elevation, but the measured heave will drift back to zero. Vessel settlement can be measured with a transit on shore and a 2-meter pole on the vessel that is positioned over the transducer (if hull mounted), or adjacent to the mount if using an over-the-side mount. The vessel makes several passes at various speeds in front of the shore station and the elevation is recorded for each pass. The elevation difference at each speed is noted and the interpolated settlement value is used as the draft correction while surveying. Application of the correct sign must be ensured when entering the correction value into the software. This correction is generally performed once for each survey area.

Settlement Measurement Using GPS Receivers. Using GPS receivers on the vessel and shore is another method for determining settlement. The GPS antenna is positioned near the center of the vessel with the vertical and horizontal distances from the antenna to the vessel's reference point measured with steel tape. Data from a nearby tide gauge can be used as a vertical reference from which to measure the elevation. The gauge should be in the survey area; if the area is large, two gauges should be used. The same survey line should be run at different speeds and under different loading conditions. GPS positions, heave, pitch, roll, vessel speed, and water levels are recorded at common times. The highest sampling rate should be used for both the GPS and HPR sensors (10Hz and 100Hz, respectively), while the water levels can be recorded at approximately 5-10 minute intervals. The antenna height should be recorded while stationary and all data should be synchronized and interpolated if necessary. The GPS antenna offsets and attitude data can be used to compute the roll and heave, and to correct the antenna elevations. Water level and heave data are subtracted from the GPS antenna elevations. With these corrections for motion and water levels, the average speed in the water and the average antenna elevation are computed with respect to the ellipsoid. A look-up table for the transducer draft correction can then be produced.

Time Delay. Time delay in the attitude sensor will result in roll errors, which greatly affect the orientation of the outer beams. Horizontal accelerations in cornering also can affect the HPR measurements, which will 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 seafloor when surveying flat and smooth areas. Coastal Oceanographic's HYSWEEP and HYPACK programs can be used to check the time delay. The CHS and University of New Brunswick's Ocean Mapping have developed UNIX-based software to assess time delays in swath data.

Time delays in the positioning system are the time lags between when the time positioning data are first received by the system and the time the computed position reaches the logging module. This difference 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 tag embedded in the GPS message will be used, then the correct synchronization between this time and the transducer or signal processing clock must be ensured.

PATCH TEST

The patch test or calibration survey is important and must be performed carefully to ensure that the data collected is accurate and reliable. This test is a small survey of several lines that are run in order to check and correct the following potential biases:

(1) Residual pitch offset
(2) Residual roll offset
(3) Residual positioning time delay
(4) Residual azimuthal offset

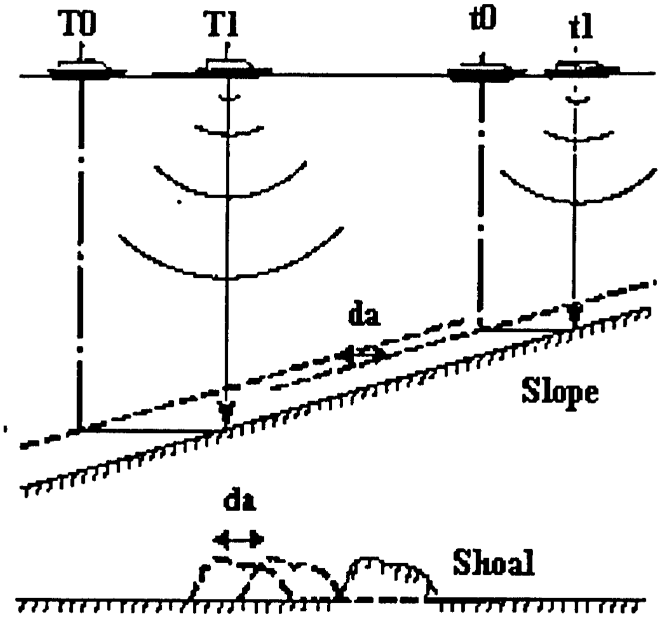

Figure 3. Profile view of two lines run over a slope at the same speed and in opposite directions showing along-track displacement, da, in the apparent seafloor (dashed lines) caused by positive pitch offset. (Figure courtesy of A. Godin.)

These offsets and delays are used to correct the initial misalignments from the installation, and to calibrate the system.

Data Acquisition. Patch tests should be performed whenever there is a significant change in the survey area or the characteristics of the vessel. In general, the tests should be performed at the start of each new survey or when a significant change in the water mass (i.e., temperature, salinity) has occurred. The values for the correction parameters discussed in the previous section should be verified and entered with the proper sign. In addition, it is assumed that the positioning instruments used will be DGPS with survey quality receivers on the vessel and the shore stations. The weather should be calm to ensure good bottom detection and minimal vessel motion. 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 survey areas encountered and will generally be less than 20 meters. The order in which the lines are run is not important although it is recommended that at least two sets of reciprocal lines are run for redundancy. Although the outer beams of multibeam sonar are subject to a larger grazing angle, these beams should provide good data if the appropriate corrections are applied from the patch test.

Positioning Time Delay and Pitch Bias Lines. These lines should be run in an area with a slope of 10 degrees to 20 degrees if possible (Figures 3 and 4). At least two pairs of reciprocal lines should be run up and down slope. If possible, a conspicuous bathymetric feature should be surveyed to assess the time delay as long as it is covered by the beam at nadir. The slope should be at least 200 meters long in order to obtain good samples. The lines should be run at two different speeds to assess the time delay.

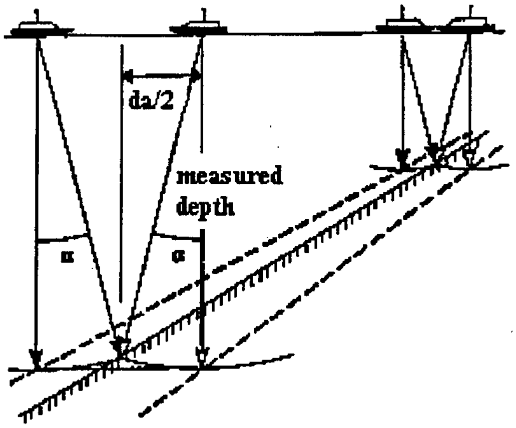

Figure 4. Profile view of a line run at two different speeds along a slope or shoal, showing along-track displacement, da, in the apparent seafloor (dashed lines) caused by positioning time delay. (Figure courtesy of A. Godin.)

Roll bias lines. In an area of flat topography, at least one pair of lines should be run for testing the roll bias. Figure 5 shows a schematic of a vessel with a roll to port of 5 degrees exaggerating a roll bias. If possible these lines should be run in deep water where it is easier to test for roll errors with the outer beams. Depending on the type of multibeam system, these lines should be run at a speed to ensure significant overlap of the beam footprint. The required beamwidth can be found in the manufacturer specifications.

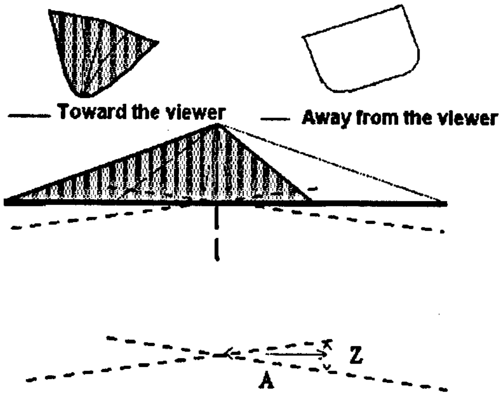

Figure 5. Profile view of two reciprocal lines run over a flat seafloor. The apparent across-track profiles (dashed lines) show a roll offset of 5 degrees. The depth difference Z and across-track distance A can be used to compute the roll offset. (Figure adapted from A. Godin.)

Azimuthal Offset Lines. Two adjacent pairs of lines should be run on each side of a prominent bathymetric feature, such as a shoal. Features with sharp edges, such as wrecks, should be avoided as there is more ambiguity in the interpretation. The adjacent lines should have an overlap of about 15 percent, 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 footprint.

Data Processing. The HYSWEEP patch test will grid the data into 100 cells before any adjustments are made; however, the reduced dataset may not be accurately representative of the test lines. The procedure stated in the CHS software uses the entire data set collected from the patch test lines without gridding. The reason for this difference is because of the processing speeds of the platforms used (PC vs. UNIX workstation). Visualization of the bathymetric data is important in both methods. In addition, the position and attitude data should be checked for errors, especially noting any 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 be followed in the sequence given below. The visualization of profiles and contours is performed on software provided by CHS and the University of New Brunswick.

Positioning Time Delay. This delay can be computed by measuring the along-track displacement of soundings from a pair of coincident lines run at different speeds over a slope or over a prominent topographic feature. Lines run in the same direction should be used so as to avoid the effect of pitch offset errors. The equation to compute time delay is :

$$TD = \frac{d_a}{v_h - v_l}$$

where TD is the time delay in seconds
d_a is the along-track displacement
v_h is the higher vessel speed
v_l is the lower vessel speed

The survey lines are processed, plotted, and compared while ensuring that no corrections are made for positioning time delay, pitch error, roll error, and gyro error. 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.

Pitch Offset. The pitch offset is measured from two pairs of reciprocal lines run over a slope at two different speeds. The important characteristic of pitch offset is that the along-track displacement caused by pitch offset is proportional to water depth. Thus, the deeper the water the larger the offset. The pitch offset can be computed using the following equation:

$$\alpha = \tan^{-1} \frac{(d_a/2)}{depth}$$

where α is the pitch offset
d_a is the along-track displacement
$depth$ is the 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.

Azimuthal Offset. The same two pairs of lines that are run adjacent to a bathymetric feature will be used for the measurement of the azimuthal offset. One pair of adjacent lines run at a time, in opposite directions, is processed to remove any potential roll offset. The azimuthal offset can be obtained from the following equation:

$$\gamma = \sin^{-1} \frac{(d_a/2)}{X_i}$$

where γ is the azimuthal offset

d_a is the along-track displacement

X is the relative across track distance for beam I

The survey lines are processed with only the positioning time delay and pitch offset corrections and static sensor offsets. The azimuthal offset is averaged by making several measurements of the displacement d_a over the feature, and by 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.

Roll Offset. The lines used for the roll offset are reciprocal lines run over a flat area. Generally, this offset is the most critical in deeper water and should be carefully measured. For small angles of less than 3 degrees, the roll offset can be estimated by the following equation:

$$\theta = \frac{\tan^{-1}(d_z / d_a)}{2}$$

where θ is the roll offset

d_z is the depth difference

d_a is the across-track distance

The survey lines are processed while applying the positioning time delay, pitch offset, gyro offset corrections, and static sensor offsets. The roll offset is averaged by several measurements of the across track displacement d_a along the test swaths. This process is performed iteratively until the profiles and contours match or achieve a minimum difference. (This is summarized in Table 1.)

The above patch test and data processing procedures are based on the CHS methods and from Godin, 1996. The equations are used to approximate the offsets encountered when running shallow water multibeam surveys. The patch test procedures used in the HYSWEEP software from Coastal Oceanographics are not as comprehensive and are based on cell sizes and average minimum ranges in the cells. This program is being updated as new algorithms and techniques become validated.

PERFORMANCE TEST

Reference Surface. A final performance test is a check of the above offsets to verify whether the data met accuracy requirements for the survey. This test is essentially a small survey run over a flat area in water depths of not more than 30 meters. Four parallel lines are run with at least 150 percent overlap. For the Reson Seabat 9001 with a swath of two times water depth, the line spacing should be less than the water depth to give enough overlap. One should ensure that the inner beams overlap enough to give redundant data. After these lines are run, four or five parallel lines are run perpendicular to the previously run lines with the same swath and overlap. The speed over ground should be the same on both sets of lines. A velocity cast should be made in this area and the corrections applied. The performance test should be run when the sensors are initially installed and whenever there is a major change in the conditions of the survey vessel (i.e., overhaul in drydock, change in vessel characteristics).

Check Lines. A pair of parallel lines should be run inside the reference surface. Overlap as described above is not needed. The vessel speed is the same as for the reference surface. The data processing for these lines should follow the general rules outlined below.

The reference surface should be cleaned of outliers. This procedure should be performed manually, and adjustment of positions, attitude, and bathymetry should be made to ensure clean data. Smoothing or thinning of data must not be made. A digital terrain model (DTM) of the reference surface is created from the cleaned data, and an averaging gridding algorithm is used to smooth the data. The gridding size should be no larger than the average footprint of the inner beams. Using large vertical exaggeration, the DTM should be observed on 3-D visualization software. Check lines are then processed individually and each beam depth reading is compared to the reference surface. A difference surface between the reference DTM surface and the check lines is then created and contoured, and statistics are computed to assess overall performance. Statistical parameters to be noted are the beam number, maximum difference, minimum difference, mean, standard deviation, and percent difference. From these differences the corrections to the system can be checked against the criteria in Table 2. It should be noted that the installation of the multibeam transducer and the sensors associated with it require time and patience to assure that valid data will be collected. The patch test will only be necessary after installation, and when surveying in a new area with different water environment conditions. Also, anytime the software is updated, either in the acquisition or the processing, the tests should be repeated. The performance test should be run as stated previously.

Table 1. Patch test procedures and computations

	POSITIONING TIME DELAY	**PITCH OFFSET**	**AZIMUTHAL OFFSET (GYRO)**	**ROLL OFFSET**
LINES REQUIRED	2 on same heading over slope or shoal	2 pairs on reciprocal headings at 2 speeds	2 pairs over bathymetric feature	2 reciprocal lines over flat area
PRIOR CORRECTIONS APPLIED	None, other than static offsets	Positioning time delay	Positioning time delay and pitch	Positioning time delay, pitch and gyro
COMPUTATION METHOD	Average of displacements in along track direction	Average of displacements in along track direction	Average of displacements 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
EQUATION	$TD = \frac{d_a}{v_h - v_l}$	$\alpha = \tan^{-1} \frac{(d_{a/2})}{depth}$	$\gamma = \sin^{-1} \frac{(d_{a/2})}{X_i}$	$\theta = \tan^{-1} \frac{(d_z/d_a)}{2}$

Table 2. Summary of Multibeam Sonar Calibrations and Criteria

	FREQUENCY OF MEASUREMENT	CALIBRATION PROCEDURE	ALLOWABLE TOLERANCE 95 PERCENT	CORRECTIVE ACTION
SENSOR ALIGNMENT/ OFFSETS				
Transducer	Initial installation	Leveling, Total Station	0.5°	Remount
Gyro	Initial installation	Self calibration	Manufacturer's specifications	Replace
HPR	Start of project	Self calibration	0.1°	Remount
GPS Antenna	Initial installation	Leveling	0.1 ft	Remount
Squat	Start of project	Transit, level, GPS	0.1 ft	None
Dynamic draft	Start of project	Transit, level	0.1 ft	None
ACOUSTIC DRAFT AND VELOCITY				
Bar Check	Start of project	Bar under center beam	0.2 ft	Stop survey and redo
Velocity Probe	Twice daily or more	Self calibration	0.01m/s	Stop survey and redo
PATCH TEST				
Pitch	Start of project	2 pairs of reciprocal lines on slope	0.2 ft	Apply correction in software
Roll	Start of project	1 pair of reciprocal lines over flat area	0.2 ft	Apply correction in software
Time Delay	Start of project	2 pairs of reciprocal lines on slope	0.2 ft	Apply correction in software
Azimuth	Start of project	2 pairs of adjacent lines over shoal	0.2 ft	Apply correction in software

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