Article



MULTIBEAM SONAR PERFORMANCE ANALYSIS VALUE AND USE OF STATISTICAL TECHNIQUES

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Abstract

The Naval Oceanographic Office uses quantitative methods employing statistical measurements to analyze and evaluate the performance and behavior of multibeam sonar bathymetry systems. Datasets are made that determine the residual differences between a reference surface and multibeam sounding files as a function of beam angle. The resultant beam-wise analysis facilitates artifact detection, trends, overall uncertainty, dataset limitations, and system performance compliance against specifications or other special requirements. The technique used is presented with examples of its application in analyzing system performance, data processing, and survey planning in two actual case studies.

Résumé

Le Service océanographique naval utilise des méthodes quantitatives employant des mesures statistiques pour analyser et évaluer le fonctionnement et le comportement de systèmes bathymétriques sonar multifaisceaux. Des ensembles de données sont constitués et déterminent les différences résiduelles entre une surface de référence et des fichiers de sondage multifaisceaux en tant que fonction d'angle de faisceau. L'analyse dans le sens du faisceau qui en résulte facilite la détection d'objets, les tendances, l'incertitude globale, les limitations des ensembles de données et la conformité du fonctionnement du système avec les spécifications ou d'autres exigences spécifiques. La technique utilisée est présentée avec des exemples de son application dans l'analyse du fonctionnement du système, le traitement des données et la planification des levés dans deux études de cas réelles.

Resumen

El Servicio Oceanográfico de la Marina utiliza métodos cuantitativos que emplean medidas estadísticas para analizar y evaluar el rendimiento y el comportamiento de los sistemas de batimetría que utilizan el sonar multihaz. Se crean colecciones de datos que determinan las diferencias residuales entre una superficie de referencia y los archivos de sondeos multihaz como función del ángulo del haz. El análisis del haz resultante facilita la detección del artefacto, las tendencias, la incertidumbre general, las limitaciones de las colecciones de datos, y la conformidad del rendimiento del sistema frente a las especificaciones o a otros requerimientos especiales. Se presenta la técnica utilizada con ejemplos de su aplicación al analizar el rendimiento del sistema, el procesado de datos, y la planificación de los levantamientos en dos estudios de casos reales.

Overview

Prior to fielding an operational multibeam echosounder aboard Naval Oceanographic Office (NAVOCEANO) ships, rigorous testing is conducted to assess the system performance and limitations associated with its use on the intended vessel. These tests include baselining system noise levels, determining the system capabilities (e.g., swath width, depth range, and target detection ability), and evaluating system performance to meet uncertainty specifications.

The NAVOCEANO multibeam sonar system (MBSS) comprises the new sonar suite life-cycle overhaul for the T-AGS 60 class ships. It includes replacing the hull-mounted Simrad EM121A deep water sonar and EM1002 shallow water sonar with the Kongsberg EM122 and EM710 sonar systems, respectively. The T-AGS 60 ships are being cycled through an overhaul rotation of one ship per year for the six ships. Currently, five ships have completed their overhaul while one more is still scheduled.

Previous sea acceptance testing had limited the test sites to hard bottom areas. After the third MBSS installation (USNS Pathfinder) was placed in operational service in August 2009, a severe degradation problem was observed in the EM122 data over an area having an acoustically "soft" bottom characterized by high absorption and low reflectivity. The characterization of the artifacts created by the degradation and efficacy of methods to resolve the problem using statistical techniques form the first case study of this paper. In the second case study, USNS Mary Sears operated the Simrad EM1002 on an operational survey with the starboard beams exhibiting inordinate system noise levels due to hardware malfunction that significantly degraded the system performance. That case study demonstrates using the beam statistics analysis to aid decision-making for data validity during post-processing and as a tool for survey planning to optimize survey execution while meeting survey uncertainty requirements.

The use of statistical techniques for examining multibeam sonar performance has been employed for over two decades at NAVOCEANO. The techniques have also been used by academia as well (for example, de Moustier 2001). The use of the techniques here emphasizes their application to the sonar baseline evaluation and capability, monitoring changes in capability and performance, and use as a tool for operational survey optimization.

Reference Surface Construction

Essential to the performance evaluation of a multibeam echosounder is the availability of a reference surface that can be used as ground truth for the test data. While independent information from sources other than the system under test is desired for establishing the reference surface, often there is no other source available. In those cases, the system is tested against itself, and only the more certain inner-beam data from the system that is being tested is used to build a reference surface. The application of certain procedures as discussed below to create the reference surface makes a valid and consistent evaluation possible. For the T-AGS 60 class ships having multiple multibeam echosounders that cover shallow and deep regimes, the overlap zones of operation are suitable for gauging one system against the other. The use of multiple ships facilitates the development and use of a calibration test area for analyzing repeatability of results between survey ships.

In preparation for collecting the sonar data used in creating the reference surface, the multibeam sonar system is configured with all necessary parameters to ensure a valid dataset is acquired. Great care is taken in ascertaining all installation locations and angles associated with the determined master reference plane. Follow-on patch tests are then conducted for obtaining any residual timing, roll, pitch, and heading corrections associated with the navigation, timing, and motion systems used.

Before collecting the reference surface line data, accurate sound velocity measurement is established with a conductivity, temperature, depth (CTD) sensor or expendable bathythermograph (XBT) for real-time application. Sound velocity is acquired at periodic intervals, depending on the environment and needs of the system under test. After the data collection, all other known reducers are applied (e.g. tides) to achieve as accurate a dataset as possible.

The tedious attention to detail involving the system configuration setup, execution of patch tests, and collection and application of environmental factors is intended to minimize systematic errors that otherwise bias the resultant data in some way and introduce unwanted error into the bathymetric measurement. The complexity of multibeam sonars along with the highly dynamic operational environment can result in very challenging efforts to control the systematic error sources, both static and dynamic (Hughes Clarke 2003).

Reference surface survey lines are spaced at much closer line spacing than routine survey lines. Reference survey line spacing is typically less than the water depth with a high percentage of overlap (45 degree outboard angle). This arrangement ensures that a very high sounding density is used in the gridded dataset and that only the most accurate and least noisy data are included in the reference surface construction. Typically, as the beam angle within the swath increases outboard, sound velocity errors and signal-to-noise degradation increase data uncertainty, only the inner 90 degrees or less of the swath is used in the reference surface.

Note: The inclusion of names of any specific commercial product, commodity, or service in this paper does not imply endorsement by the U.S. Navy or NAVOCEANO.

A flat, featureless seafloor is desired for the reference surface. Flat bottoms facilitate uncovering system artifacts that are often masked with sloping or featured bottoms and minimize errors associated with positioning. As a minimum, the dimensions of the reference surface should ensure that the swath width coverage of the system under test is completely contained within the reference surface for both inline and orthogonal line azimuths.

Following the collection of the reference lines, the data are carefully reviewed to ensure removal of blunders, outliers, and otherwise bad data. These cleaned lines are then input into a gridding program to generate the reference surface. Bin size for the grid is nominally set between one to two times the footprint size of the sonar in the nadir region.

Beam-Wise Statistics Generation

NAVOCEANO typically collects a full set of reference data in orthogonal directions and uses all data from both directions in the reference surface as seen in *Figure 1*. The test data being evaluated are minimally edited (or not at all). Outliers that are not caused by the system itself under normal operation but are caused as a result of extreme environmental factors such as transducer aeration from rough seas or acoustic interference from other sources are removed from the test data.

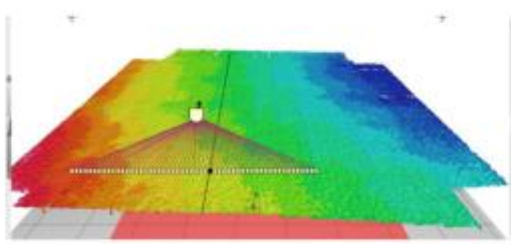

Fig. 1. *Reference surface created from a full set of reference data collected orthogonal directions. The tracking of one beam of the swath across the reference surface is diagramed.*

The previous T-AGS 60 sonar system (EM121A) provided 121 non-overlapping equi-angular distributed beams, having 1° x 1° nominal footprint size. This distribution allowed for referencing beam angle synonymously with beam number. The current generation of sonars can produce over 400 overlapping beams per swath in selectable distribution patterns. For each beam in the test data file, the residual depth is calculated by subtracting the beam depth from the reference surface, and these residuals are then binned to the nearest 1° interval. The mean and standard deviation for each angle bin are then calculated and displayed. In this way, the beam statistics can still be plotted against "beam angle," forming the basis of the beam-wise evaluation technique described in this paper.

Plotting the Statistical Data

The beam statistics tabular output is plotted in profile for system performance analysis. The graphs generally depict the mean depth residual of each beam (in 1-degree bins) and associated standard deviation (dispersion) as a relative percentage of depth or absolute depth. Beam angles are plotted with the outboard port side (left) to the outboard starboard side (right).

An example beam statistics plot is shown in Figure 2, which is derived from an entire set of EM122 test lines over an EM710 reference surface in a hard bottom area approximately 800 m deep. The following is an explanation of the key elements of the plot:

(1) The plot header provides basic information about the plot. In this case, the *%depth residual* term indicates the vertical scaling is referenced as a percentage of depth residual rather than depth residual.

(2) The *(1.96 sigma)* term indicates that the plotted dispersion values for each beam angle are based on the 95% two-tailed normal probability distribution computed for that beam angle for the test dataset.

(3) The <*Order1*> term indicates the IHO Order level of uncertainty applicable for the test data depth that will be plotted as horizontal red bars above and below the abscissa axis of the plot. These bars are provided for comparative convenience to observe whether the system under test is compliant with any desired IHO level requirement for total vertical uncertainty (TVU) of the system-determined beam depths. The TVU computed is based on the average depth of the reference surface (as a single point) and formulae published in IHO S-44, 5th edition standards (2008) for hydrographic surveys. The IHO standards assume a 95% confidence level of the data, which is a 1.96 sigma (1.96σ) dispersion based on a normal distribution.

(4) The last parameter on the top header line between the arrow brackets, in this case <*NWGem122-b.bmsts*>, is the filename source containing the data used to construct the beam statistics plot.

(5) The term *avg(z, num pts, bias)* is annotated on the second header line. The *avg (z)* corresponds to the overall average (mean) depth of the dataset (839.8 m in this case). The *avg (z)* value here is the depth value used for the IHO uncertainty calculation discussed in (3) above.

(6) The *avg (num pts)* term corresponds to the average (mean) number of points used in the sample set per beam angle (36,087 in this case). The *num pts* parameter is indicative of the reasonableness of the sample size for computation of the descriptive statistics. Multibeam sonar ping rates rise significantly as the water shallows resulting in tens or even hundreds of thousands of soundings averaged per beam angle, depending largely on whether one or more test lines are included in the test dataset. Correspondingly, water depths on the order of 4,000 m often result in *avg (num pts)* values that are tens-of-times less than shallow water testing. The distribution of *num pts* as a function of beam angle is not uniform but is U-shaped by the nature of the geometry and the sampling involved as well as system parameter settings. The extreme outboard beam angles may have from 2 to 5x the *num pts* value as at nadir, so if *avg (num pts)* is 2,000, the nadir beam angles may have 1,000 samples each, whereas the outboard angles may have 4,000 each. The more samples that are available for each beam angle presumably results in more accurate statistics for evaluating the system performance and behavior. However, the duration time of collection must ensure proper sounding controls are maintained, e.g., tides and sound speed profiles.

(7) The *avg (bias)* term corresponds to the overall average (mean) value of all beam-angle depth residuals in meters of the test dataset over the reference surface. In this example, the bias is computed as +0.377 m, meaning that, on average, the depth for any beam angle is 0.377 m above the reference surface. A negative value infers the test data having an average depth below the reference surface.

(8)Three curve-sets are graphed on the plot: (a) The mean depth residual value as a function of beam angle is graphed as the red-green curve. (b) The associated scaled standard deviation values for a particular beam angle are colored blue and graphed in error-bar style about the mean value. (c) The pronounced red horizontal lines provide an IHO metric for system performance. The metric may be a strict compliance requirement dictated by the operational water depth (e.g., water depths 40 m or less) or may indicate an extrapolated uncertainty requirement provided for comparative purposes. *Figure 2* shows the IHO Order 1a confidence level specification as projected to a depth of 840 m. Technically, IHO Order 2 would be the proper compliance order to use if a survey was to be conducted to meet IHO requirements at this depth. However, most multibeam sonars easily meet Order 2 specifications, and it is of more interest to gauge the system by more stringent requirements, particularly if the system may be used in a wide range of depths.

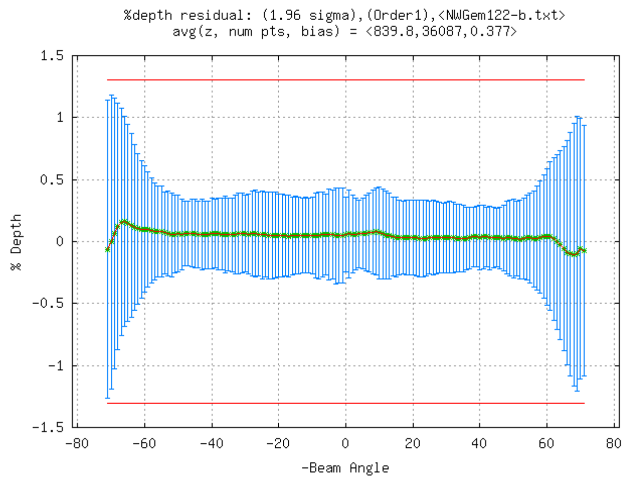

Fig. 2. *Beam statistics plot of the EM122 against an EM710 reference surface over a hard bottom in 800-m water depth. This graph shows the expected U-shaped pattern of uncertainty revealed by the profile of the blue standard deviation error bars, where the uncertainty increases with beam angle. All data fall within the IHO Order 1a specification indicated by the horizontal red lines.*

In the case of *Figure 2*, all of the error bars across the swath are between the red horizontal bars indicating the system is compliant with extrapolated IHO Order 1a requirements.

The wide, flat U-like shape of the blue error-bars profile in *Figure 2* is also consistent with the modeled performance of multibeam sonars where the uncertainty increases in outer beams (Hare et al. 2004).

Analysis of Plots

As discussed previously, the beam statistics plots display the mean depth residual values as a function of angle with associated scaled standard deviation and IHO uncertainty bounds. The mean depth residual values are considered to best represent systematic errors or biases. The standard deviation values for each beam angle are created from both random error sources and dynamic systematic error sources. Hughes Clarke (2003) discusses dynamic systematic error sources in mulitbeam sonar systems at length. For the beam statistics analysis presented here, the standard deviation values are considered just random errors that follow a normal distribution. The empirical rule of statistics for a normal distribution is applied (Ott and Longnecker 2001), and the confidence interval for any beam can be computed as the sum of the mean and a scaled value of the standard deviation (Coleman and Steele 1999). Using typical 95% confidence level guidance utilized in hydrographic applications, these plots graph both the mean value of each beam angle and the maximum magnitude of the mean value of each beam +/- 1.96 standard deviations for that beam angle.

Analysis of the beam statistics plots can facilitate:

- Detecting artifacts
- Identifying across track trends
- Assessing overall uncertainty performance
- Evaluating system performance compliance against the manufacturer's specifications, IHO specifications, or other special requirements

Figure 3 contains a sample beam statistics plot (top) and bathymetric view of depth (bottom) for an EM122 test line across an EM710 reference surface in a shallow water area (150 m). Normally, only the EM710 would be operated in this water depth, as the EM122 is intended for deeper water operation. However, *Figure 3* provides an excellent example to correlate features between the two graphics and highlight the beam statistics benefits mentioned above.

(1) The EM122 sonar system supports yaw stabilization by breaking the transmit swath into multiple sectors. The angular coverage of each of the four transmit sectors composing the swath is annotated in the beam statistics plot along with each sector's respective seafloor coverage extent in the bathymetry view. Notice that at each sector boundary, 1-2, 2-3, and 3-4 are observed standard deviation peaks (blue error-bars), which indicate artifacts present at the sector boundaries at this unusually shallow operating depth. Although the standard deviations peak at the 1-2 and 3-4 sector boundaries, the mean difference plot (green trace) dips rapidly to zero at the corresponding boundaries (A and B marks). This statistical combination means that although the mean depth residual values at these sector boundaries are zero (i.e., agree with the reference surface), there is actually considerable variance in the residual depth difference values at these beam locations when compared to the reference surface. The higher variance indicates the sector boundaries tend to be a "noisier" location in the swath even though the overall average of the noise is zero.

(2) The beam angles associated about the A and B locations in the beam statistics plots are associated with the elongated ovals marked in the bathy view. Here, the A and B points become lines representing the beam angle tracking along the surface. Short dotted guidance lines are drawn within the orange ovals to represent the A and B tracks. The starboard (B) side has a particularly noticeable blue-green-yellow color delineation all the way along the survey line, correlating with the notable dip observed at A and B.

(3) For the beams between the A and B locations, it can be observed that the mean difference plot (green trace) shows all beams having positive depth residuals, indicating the EM122 beams are all reading values shallower than the EM710 surface. The curve slopes up from A to the left side of zone C. In the C area, the mean difference curve decreases somewhat, indicating a slight channeling or trenching effect could be anticipated in the data. A peak in the mean difference occurs at D, about +18 degrees beam angle, and decreases down to point B. These observations show the use of beam statistics to capture across track trends.

(4)The C area is annotated on the lower bathy image, and a particularly distinct trenching area is seen in the dark blue stretch of pixels. The area is associated with a sector boundary area. White pixels are entire beam dropouts. High variations in the nadir area along track are represented by the yellow, green, and blue soundings. Even the red IHO Order 1 maximum allowable uncertainty is exceeded, demonstrating beam statistics use at assessing artifact impact on meeting survey specifications.

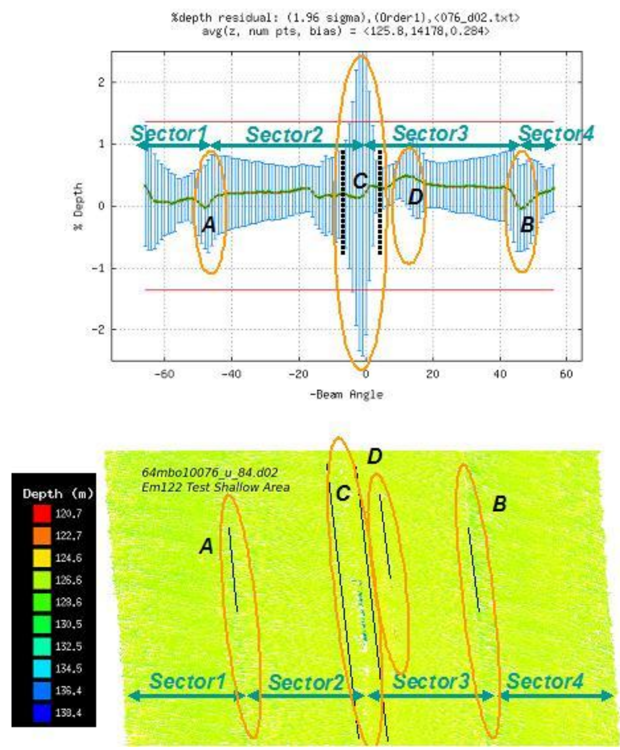

Fig. 3: *A sample beam statistics plot (top) and bathymetric view of residual depths (bottom) for the EM122 across the EM710 reference surface as an example to correlate features between the two graphics.*

EM122 Case Study in an Acoustically Soft Bottom

The EM122 data degradation problem reported for an acoustically soft bottom detection aboard USNS Pathfinder was manifested in the sonar waterfall display during acquisition. Figure 4 shows the symptom over a flat bottom at 800-m depth. Here, the upper image (waterfall view from the sonar display) is severely corrupted in the nadir region. The black areas at nadir are beam dropouts. The lower section shows an across track profile of a survey line that clearly demonstrates the center area suffers a trenching artifact that renders the beams overall deeper (basic shape outlined by orange curve).

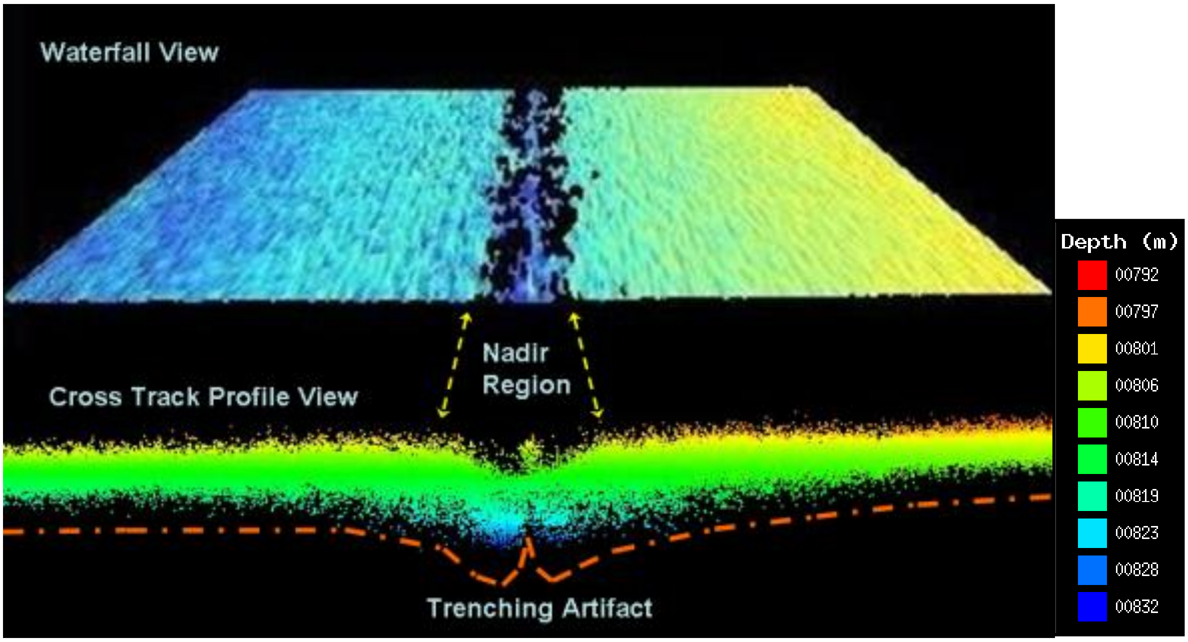

Fig. 4: *Penetration problem on USNS Pathfinder, 600409.*

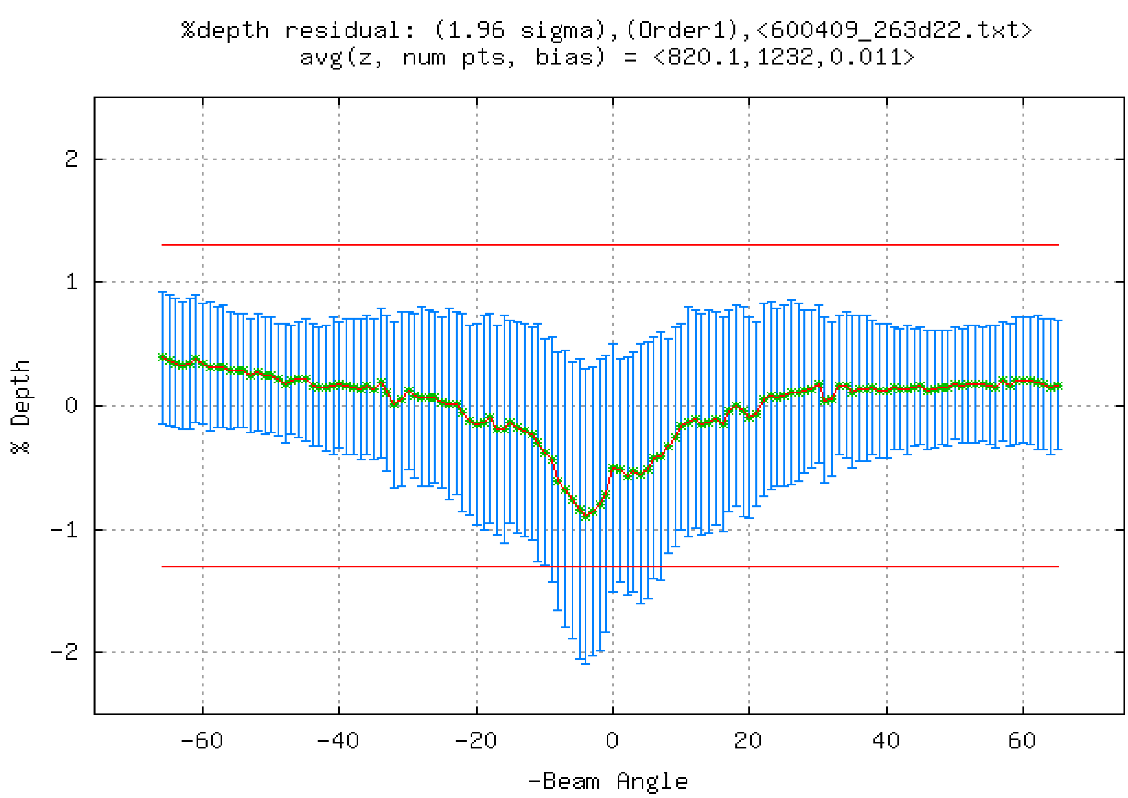

Fig. 5: *Statistics plot of EM122 test line over EM122 reference surface from Pathfinder 600409 data. The excessive uncertainty in the nadir region is uncharacteristic of the typical uncertainty footprint for multibeam systems demonstrated in Figure 2.*

An EM122 reference surface was constructed with the EM122 data to calculate the beam statistics shown in *Figure 5.* Ironically, in this case, the inner beams had to be excluded, and only the outer beams were used to construct the reference surface because of the data degradation and dropouts in the nadir area. Beam statistics determined that the depth errors were in the range of 2% of water depth at a depth of 800 m.

A system failure was initially suspected of causing the degraded performance. That explanation was dismissed once a second EM122-equipped ship and another ship with the legacy EM121A sonar surveyed the same area and replicated the degraded performance. (No other deep water non-Kongsberg sonar systems were available for comparison testing to determine if the phenomenon is the result of a system artifact associated with bottom detection algorithms or if the basic physical acoustics would likewise degrade the performance of similar systems.)

After consultation with the manufacturer, it was assumed that these 12-kHz deep water sonars were suffering a bottom penetration problem caused by the acoustically "soft" seafloor. Three 10-foot cores were obtained in the area to start facilitating a better understanding of the sediment acoustical properties that may be causing the penetration problem.

All the cores demonstrated a greenish-brown sticky clay-mud throughout. The bottom was so soft that the entire core barrel penetrated the bottom, as evidenced by mud remaining on the top of the coring barrel after recovery. As a result of those findings, the manufacturer worked on resolving the problem, and during the follow-on testing aboard USNS Heezen, these solutions were tested and evaluated.

The EM710 sonar operates in a much higher frequency band (70-100 kHz) than the EM122, providing much better spatial resolution, but at significantly less range capability. Normal operations would switch from EM710 use to EM122 use at about 500-m depth since the EM122 swath coverage has well surpassed the EM710 swath coverage at this depth. As a contrasting system, the EM710 was used on Heezen sea trials to construct a reference surface for evaluating EM122 performance. The EM710 did not experience any performance degradation in the same area. This resultant EM710 reference surface is shown in *Figure 6.* The reference surface constructed employed a 20-m cell size using the standard inner 90 degrees of swath from overlapping data files collected in both north-south and east-west directions

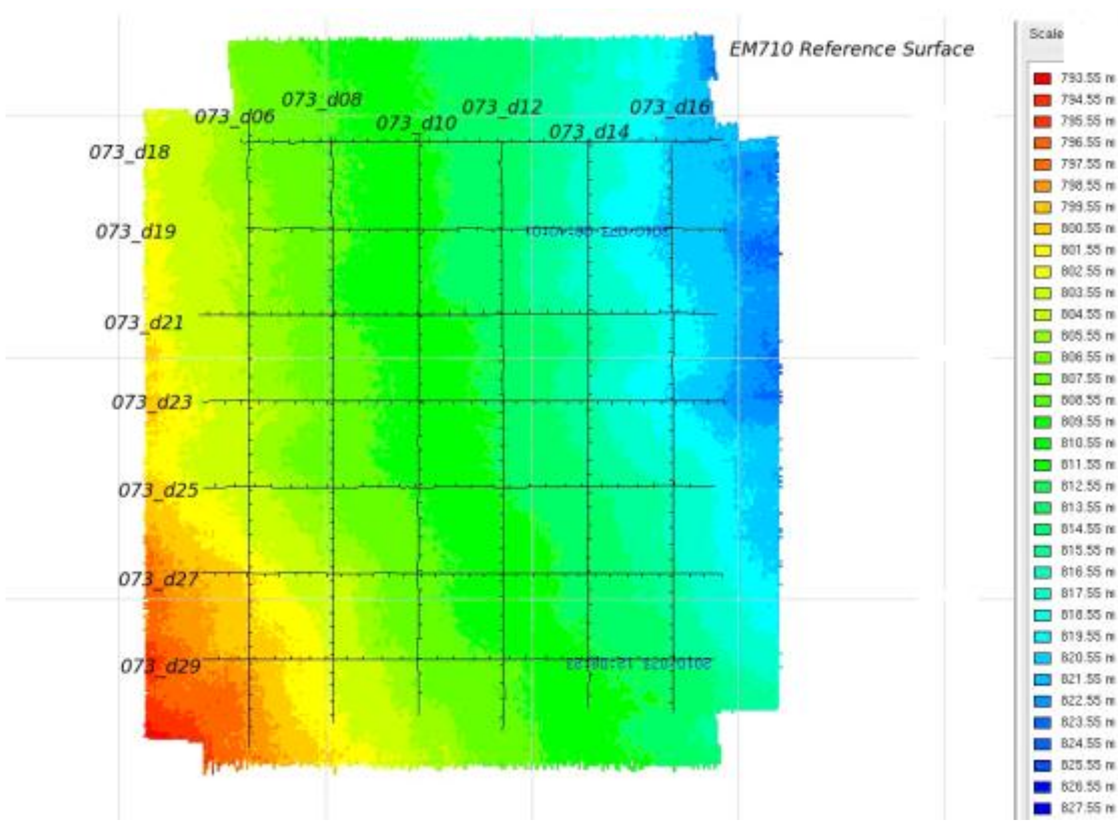

Fig. 6: *EM710 reference surface in 800-m test area.*

The first beam statistics plot of the EM122 line run against the EM710 reference surface before any system and processing unit (PU) upgrades is provided in *Figure 7* with the corresponding color-coded 3D perspective bathymetric view in Figure 8. By comparing Figures 5 and 7, it can now be seen that using the EM710 as the reference surface source provides a more accurate representation of the severity of the penetration effect on the EM122 system. Figure 5 has a mean difference curve with beams outboard of 20 degrees being above the reference surface and the inner +/- 20 degrees below the reference surface. The average mean difference for all beams, *avg* (*bias*), is 0.01 m. Figures 5 and 7 are scaled identically, and a quick observation shows the entire swath having a negative mean difference curve, indicating the whole swath is deeper than the EM710 reference surface. Thus, the penetration problem is affecting the entire swath. The very large -5.5-m *avg* (*bias)* value computed using the EM710 reference dataset in *Figure 7* is a simple descriptive statistic that helps illustrate the penetration problem severity, as typical *avg* (*bias)* values with other datasets comparing the two sonars are generally 0.3 m or less. A pronounced region of trenching occurs around +/- 15 degrees about nadir, with the 95% confidence level of the data in this region well outside the 1.3% IHO Order 1 requirement and even exceeding 2.5% of depth near nadir.

The white and dark blue patches on the bathymetric survey line view in Figure 8 show the dropouts and trenching at nadir.

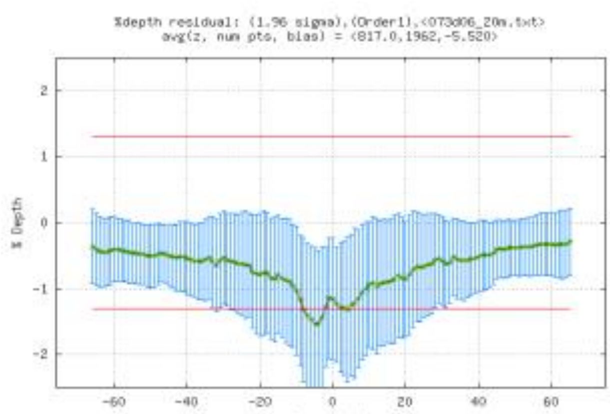

Fig. 7: Beam statistics plot of the EM122 against the EM710 reference surface before implementing the upgrade. A substantial central area between beams +/-15 degrees well exceeds Order 1a specification (red lines). The -5.52 bias value, avg (bias), with all beam angles having a negative residual mean value indicates enetration over the entire EM122 swath when compared to the EM710 reference surface.

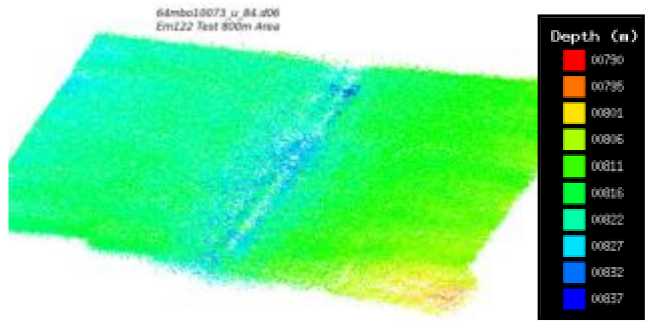

Figure 8: *Single line data file, corresponding to Figure 7, before the PU upgrade. Note the dark blue areas in the swath center area that show the trenching problem caused by bottom penetration.*

Sonar System Changes

Once the initial baseline dataset was acquired, the EM122 system was upgraded from version 3.6.5 to 3.7, which included sonar transceiver upgrades. This upgrade added two new features intended to mitigate the EM122 penetration problem. The first feature is an operator-selectable penetration filter with settings of Off, Weak, Medium, and Strong.

Whereas the penetration filter works on the received echograms, the second new feature attacks the problem by adjusting the transmit beam pattern and provides an automated selection for along track directional steering or tilting of the transmit beam. Normally, the along track steering direction parameter is set to zero, and the system dynamically beam steers the transmit beam directly vertical (nadir) to the ship for all pings as the ship pitches. The EM122 can also be forced to manually steer the transmit beam to both nadir and non-nadir angles ranging from -10 degrees (aft) to +10 degrees (fore).

The automated steering capability self-examines signal returns and decides on an optimal selection for the along track steering. In Heezen sonar tests, the steering chosen was varied, ranging from -8, -9, and -10, which is code for automated selection of the along track steering within fore and aft nadir angles of +/-2, +/-3, and +/-4 degrees, respectively.

Datasets were collected at the various penetration filter and along track steering selections.

Sonar Parameter Setting Test Results

Figures 9 and 10 show the first data file acquired after the EM122 Seafloor Information System and PU upgrades on Heezen. Significant differences between the plot and image sets of Figures 7 and 8 (before the upgrade) can be observed compared to Figures 9 and 10 (after the upgrade). Most notably, the peak excursion around +/-8 degree beam angle of the error-bars has dropped by some 25% from Figure 7.

The width of the error bar region that exceeds the Order 1a specification is now a much narrower region about the nadir area, indicating a marked uncertainty improvement in the overall swath also reflected by the overall bias value, *avg (bias*), dropping from 5.3 m down to 4.1 m.

These data show some initial success in mitigating the penetration problem even without invoking the new penetration filter or along track steering feature settings. Because of the significant improved performance from the upgrade, the along track steering and penetration filter features are now standard features with the EM122 sonar and constitute a permanent firmware change that establishes a new performance baseline.

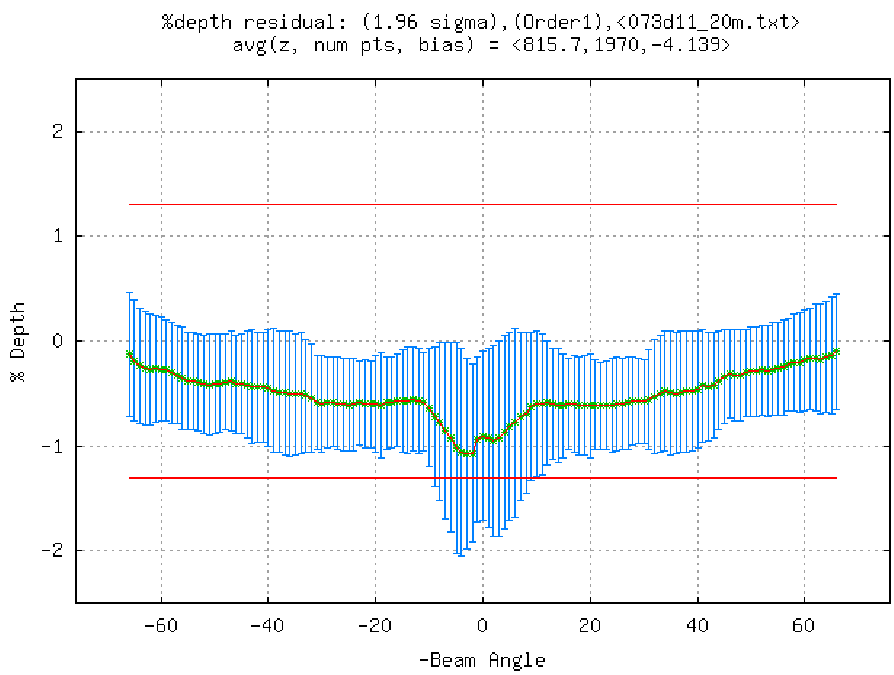

Fig. 9. *Beam statistics plot of the EM122 against the EM710 reference surface before implementing the upgrade. A substantial central area between beams +/-15 degrees well exceeds Order 1a specification (red lines). The -5.52 bias value, avg (bias), with all beam angles having a negative residual mean value indicates enetration over the entire EM122 swath when compared to the EM710 reference surface.*

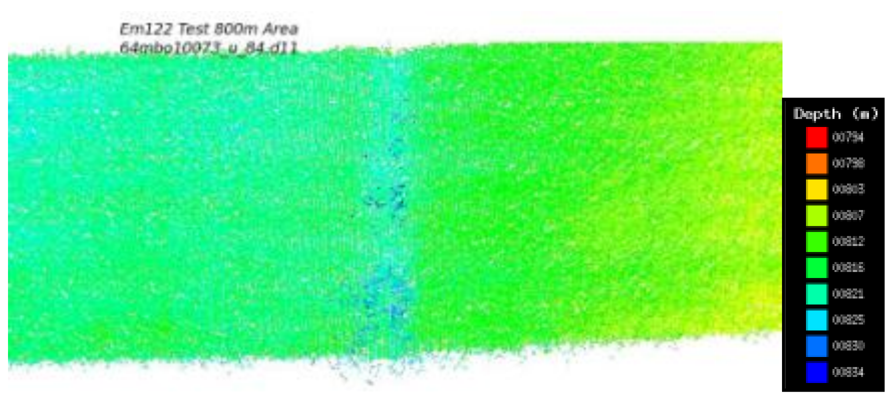

Fig. 10. *: First data file, corresponding to Figure 9, after the upgrade with filters turned off. Note the lessening of the dark blue nadir area compared to Figure 8.*

Figure 11 shows the effect of the penetration filter alone at its various settings and leaving the along track steering in the default nadir steering mode. Starting in the upper left and going clockwise, the penetration filter was set to Off, Weak, Medium, and Strong, respectively. Again, note the improvement in overall penetration alleviation as indicated by the lower overall mean difference value, *avg* (*bias*), and successive reduction in peak uncertainty. It was concluded from these plots that the Off and Weak settings did not make any major impact on the beam statistics results. However, a considerable change is made between the Weak and Medium selections, and little change occurs between the Medium and Strong modes.

The mean curve plots in the four graphs of Figure 11 all trend in a bowl-like shape from port to starboard, and all mean values for each beam angle are negative, indicating that the entire swath is still affected by the penetration problem. The situation is improved, but not resolved. While in this specific test area, a Medium or Strong setting is best; in other areas, when transitioning from a soft to harder bottom, these settings may be too aggressive, and a Weak setting may be needed. Beam statistics processing in a different area could help determine the optimum filter setting there.

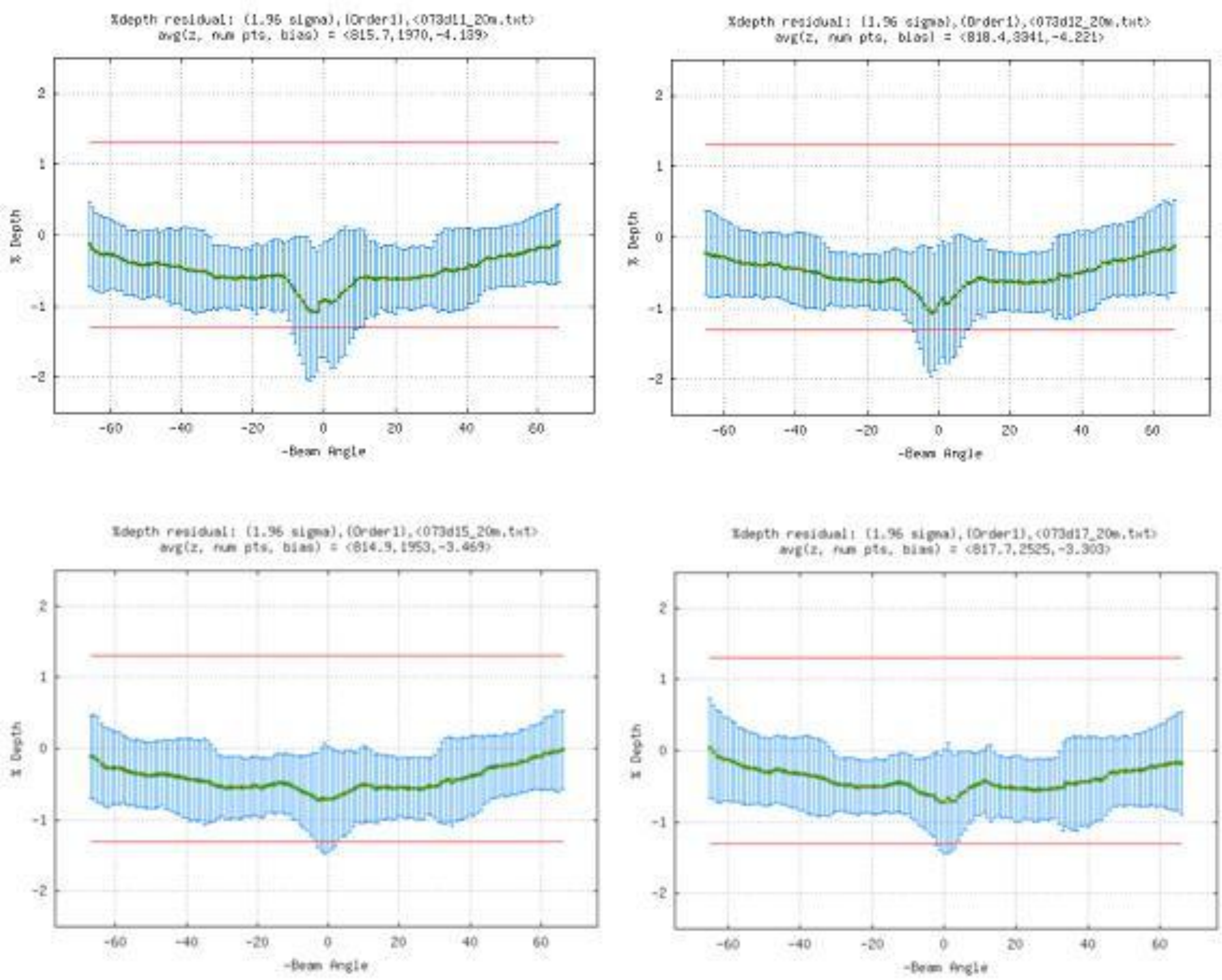

Fig. 11. : Effects of the penetration filter alone. Starting in the upper left and going clockwise, the penetration filter was set to Off, Weak, Medium, and Strong, respectively.

Figure 12 shows the effects of changing the along track steering direction from static nadir to automated non-nadir. Starting in the upper left and going clockwise, the along track beam settings were set to Off, +/-2, +/-3, and +/-4 degrees, respectively, with the system determining the optimum steering angle to skew the 1° transmit beam fore or aft and to avoid a direct specular hit on the seafloor and instead slightly graze it.

Figure 12 seems to indicate that the best along track steering selections are settings of -9 and -10 (+/- 3 degrees and +/-4 degrees, respectively) based on peak mean difference curves. The OFF and +/- 2° plots look very similar to each other, but a noticeable improvement in lowering the overall bias, *avg (bias)*, value is obtained with a steering of +/-3° or +/-4°.

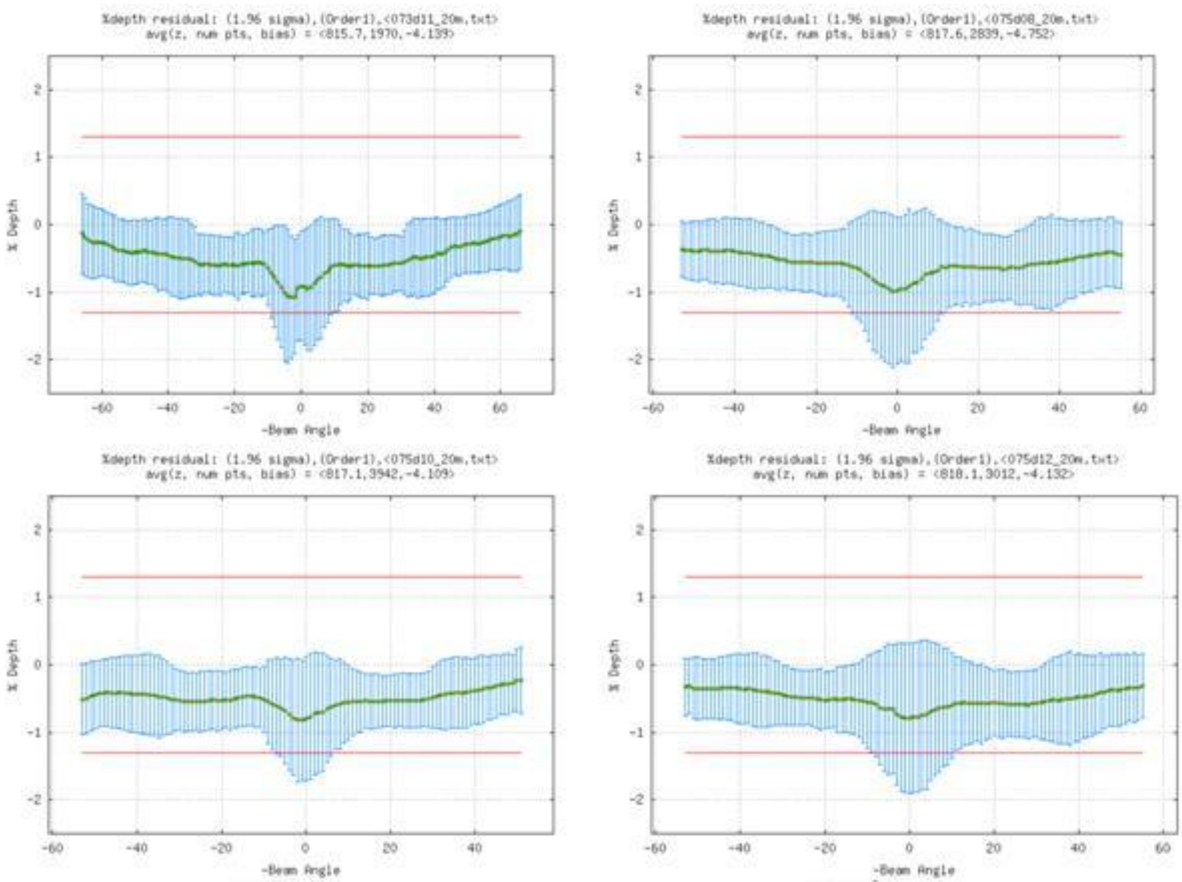

Fig. 12. *: Effects of changing the along track steering direction from static nadir to automated non-nadir. Starting in the upper left and going clockwise, the along track beam settings were set to Off, +/-2, +/-3, and +/-4 degrees, respectively.*

Figure 13 shows the best beam statistics results achieved with a combination use of both penetration filter setting at Medium and along track steering set at +/-2 degrees. A definite improvement can be seen in comparing these plots from those of Figures 7 and 8. Note in *Figure 13* the nadir area error-bar peak zone is greatly suppressed, and a much more level spread of uncertainty is present across the swath with all standard deviation bars below the IHO Order 1 threshold. (Still, an overall average difference, *avg* (*bias*), of about -3 m exists between the data file and the reference surface.)

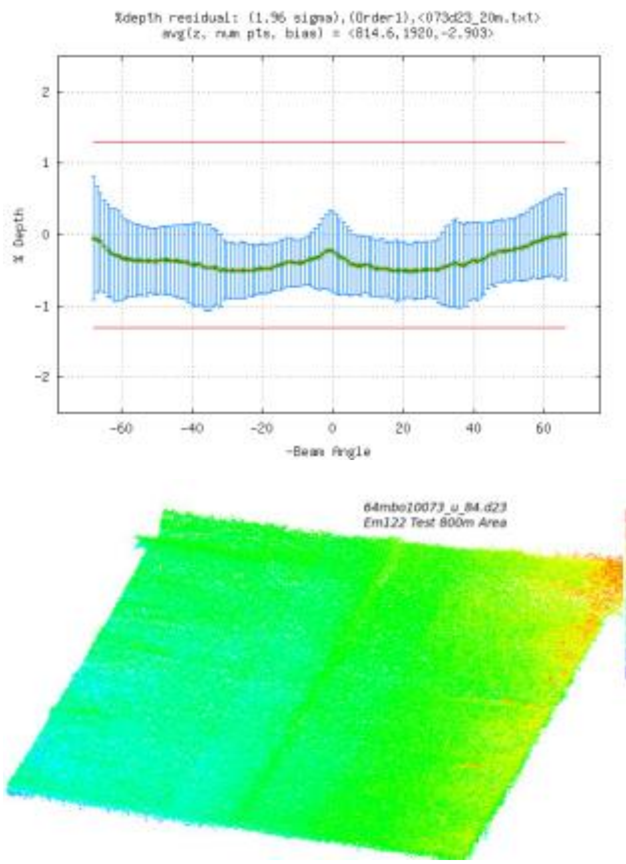

Fig. 13. *: Best results using a combination of parameter settings; penetration filter was set to Medium, and the along track beam steering was +/-2 degrees.*

Case Study of Beam Statistics Use for Survey Planning and Post-Processing

The beam statistics technique may also be used to evaluate data collected during an operational survey and provide key guidance for survey planning to optimize survey execution and subsequent post-processing. On a recent bathymetry survey aboard USNS Mary Sears, the 95-kHz Simrad EM1002 multibeam sonar was employed in shallow water depths, averaging 53 m deep. For the first four survey days, the starboard beams exhibited excessive noise until hardware troubleshooting relieved the problem. Figure 14 shows raw data from a swath profile view of an EM1002 line, demonstrating the degree of noise on the starboard side. The beam statistics technique was used to determine what portions of the swath were acceptable to use in later post-processing stages. From the results, survey planning was adjusted to ensure 100% coverage was achieved from adjacent swaths with acceptable quality data.

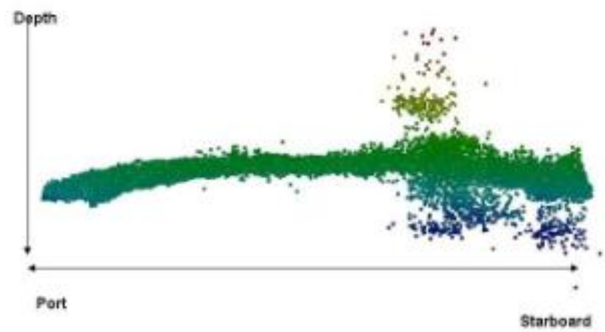

Fig. 14. *: Swath editor north-looking display of raw EM1002 errant starboard beams.*

The nearshore location of this survey area resulted in a highly dynamic and unstable sound speed profile structure both spatially and temporally with heavy influence from fresh water inflow altering temperature and salinity profiles. The ship did not possess either an underway CTD or sound velocimeter profiler sensor, and on-station CTDs were collected but were too time-consuming and spatially limiting to employ as often as needed. XBTs were dropped frequently, but they provided no salinity data and thus produced an inherently less accurate sound speed profile than CTDs. Even latencies from XBT processing times degraded the sound speed profile data temporally. Spatial under-sampling of sound speed profiles typically results in sound refraction errors causing “frowns” or “smiles” on a swath profile view for an otherwise flat bottom. The refraction effect can add significant error to the estimated depths across the swath, most notably affecting the outer beams.

The EM1002 transducer array has a draft of about 5.5 m. On some lines within the survey area, variations of the sea surface sound velocity at the transducer array would drop by 6 m/s for a few minutes at a time. At 9-m depth, sound speed profiles were observed to vary by as much as 40 m/s throughout a 2-day period. *Figure 15* depicts swath profile views of several adjacent survey lines to illustrate the severe outer beam curvature. The initial explanation for the frown-shaped profiles assumed under-sampled sound speed profiles throughout the water mass and limited accuracies with XBTs as the sensor probe rather than CTDs. However, a later examination appears to indicate that an erroneous outer beam calibration value also contributed to the curvature problem, and may in fact be the predominating factor. The substantiating reason for con-outer beam angle calibration value as the predominating influence on the outer beam profile curvature is because *Figure 16* clearly demonstrates a fairly flat mean curve (green/red trace) from -15 degrees inboard to -50 degrees outboard. The EM1002 begins beam steering its beams out past 50 degrees, which matches where the beam statistics plot begins the downward curvature. The outer beam calibration value was also re-inspected and found to be at an unusually large value than what had been typically used on that vessel.

The difference between the nadir depths (generally considered to be the best estimate of the actual bottom depth because they are minimally affected by refraction) and the deepest outer beam depths for the several swaths in *Figure 15* is about 1.3 m. The IHO Order 1a 95% confidence level specification for 53-m water depth is +/-0.85 m, indicating an initial visual failure to comply with IHO requirements at these beam angles. Beam statistics analysis determined the available swath width able to meet the Order 1a requirement.

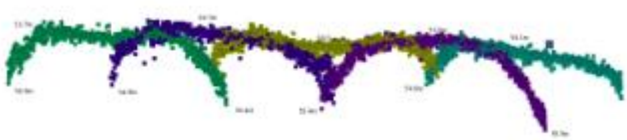

Fig. 15. : Example of pervasive outer beam error exceeding IHO Order 1a requirement.

Beam Statistics Results

The selection of data that was even suitable to build a reference surface was assessed by inspection of the tabular values by a file viewer program. Visual examination of the beam number with corresponding depth and beam angle provided a rough, qualitative determination for avoiding data that were clearly noisy (by virtue of significant depth change in adjacent beams) or affected by outer beam curvature. Beam angles between -55 and +40 degrees were selected for constructing a reference surface. The beam statistics plots of raw (unedited) sample data over the reference surface are shown in *Figure 16*, which largely confirms the visual inspection of the tabular data. The red lines bound the Order 1a specification. The red/green mean trace in the plot bends down on both port and starboard sides, indicating both sides suffer the apparent erroneous outer beam calibration value while the starboard side is also subject to excessive noise caused by the malfunctioning hardware.

Now having the plotted results of *Figure 16* rather than merely eye-balling suspect data to be rejected in the first stages of post-processing while visually scanning the data, the processor can collectively remove those beams within the offending beam angles exhibiting degraded data noted by having error bars extending beyond the Order 1a bounds or that are part of the outerbeam calibration problem.

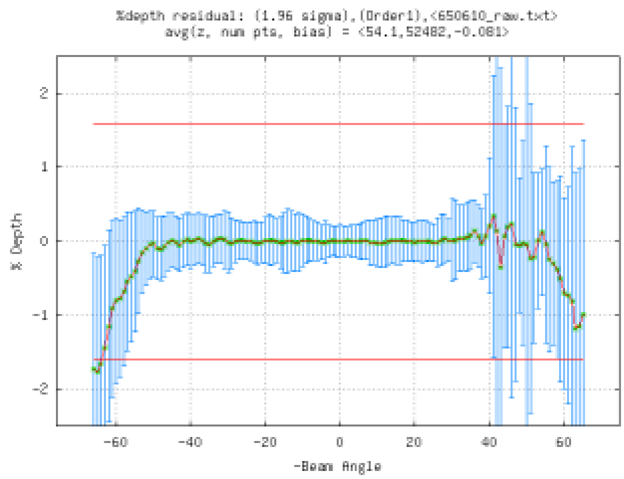

Fig. 16. *: Beam statistics results of unprocessed EM1002 test data over a reference surface. Beams outboard of -50 degrees depict a quickly increasing uncertainty in depth determination for the port side, while beams outboard of +40 degrees depict an escalating uncertainty for the starboard side.*

Using these results, the data collection strategy was adjusted so that the survey line spacing was decreased to facilitate covering the starboard side noise with adjacent beams until the damaged EM1002 hardware was replaced.

To mitigate the excessive error in the outermost beams, the swath width was decreased to +/- 55 degrees for the remainder of the survey operation. Figure 17 shows the final processed data after beams were removed and swath editing of the remaining portion of the data was completed. All remaining data then fell within an acceptable uncertainty tolerance.

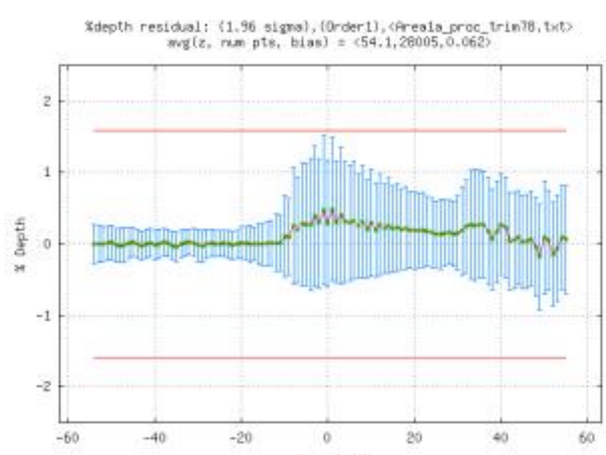

Fig. 16.: Example of pervasive outer beam error exceeding IHO Order 1a requirement.

Conclusions

The use of beam statistical application and analysis for multibeam sonar systems can help evaluate sonar performance. Specific benefits include characterizing sonar system artifacts and trends, assessing the operational performance capability and limitations of systems and/or datasets against requirements, and evaluating the effectiveness of sonar features and parameters. The particular lessons from the first case study involving USNS Pathfinder EM122 sonar began with the major advance that was made by the manufacturer in mitigating the soft bottom penetration problem associated with this 1° x 1° deep water sonar. Implementation of two new features in the sonar collection software was successfully and quantitatively analyzed by using the beam-wise statistics technique, with the conclusion that in an acoustically soft bottom test area, a medium or strong penetration filter worked well to address the penetration problem. Beam steering using the automated along track beam steering setting also helped mitigate the penetration problem. However, the combinational use of penetration filter and beam steering was the most effective and best means of mitigating the penetration problem.

The second case study showed that the beam statistics analysis can provide valuable input to post-processing the multibeam data to help determine data degradation trends, flag beams within angles that should be systematically rejected, and diagnose problem sources. This knowledge can then be used as feedback for survey planning to prevent degraded data at the collection stage.

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David H. Fabre is technical lead of the Bathymetry Databases Division of the Naval Oceanographic Office. He received BS and MS degrees in Applied Mathematics from Nicholls State University, in Thibodaux, Louisiana, in 1987 and 1989. Since 1990, he has been working indirectly and directly to support the U.S. Navy. His past efforts include software implementation for multibeam patch testing, total propagated error modeling, and multibeam sonar acceptance testing. Recently, he has been working toward providing uncertainty attribution for archive bathymetry. He strives to enhance bathymetric and hydrographic processing capabilities.

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