Automated Multibeam Crosscheck Analysis in an Operational Environment

By

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Abstract

Multibeam swath crossings generate thousands of collocated depths whose residuals, or depth differences, can be used to perform a statistical analysis at the crossing. The data discrepancies can reveal much about how the data have been collected and can provide valuable, near-real-time feedback to the surveyor. Two types of analysis methods can be performed to reveal trends along a track line in addition to depicting beam dependent errors. The area method produces a single quality indicator for the area ensonified by both development and crosscheck lines. In the beam method, the nadir beam of one line is compared to each beam of the swath in the crossing line.

Cross line analysis is a tedious process involving multiple steps, which include determining the location of the intersection, analyzing the overlapping bathymetric data, and plotting of the statistical results. Without automation, this process is virtually impossible to perform for more than just a few crossings. However, advances in multibeam processing software are such that these crossings can be analyzed continuously while the survey is in progress. From this ongoing analysis and feedback as to the sources of the prevalent errors, data collection processes can be improved, thus reducing input errors and also reducing manual editing required of the final data set.

This paper describes how the Naval Oceanographic Office (NAVOCEANO) implemented near-real-time application of crosscheck analysis during a recent shallow, relatively flat bathymetric survey conducted in the summer of 2004. A total of 1,440 crosschecks were obtained in a 200-nautical-mile-square area and analyzed with minimal increase in the overall processing time. Without automation, these crossings could not be analyzed efficiently or easily. Results of the crosscheck analysis provided feedback to improve the real-time data collection.

Introduction

Redundancy is perhaps the most useful quality control tool used in bathymetric or hydrographic data collection to analyze data differences where more than one survey line crosses the same geographic location. The redundant data could be along-track where swaths overlap, or as a result of track crossings, more commonly referred to as crosscheck lines or crosscheck intersections. Intersecting multibeam echosounder tracks produce thousands of redundant depth measurements that require crosscheck analysis to assess the quality of the data collected along each respective survey line.

NAVOCEANO has collected multibeam data since 1967. Since then, NAVOCEANO has either manually estimated crosscheck analysis by comparing sounding depth differences in close proximity, or more recently by employing a series of NAVOCEANO-developed software programs to analyze crosscheck data. Neither method was practical for a thorough analysis of the hundreds, sometimes thousands, of crossings generated each survey. The issue is compounded as the survey depths become shallower and the number of crosscheck lines increase due to decreasing survey line spacing. To manually evaluate crosschecks or to do repetitive execution of crosscheck software is labor-intensive and virtually impossible to accomplish real-time in shallow bathymetric environments. The need for automation in performing crosscheck analysis has become overtly apparent.

The technique of conducting an automated multibeam crosscheck analysis was originally presented in a technical paper presented at the 2003 Hydrographic Conference by Susan Sebastian and Dr. Dave Wells [1]. Sebastian and Wells describe two methods of multibeam crosscheck analysis, the area method and the beam-by-beam, or beam, method.

The first method is an area-based approach where a single statistic, the root mean square (RMS), can be calculated from the residuals of all collocated depths collected at the crossing of two multibeam swaths. The RMS is multiplied by 1.96 to get a 2-sigma value that is then used as a quality indicator. The quality indicator is then compared to a quality threshold based on the maximum allowable error (IHO SP-44, Table 2 [2]) and plotted geographically with a pass/fail color scheme as an indicator of along-track data quality.

The second method is to examine the depth residuals beam-by-beam across the entire swath of one line, compared to the more accurate nadir beams of the crossing file. These depth residuals can be plotted, beam-by-beam, as an across-track profile. The profile signature can reveal the source of error, or errors, that correspond to the quality indicator statistic calculated in the area-based method. Beam profiles can show whether roll bias, tide, sound speed, or other errors contributed to a cross line discrepancy [1].

Crosscheck Analysis Automation and Workflow

Automated crosscheck analysis can now be accomplished using the Survey Analysis and Area Based Editor (SABER), which was developed for NAVOCEANO through a cooperative research and development agreement with Science International Applications Corporation (SAIC) [3]. Crosscheck analysis techniques described in the 2003 paper were incorporated into SABER through technical exchange with SAIC. SABER is now employed on all NAVOCEANO survey platforms.

The entire automated crosscheck analysis process, depicted in Figure 1, is executed within the SABER 3.0 software suite with exception of the generation of crosscheck intersection graphics. The crosscheck profile graphics seen in this paper were generated with a *gnuplot* software program written by NAVOCEANO surveyors during the July 2004 survey. The automated generation of crosscheck profile graphics is not available within SABER 3.0 software.

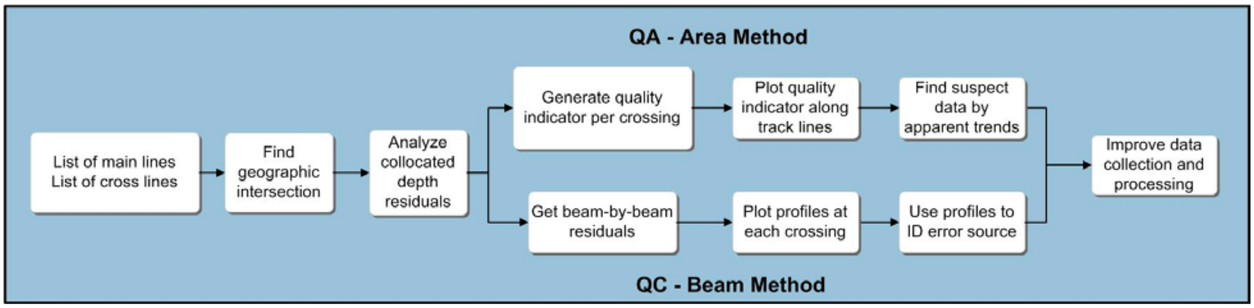

Figure 1. Crosscheck analysis process flow.

Once a survey line is completed, the analyst compiles one or more data files for the survey line into the survey line list file. The crosscheck line list files are used to locate and analyze the crosscheck intersections along the recently completed survey line. The software prompts the operator for a search radius within which the soundings are considered to be collocated for the quality indicator calculations. The operator then inputs the section of nadir beams in degrees that are to be used for beam profile residuals. The operator specifies the quality threshold for comparison, and this is usually a value based on the IHO SP-44 Table 2 maximum allowable error. The RMS output statistic is plotted at the crosscheck intersection in one of two colors, as seen to the right in Figure 2. If the RMS is equal to or less than the quality indicator statistic, the intersection RMS is plotted in green. Conversely, if the RMS exceeds the quality threshold, the value is plotted in red. It is important to note that the RMS serves as a quality assurance indicator in regards that it indicates only the relative residual value between the two files, not an absolute indication of the data error. Systematic errors common to both crosscheck data files will not be detected in this process [1].

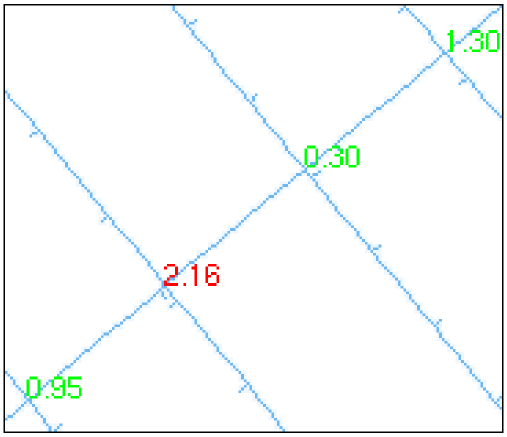

Figure 2. RMS values plotted at crosscheck intersections. The red value exceeded the 2.0-meter quality threshold.

Once failed intersections are identified on the area survey line, the next step is to determine the cause of the failed crosschecks identified by the plot. At this point the beam-by-beam method is employed, where all beams of one swath are compared to collocated nadir data depths of the opposing file. These beam-by-beam residuals can be plotted to produce a profile whose characteristic shape can be used to determine error sources. SABER produces a beam statistics file that can be used to generate these profiles. Quality control of the crosscheck intersection profiles provides clues as to probable cause of the errors that might be eradicated with proper interpretation of the crosscheck profile. This analysis must be done in both directions. The first direction uses the full swath of File 1 compared to the nadir depths of File 2, and the second profile uses the nadir of File 1 compared to the entire swath of File 2. All profile plots will show two curves.

Operational Application and Evaluation

Two surveys were conducted in 2004 in waters where the seafloor depth ranged from 80 to 110 meters and was primarily flat and featureless. Survey specifications for the approximately 15,000-square-nautical-mile survey illustrated in Figure 3 required 100% ensonification of the seafloor with survey lines 150 meters apart due to side-scan requirements. Crosscheck lines were set at ten times the survey line spacing, or 1,500 meters apart during the survey. The survey lines follow the bathymetric contours and so were at a diagonal from the area boundary. This resulted in the shortest survey line crossing only three crosscheck lines. The longer lines in the middle of the area crossed up to 30 crosscheck lines. This generated thousands of crossings, which would be impossible to analyze without automation.

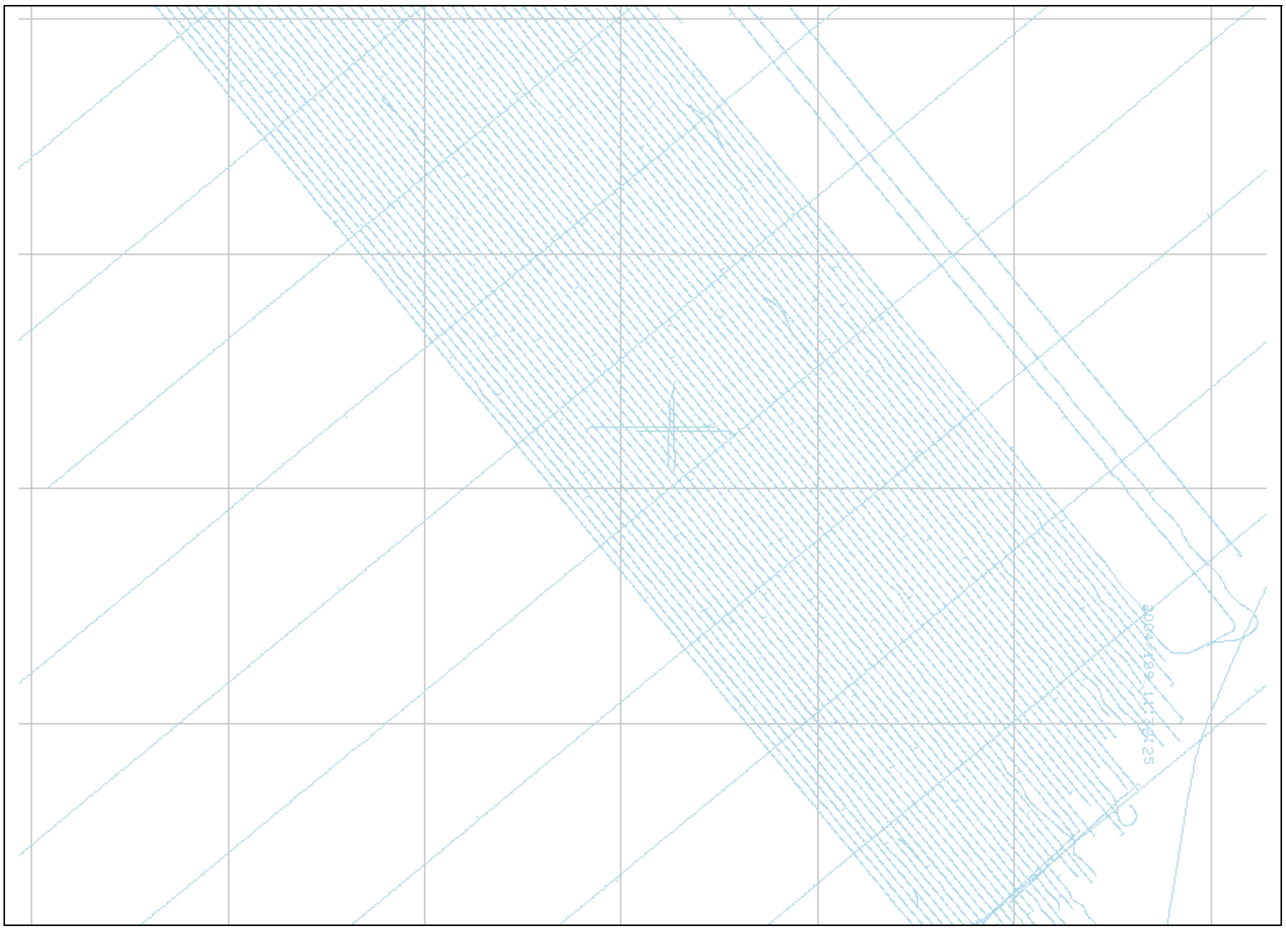

Figure 3. Survey lines 150 meters apart from the July 2004 survey are oriented northwest to southeast. Crosscheck lines 1,500 meter line spacing are oriented northeast to southwest.

The quality threshold limits of the area are 2.09 meters in 80 meter depths, and up to 2.72 meters in 110 meter depths to meet IHO Order 2 specifications for the working depths of the survey. One limiting factor discovered during the survey was that the quality indicator could not be adjusted with changing depths and could only be a static entry throughout the crosscheck analysis. To err on the side of caution, a pessimistic 2.0-meter threshold value was selected for the entire survey area.

The “Find” and “Analyze” functions of the program worked well as a quality assurance tool, and the quality indicator was successfully plotted on screen. However, the beam statistic file was to be exported to Excel to generate the corresponding profiles, as recommended by the SABER Manual. The survey team did create a fraction of the crosscheck intersection profiles by using Excel, but this method proved to be very labor intensive and required the full-time attention of one surveyor. Only 200 crosscheck profiles could be produced in three days. These few profiles had some usefulness as a quality control tool but could not be generated close enough to real time. It was painfully evident that the profile generation would also have to be automated.

During the subsequent month of operational testing, the survey team wrote a Linux-based *gnuplot* script to convert the beam statistics file into beam-by-beam profile plots of the crosscheck intersections. This automation greatly decreased the amount of time and manual labor required to analyze and produce the intersection profiles. The crosscheck profiles produced by the *gnuplot* program gave indications as to problematic causes of the remaining poor crosschecks. Possible sources of error include tidal offsets, draft error, roll bias, sound speed errors and manual editing errors. It is important to note that the crosscheck profiles work well in flat seafloor topography, but due to position error, large variations in the seafloor are likely to distort the crosscheck profile signatures.

The profile in Figure 4 represents the ideal crosscheck cross section, 220 meters in width. The topography of the ocean floor was very flat and featureless throughout the 2004 survey. The development line was run August 4, 2004, and the crosscheck line was run September 21, 2001. Note how the two profiles are nearly coincident with each other and both are very near the 0.0 vertical offset. Further, the flat ends of the profiles indicate the sound speed profile employed during data collection was appropriate for both files.

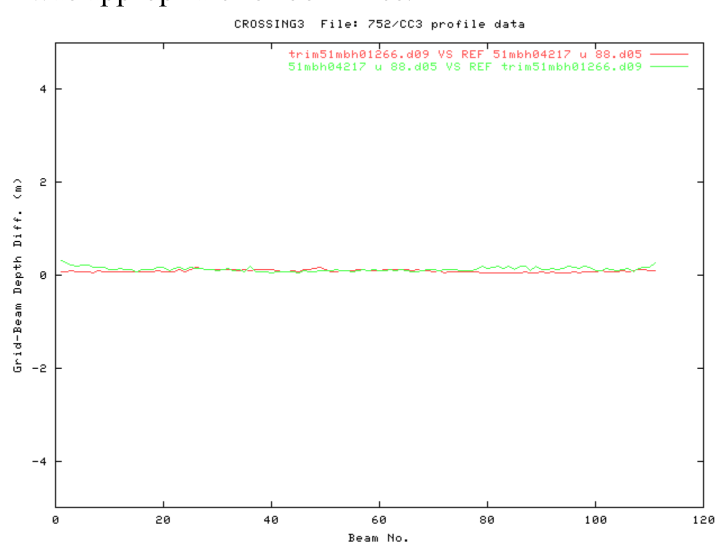

Figure 4. The ideal crosscheck profile of the 111-beam EM1002 multibeam sonar from surveys 3 years apart.

Water Level Errors

The *gnuplot* script automation of intersection profile graphics proved to be quite revealing. In the northwest corner of the survey area, it was evident that many crosschecks failed due to the high number of quality indicators plotted in red, as seen in Figure 5a. Figure 5b shows the swath coverage as the survey vessel was traveling to the northwest. At the time of crossing of the tidal boundary, the depths showed an instantaneous increase due to the predicted tide correctors at the zone boundary. These failures seemed to correspond with crossing the tide zone boundary. This was confirmed by plotting the profiles, which showed a constant offset close to 2 meters in both directions, as seen in Figure 5c. To remedy, a request was made to the in-house Tides Group to provide new constituents. This was done with good results, and improved predicted tide correctors were obtained. Unfortunately, no real tide gage data was available in this area. Tide correctors were recalculated and reapplied, and many of the quality indicators were then plotted green instead of red.

In the southeast region of the survey area, tide zone problems were not as extensive as in the northwest. This was determined by crossing analysis where both data files were from the current survey, using the same draft values. However, in the southeast area, there were also numerous failures (Figure 6a) and vertical offset problems (Figure 6b). A typical profile at these failed crosschecks, seen in Figure 6b, shows a vertical offset of nearly two meters between data files, indicating water level problems. After reviewing the vessel draft and tidal offsets and ruling out a large tide error, the survey crew clearly needed to do additional research to diagnose the offset problem.

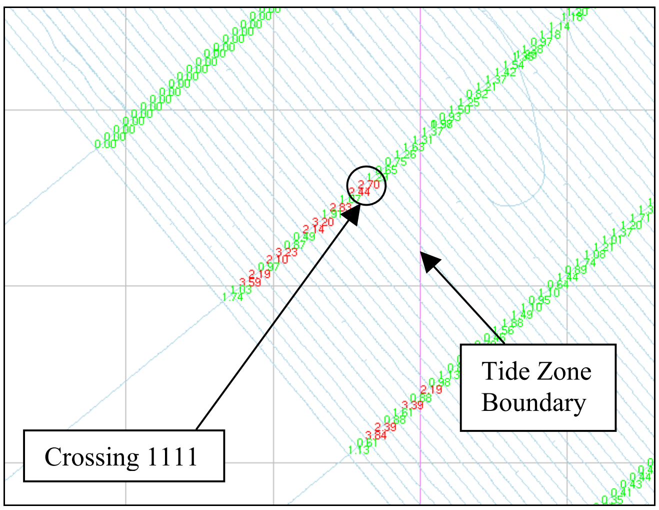

Figure 5a. Plan view of survey lines with failed (red) RMS95 quality assurance indicators when crossing the tide zone boundary.

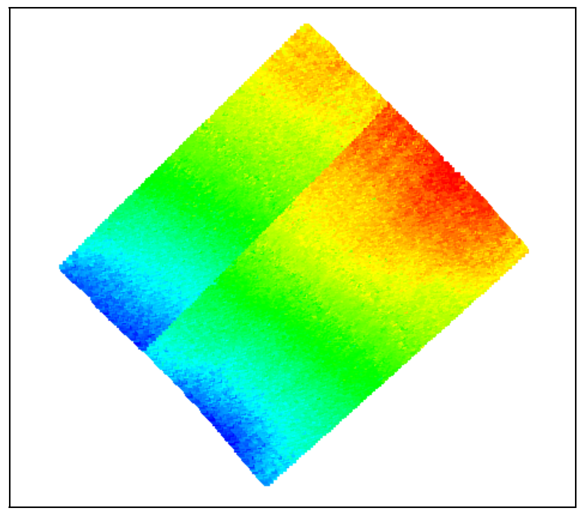

Figure 5b. Multibeam swath of survey line showed depth increase due to the predicted tide boundary.

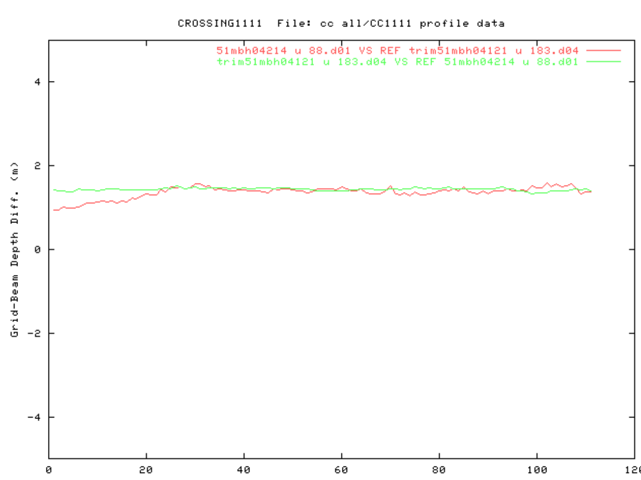

Figure 5c. The crosscheck profile showing a vertical offset in both directions of crosscheck 1111.

Multiple Survey Draft Errors

Many crosscheck lines in the survey area were accomplished during six different surveys dating back to 2001. Archived crosscheck lines were retrieved and uploaded in order to perform the crosscheck analysis. Initial analysis of survey line 752 showed a single crosscheck exceeding the quality threshold when viewed as a single line. But when the line was combined with adjacent survey lines, as seen in Figure 5a, a pattern was revealed that showed multiple failures following the crosscheck line.

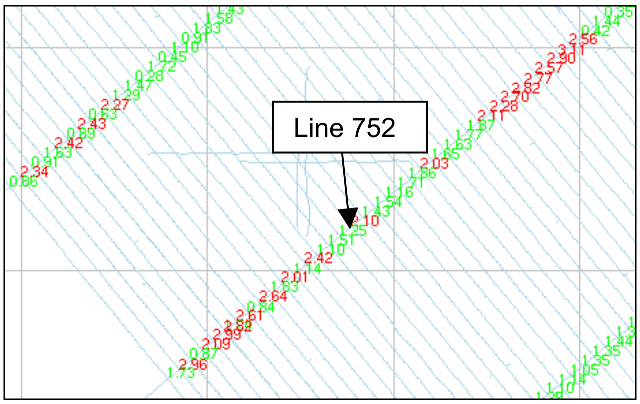

Figure 6a. Plan view of survey lines with failed (red) quality assurance indicators.

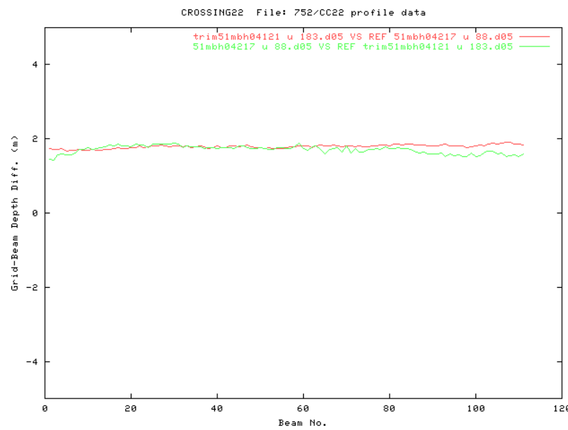

Figure 6b. A quality control crosscheck profile showing a positive vertical offset in both beam method views of crosscheck 22 on survey line 752.

Eliminating large tidal offsets meant the error must be draft related. Investigation of vessel deck logs for the five cross line surveys conducted in the region yielded multiple draft discrepancies when compared to the survey draft values in the multibeam index files as noted in Table 1. (This is largely attributed to the ever-confusing "waterline" parameter used by the Simrad EM1002.) The depth of the EM1002 transducer is added to the deck log value for final draft.

Table 1. Draft errors by survey.

Survey Start Date	Survey End Date	Deck Log Value in meters	Deck Log Value Plus EM1002	Draft Value in Data Files	Delta Draft Error
14 Aug 01	9 Sep 01	4.13	4.61	4.37	-0.24
18 Sep 01	9 Oct 01	4.29	4.78	4.37	-0.41
26 Apr 04	17 May 04	4.11	4.60	4.06	-0.54
21 May 04	12 Jun 04	4.09	4.57	4.37	-0.20
21 Jun 04	12 Jul 04	4.09	4.50	4.11	-0.39
16 Jul 04	9 Aug 04	4.19	4.67	4.67	0.0

Draft correction deltas applied to all survey files decreased the mean depth differences of the 1,440 crosschecks, along with all other survey measurements, by as much as 54 centimeters. Depth difference distributions before and after the applied draft corrections are seen in Figures 7a and 7b. Figure 8 illustrates a dramatic increase in passing quality assurance indicators over Figure 6a, where the frequency of red quality indicators is much less.

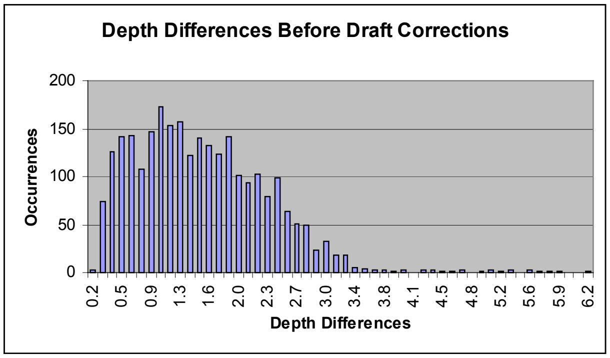

Figure 7a. Depth difference distribution of six surveys prior to draft corrections.

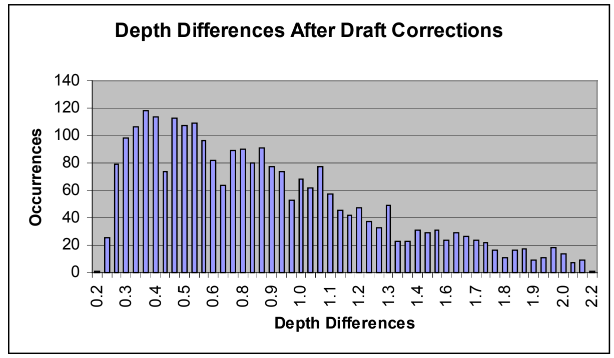

Figure 7b. Depth difference distribution of six surveys after draft corrections.

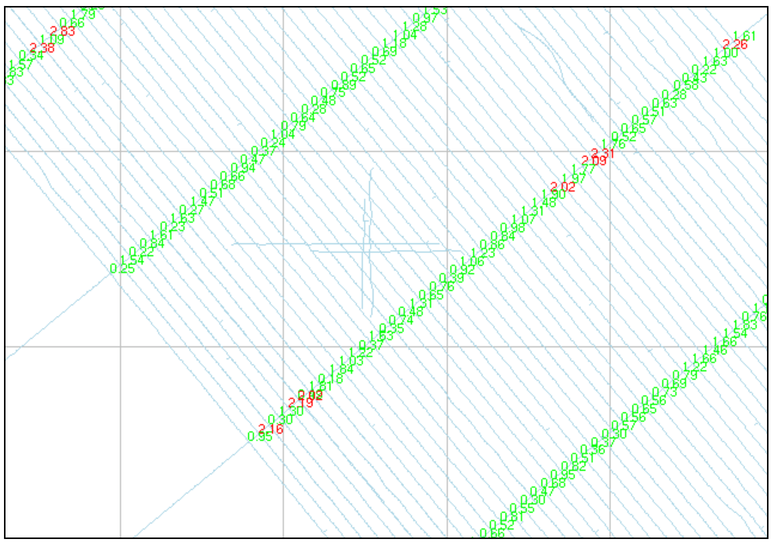

Figure 8. Plan view of quality assurance indicators after draft corrections.

With the multiple survey files now leveled with respect to draft, a larger percentage of crosscheck intersections passed the quality assurance test. But there were other intersections that continued to fail. Further analysis of the intersection profiles was needed to perform quality control measures. Output from the analysis, illustrated in Figure 9, produced a mean error of 0.46-meter and a 1.73-meter RMS95 confidence level for all intersections in the data set after manual editing and applying all corrections.

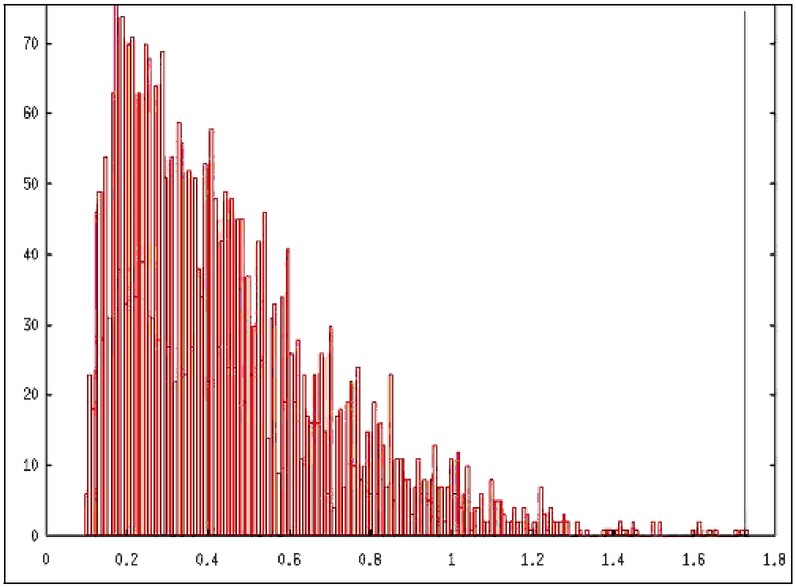

Figure 9. Survey histogram plot of 1,440 crosschecks analyzed during the 2004 survey. The vertical black line on the right represents RMS95 confidence level of the data is within 1.73 meters.

Other Errors

During the July 2004 survey, sound velocity profile (SVP) estimation became problematic and presented a significant challenge during the afternoon hours. When the surface wind became less than 10 knots and the resulting sea state relatively flat, shallow pools of localized warm and cool sea surface temperature zones form. It was not uncommon for the sea surface sound velocimeter (SSSV) indicator, which is mounted at the transducer depth, to change from 1538.5 m/s to 1542.5 m/s in less than a minute. The surveyor had to maintain a strict watch of the SSSV, changing the profile when necessary to maintain a good sound speed profile. Incorrect SVPs cause the outer beams to bend from their normal horizontal profiles. In Figure 10, which depicts the crosscheck analysis of development line 753 at crossing 26, the green profile is curling upward noticeably. This is an example of the SVP transducer depth exceeding the sound velocity that the SSSV was measuring. Of the two files, it was the development line run on August 3 that had the SVP problem because the reference file (noted by "REF" in the survey line name at the top of Figure 10) was the nadir beam depths from the crosscheck line ran by the same survey crew on June 29. Conversely, when viewing the red profile of the across-track beams from the crosscheck line against the reference nadir beams of the development line, the SVP produced a relatively flat profile. Thus, the error was a sound speed error incurred on the development line.

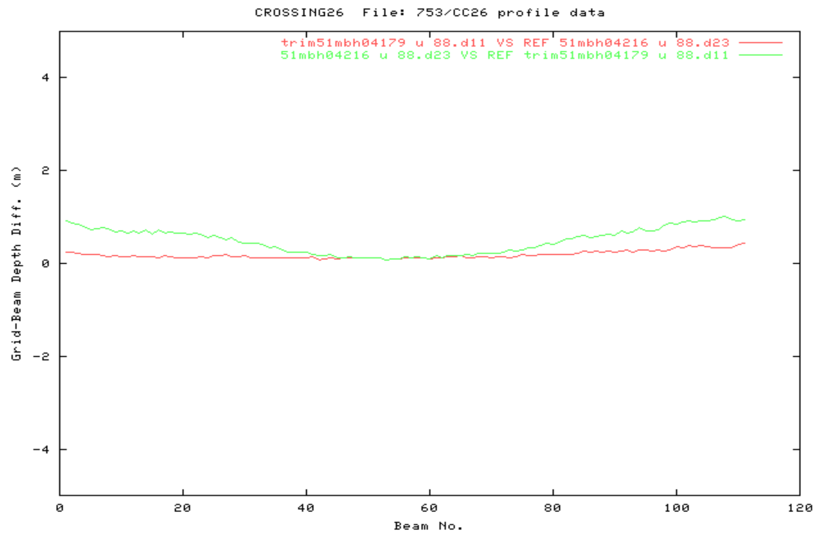

Figure 10. A bad crosscheck due to sound speed error in the green profile. Here the SVP exceeded the SSSV sound speed, causing the outer beams to curl upward.

Figure 11 is a crosscheck analysis of development line 931 at crossing 1. Here the green profile is curling abruptly downward. The SVP entered into the EM1002 was slower than the sound velocity detected by the SSSV, causing the outer third of the beams to bend downward. To identify the file, the reference file nadir beams in the green profile are from the September 2001 survey, and the development line was from July 2004. When viewing the crosscheck intersection from the crosscheck line of September 2001, the red profile indicates good sound velocity when compared to the July 2004 nadir beams. Another problem at this intersection is the vertical depth difference between the two files. Both files are centered just over 2.2-meter difference when compared to each other. This is an indication that one or possibly both files have a tidal offset problem. The only way to differentiate which file has the problem is to compare adjacent crossings along the same development and crosscheck lines.

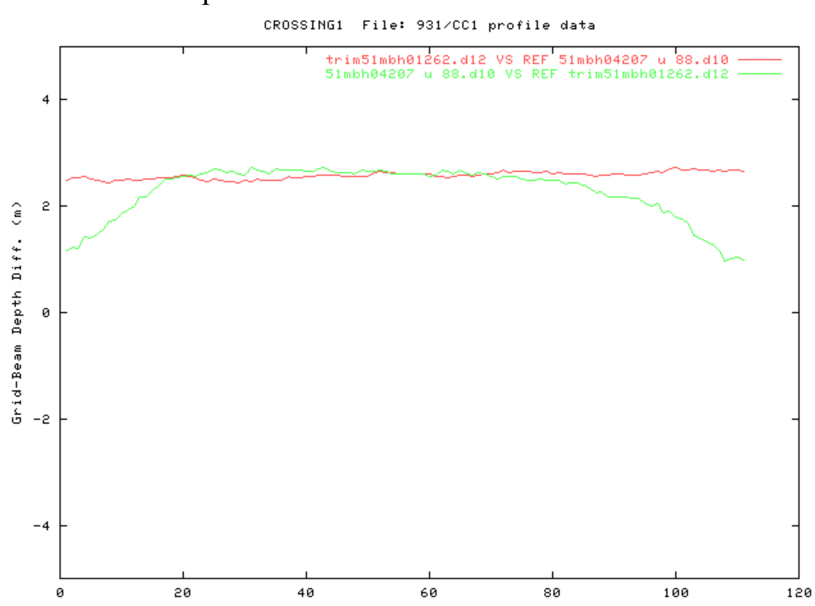

Figure 11. A bad crosscheck due to sound speed error in the green profile. In this case the SSSV exceeded the SVP sound speed, forcing the outer beams to curl downward.

In Figure 12a, the green profile on development line 751 at crossing 2 indicates a possible starboard bias in the vessel roll. To verify this additional cross section, profiles on the same survey line need to be evaluated. In this case, the roll bias was confirmed at crossing 4, Figure 12b. A full set of vessel calibrations was performed to the starboard roll bias.

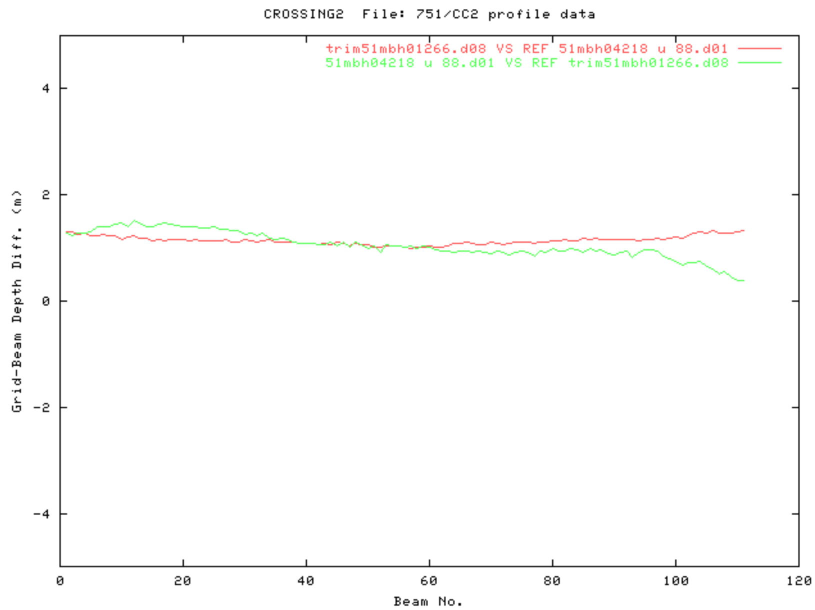

Figure 12a. Bad crosscheck at crossing 2 on transect 751 due to a starboard roll bias.

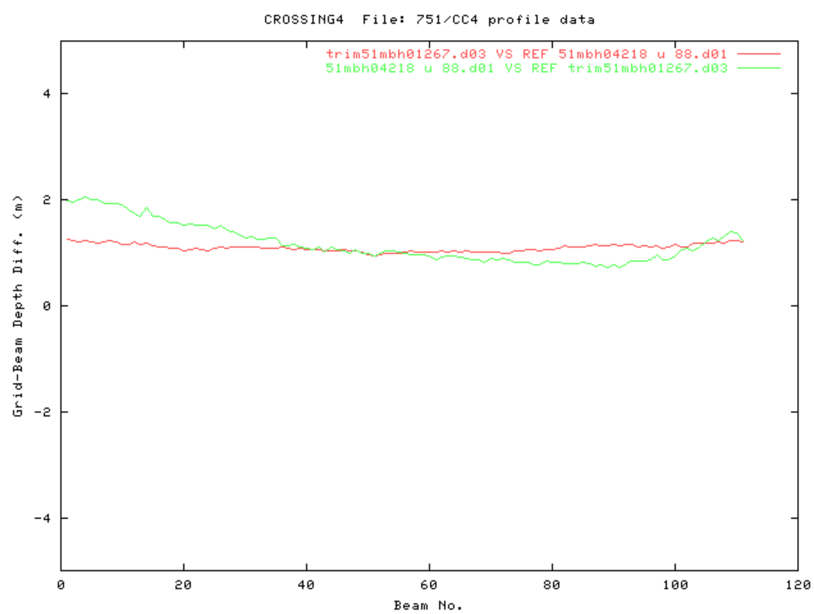

Figure 12b. Starboard roll bias confirmed with crossing 4 on transect 751.

In the final category, blunders are typically caused by poorly edited multibeam files. In Figure 13, the red profile from September 2001 indicates a vast depth difference with the nadir beam data from July 2004. Further investigation revealed unedited outliers in the July data caused the spike in the depth differences.

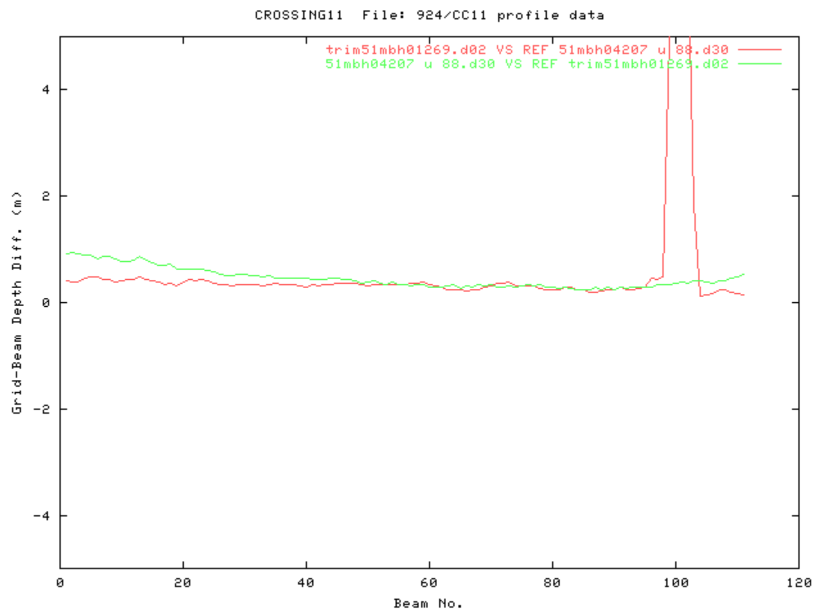

Figure 13. Failing to properly edit the multibeam data will result in data spikes in crosscheck analysis.

Ideally, crosscheck analysis should be accomplished at the end of each development line to determine the quality of the line. This allows data quality feedback so that adjustments can be made to the equipment or vessel configuration before starting the next development line. Through this process, the evaluation to feedback time frame was tremendously decreased, and for the first time, graphic output was provided to evaluate possible sources of error for timely feedback into the survey data collection process.

RMS95 Versus Sorted 95% Confidence Level

During the post-survey analysis of the data in preparation for this paper, the authors noticed a consistent discrepancy in the magnitude of RMS95 values calculated by the SABER analyze crossings program. The program calculates and plots the RMS95 value from the depth residuals, which is multiplied by 1.96 to approximate the second standard deviation. When the plotted RMS95 quality assurance values were compared to the profile plots, the RMS95 numbers were higher than the crosscheck profiles indicated. Discussions with Dave Wells, University of Southern Mississippi, led to the conclusion that using a calculated statistic is more ambiguous than using the sorted 95th percentile. Figure 14 shows calculated RMS95 values in dark blue trending higher than the sorted 95th percentile of occurrence values shown in pink. The sorted residuals at 95% appear to be a truer quality assurance indicator. Figure 15 shows the corrected and recalculated crosscheck intersections using the sorted 95th percentile confidence levels; all crosschecks in the image are within IHO Order II specifications. A request has been made to SAIC for modifications to the SABER software, which will replace the calculated RMS95 value with the sorted 95th percentile value.

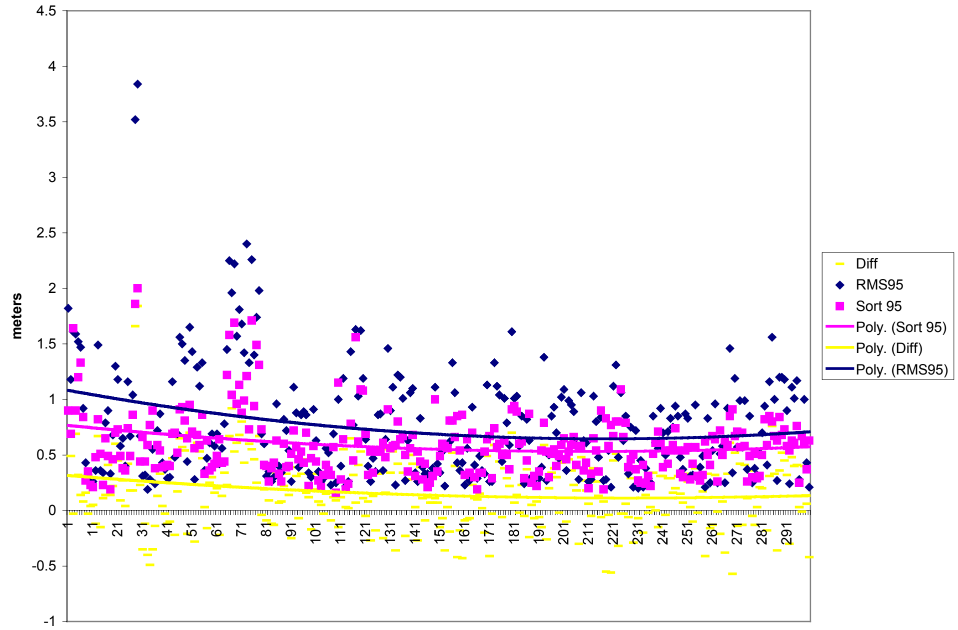

Figure 14. Calculated RMS (blue) values for 1,440 crosscheck intersections verses sorted 95th confidence percentile (pink) and the delta between the two (yellow).

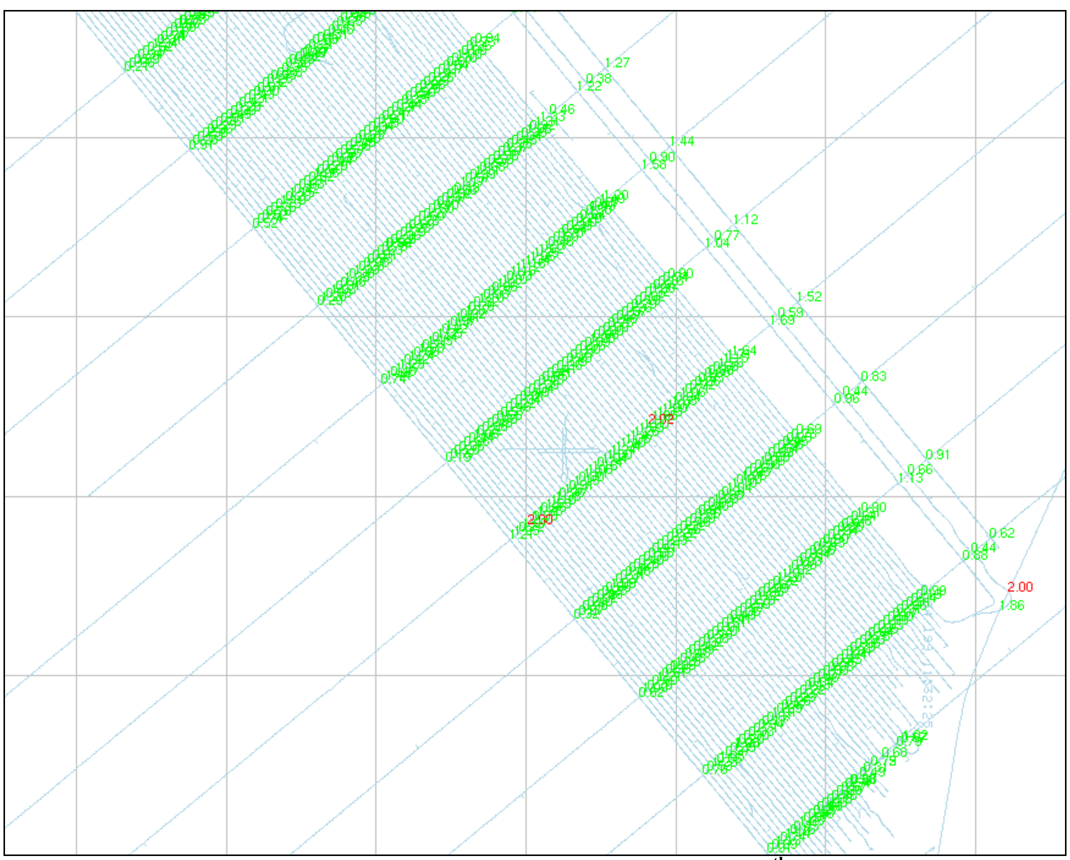

Figure 15. Plan view of 1,440 crosscheck intersections using sorted 95th percentile quality indicator after draft corrections. Note: All red quality indicator numbers in the image are within the IHO Order II specifications for the working depths of the survey at those locations.

Conclusion

Quality assurance and quality control of hydrographic and bathymetric data collection are enabled by redundancy. The ability to collect and analyze thousands of collocated depth differences for one geographic location from two or more survey lines of data is the foundation of confidence in the data set. With the advent of multibeam collection systems growing in complexity since the mid-1960s, the ever-increasing volume of data hampers the ability to employ quality control methods real-time during data collection. Automation of quality assurance and quality control of data collection is critical in keeping up the pace while ensuring quality.

The automated crosscheck analysis tests were conducted in an ideal region where the seafloor was flat and featureless. The test highlighted the importance of ensuring the vessel draft parameter is correct in the multibeam configuration files. The water level error became apparent only when the multiple surveys were compared simultaneously in the crosscheck quality indicator values. Second, as discovered after the first month at sea, graphic profiles of beam statistic files are necessary for quality control interpretation and employment of appropriate corrective actions. Without a real-time quality assessment tool to gauge the quality of the collected data, corrective actions could not be employed in a timely manner.

Finally, the question of proper statistics led to the realization that the calculated RMS95 value may not be the most appropriate statistic to use due to its inflation of the quality indicator statistic. As visible in the profile graphics and screen grab imagery, it appears the sorted 95th percentile statistic is the better statistic because it does not induce any ambiguity as a result of mathematical manipulation.

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