Article

THE ANALYSIS OF ERROR SOURCES AND QUALITY ASSESSMENT OF MULTIBEAM SOUNDING PRODUCTS

By C. HUANG [1], G. BIAN [2] , X. LU [1], M. WANG [2], X. HUANG [1], K. WANG [1]

Abstract

The use of multibeam sounding systems for bathymetric surveys requires an understanding of the gross errors and deviations caused by the dynamic marine environment and the instrumentation in use. This paper discusses these errors and the quality inspection specifications and processes applied to multibeam system measurements. The quality control plans covering the multibeam sounding data collection and stages of processing including pre-production, data evaluation, checking and final acceptance are then identified.

Résumé

Le recours à des systèmes de sondage multifaisceaux pour l'exécution de levés bathymétriques requiert une compréhension des erreurs grossières et des écarts causés par le milieu marin dynamique et par les instruments utilisés. Cet article traite de ces erreurs ainsi que des spécifications et procédures d'inspection de la qualité appliquées aux mesures du système multifaisceaux. Les plans de contrôle de la qualité couvrant la collecte de données provenant de sondages multifaisceaux ainsi que les étapes de traitement incluant la pré-production, l'évaluation des données, la vérification et l'approbation finale, sont ensuite identifiés.

Resumen

El uso de sistemas de sondaje multihaz para levantamientos batimétricos requiere una comprensión de los errores gruesos y las desviaciones causados por el medio ambiente marino dinámico y por los instrumentos que se estén utilizando. Este artículo aborda estos errores y las especificaciones de la inspección de la calidad y los procesos aplicados a las mediciones de los sistemas multihaz. Se identifican entonces los planes de control de calidad que cubren la recogida de datos de sondajes multihaz y las etapas del procesado, incluyendo la producción previa, la evaluación, la verificación y la aceptación final de los datos.

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1. Introduction

Marine topographic data is an important component in any model (or similar abstraction) being developed for the marine environment. The majority of this information is obtained by ship-borne measurements using single beam echo sounding (SBES) and multibeam echo sounding (MBES) technologies. Due to the improved seafloor coverage, efficiency and precision of MBES, this technology is now widely employed in the surveying of important port and channel routes and for detecting underwater obstructions (LI JB et al., 1999; ZHAO JH et al., 2008). The nominal precision and resolution can be in the order of centimetres for new generation MBES technologies and errors caused by the sounding system, in comparison to other factors, can have little influence on the quality of the sounding data. Therefore, these other factors need to be considered to evaluate the impact on products generated from MBES data collection. These factors include field organization and the standardization of data processing activities including comprehensive product inspection.

An analysis of multibeam sounding data collected in recent years by different survey units indicates that the quality of products are mainly affected by the following factors:

- dynamic environment factors (wind, air pressure, temperature, salinity, density, wave, tide and current);
- diligence of field work practices; and
- data processing.

A number of gross and systematic errors were found to exist in the products and these affect the value of the MBES data collection and the application of the products. In addition, quality problems can be due to system hardware configuration and the improper maintenance of the equipment. These can be difficult to understand but must be given the appropriate attention by the hydrographic system engineers responsible for maintaining the equipment.

Therefore, rigorous quality control and assurance processes must be applied during the data acquisition, data processing and product generation steps to eliminate each type of gross and/or systematic error. Furthermore, the quality control schemes must be described with enough detail and rigor to assure a third party of the data quality. These schemes must address the operation of the equipment to ensure system characteristics and capabilities are comprehensive, have wide applicability and meet the expected level of operation.

2. Analysis of MBES Error Sources

2.1 Gross Errors

A MBES survey operation typically combines a number of systems including a transducer, positioning system, surface sound velocity probe, Position and Orientation System (POS), sound velocity profiler, tide gauge and other auxiliary systems. Abnormal data will inevitably exist in the collected sounding data e.g. position, attitude, sound velocity, tide, depth. These data abnormalities are caused by equipment noise, the complex and dynamic environment and the sonar parameter complexities. During processing operations, if these abnormal data are not correctly identified and dealt with to correct the issue, isolated depth and position abnormalities will exist in the sounding data. This kind of gross error is also named a pseudo signal. Hence, a false picture of the marine topography will be presented by the gross errors and these must be determined and eliminated.

When analyzing MBES data, the common processing methods include artificial translation, trend surface filters, robust estimation and the Combined Uncertainty Bathymetry Estimator (CUBE) algorithm (YANG FL et al., 2004; LI MS et al., 2007; HUANG CH et al., 2010; HUANG XY et al., 2010; HUANG MT et al., 2011). An example of bathymetric data being analyzed and cleaned using the CUBE algorithm method is shown in Figure.1. The gross errors that exist in Figure 1(a) have been eliminated by the application of the CUBE algorithm in Figure 1(b). A more faithful and accurate representation of the marine topography can be depicted after eliminating the errors.

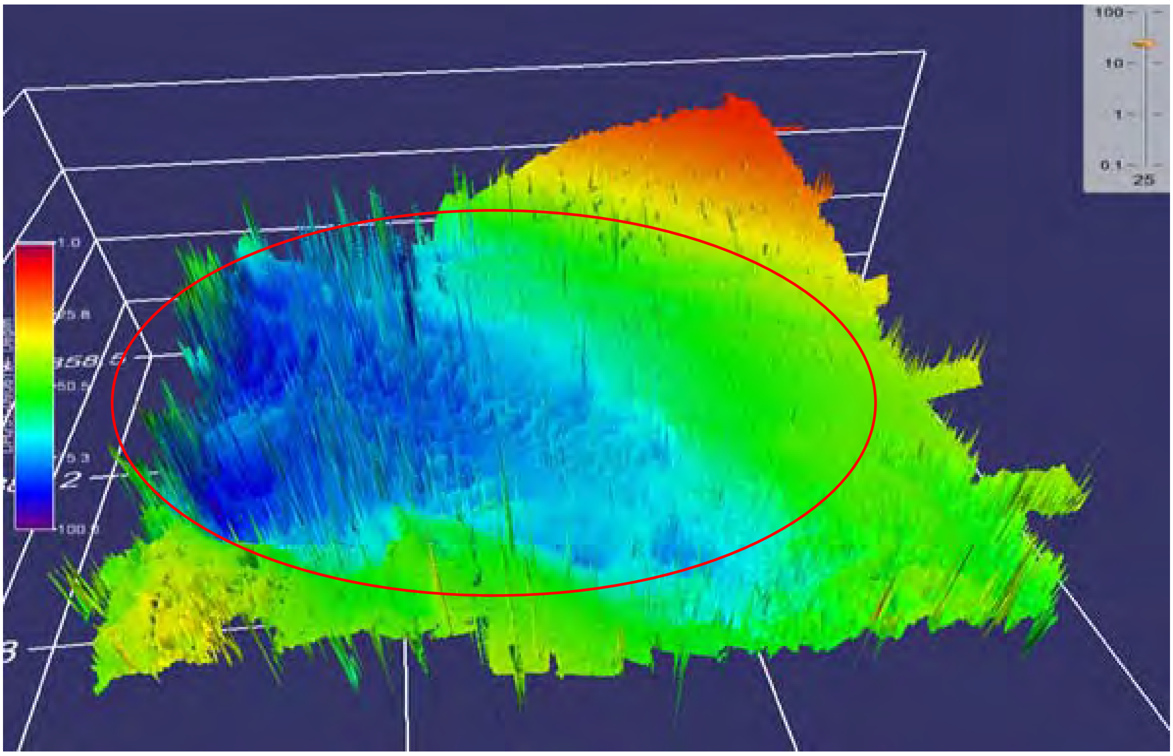


Figure 1(a): *Before filtering*

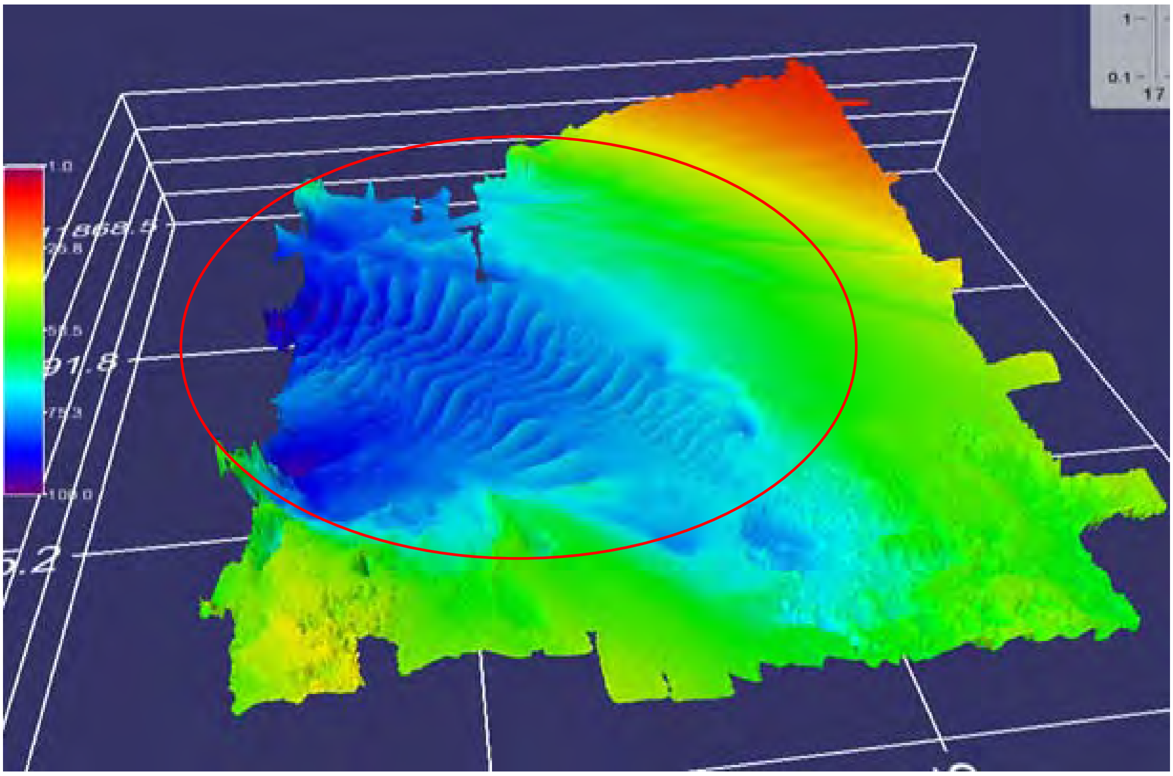


Figure 1(b): *After Filtering*

Figure 1*: A typical gross error and filtering effect – (a) Before Filter (b) After Filter*

2.2 Systematic Errors

Based on the MBES equipment configuration, systematic errors can occur in position, attitude, sound velocity, tide and sounding system measurements. Furthermore, these errors affect position and depth data. Systematic errors need to be qualitatively and quantitatively analyzed.

The systematic errors in position data can be detected and calibrated by the fixed deviation in the plane position. This is obtained by the stability test of the positioning system. Furthermore, where the positioning signal is lost by an equipment malfunction and poor environment, the sampling interval of the position information can be considered to be reasonable and accurate by using interpolation and extrapolation measures.

The systematic errors caused by poor calibration of the transducer installation results in the undulation of "V" phenomena of the marine topography. This will be visible along the track showing pitch, roll and heave errors as shown in ***Figure 2***. Although the transducer installation errors can be corrected, systematic errors can also be caused by environment conditions such as wind, wave and current. Meanwhile the systematic errors will result in a slow linear change during the capture process. Hence, these errors must be corrected in post processing.

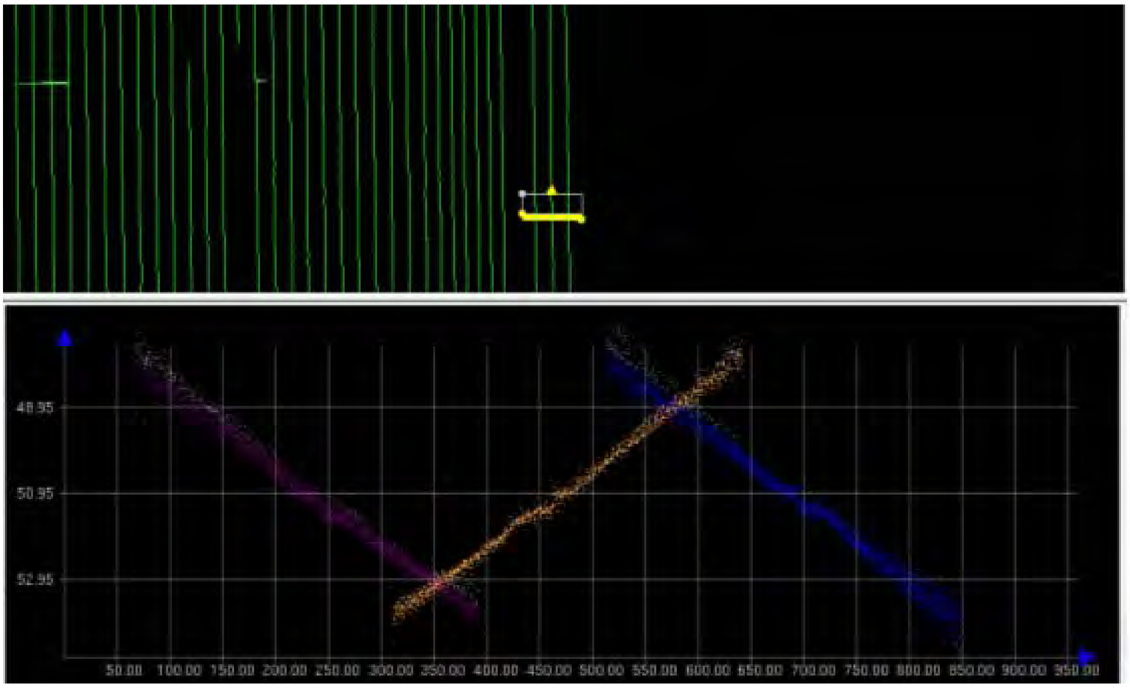


Figure 2: *The systematic error of "V" phenomena in sounding swath*

Systematic errors from an incorrect attitude correction occur for two primary reasons:

- The instability of the transducer installation - the real attitude will not be in accordance with the observed attitude of the POS. There will be a high frequency resonance of the transducer and survey platform, which is also influenced by the environment factors such as wind, wave and current (YANG FL et al., 2009). If this influence can not be reduced, regular undulations will be found in the sounding data.
- Due to possible un-synchronized GPS 1PPS signals, inconsistent time lags can exist between the POS and transducer, so the attitude data and sounding data will not be synchronized and a "butterfly" phenomena will be observed in the swath as shown in ***Figure 3***.

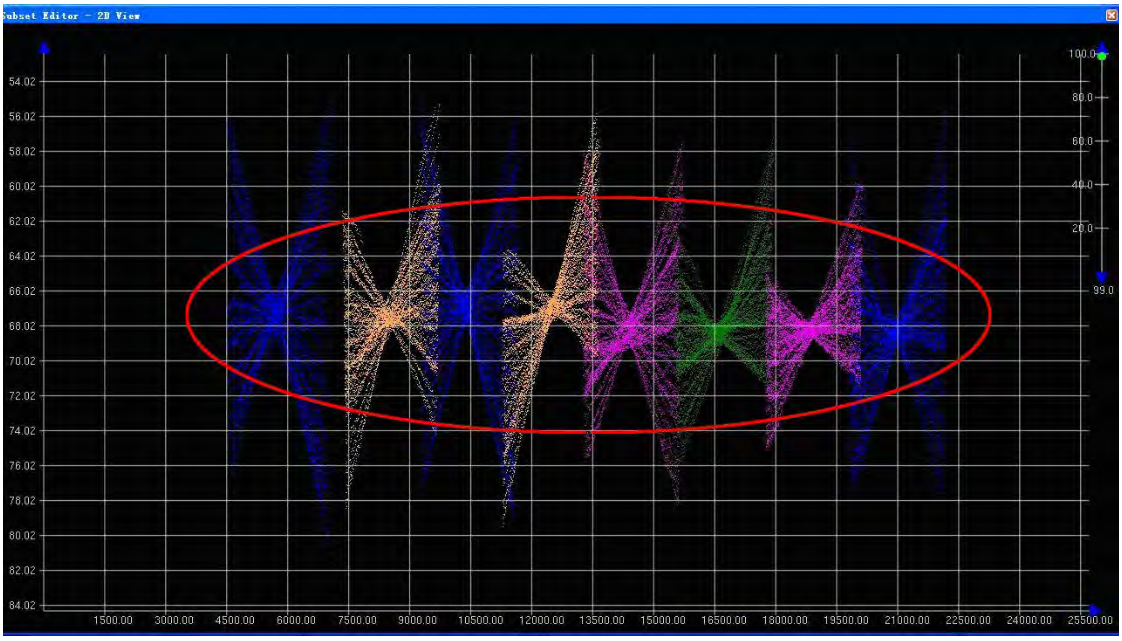


Figure 3: *The systematic error of "butterfly" phenomena in sounding swath*

The accuracy of the marine topography will also be affected by any inaccuracy in the sound velocity profiler. The "smiling face" or "weeping face" phenomena will be visible, especially for the fringe beams, shown in ***Figure 4.*** Research on the influence of the sound velocity error and the sound ray tracing theory indicates these systematic errors can be removed by adjusting the sound ray value step by step. In addition, the surface sound velocity probe must be deployed during the actual time of sounding capture to ensure the accuracy and reliability of the sounding data (LIU SX et al., 2009, 2011; DONG QL et al., 2011).

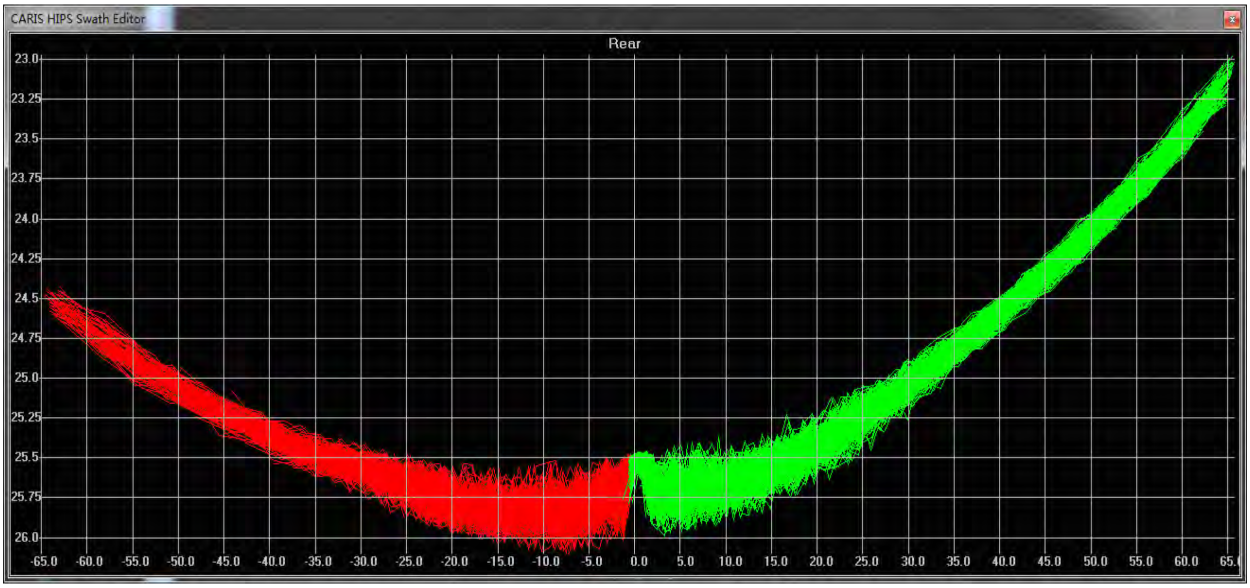


Figure 4（a）: "smiling face"

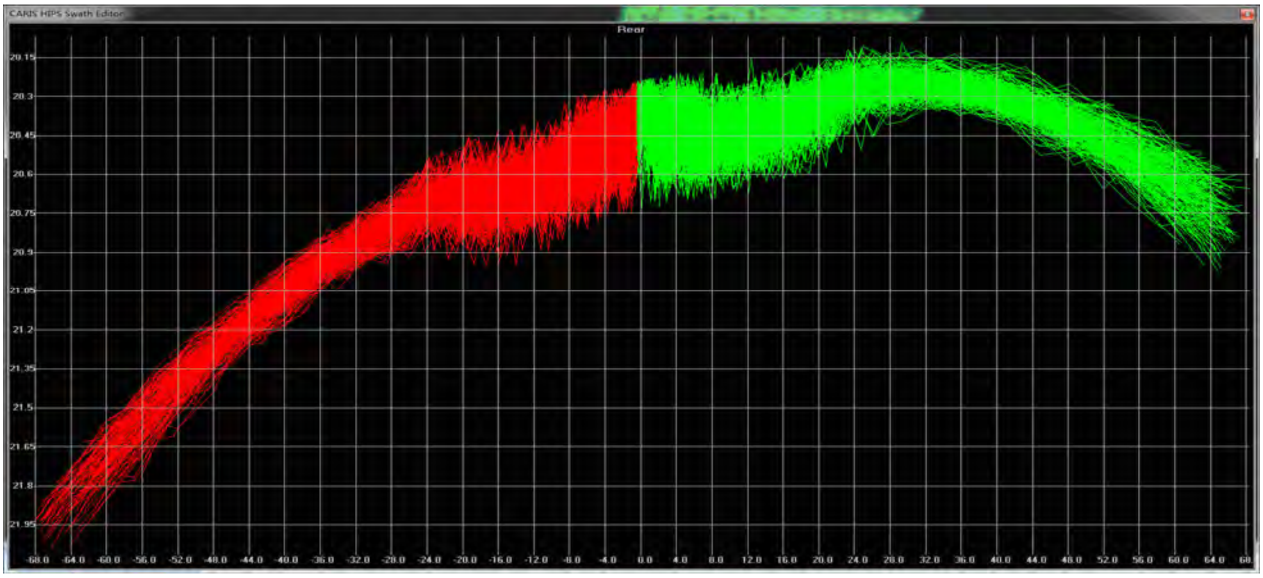


Figure 4（b）: "weeping face"

Figure 4: *The systematic error of (a) "smiling face" or (b) "weeping face" phenomena in a sounding swath due to the inaccuracy in the sound speed profiler.*

The effect of systematic errors due to incomplete tide adjustments are shown in ***Figure 5***. These errors can be removed by improving the tide gauge station distribution, use of tidal predictions, non-tide GPS mode and tide calculation based on the residual water level collocation (OUYANG YYZ et al., 2005; BAO JY et al., 2006; LU XP et al., 2008; HUANG CH et al., 2011, 2013).

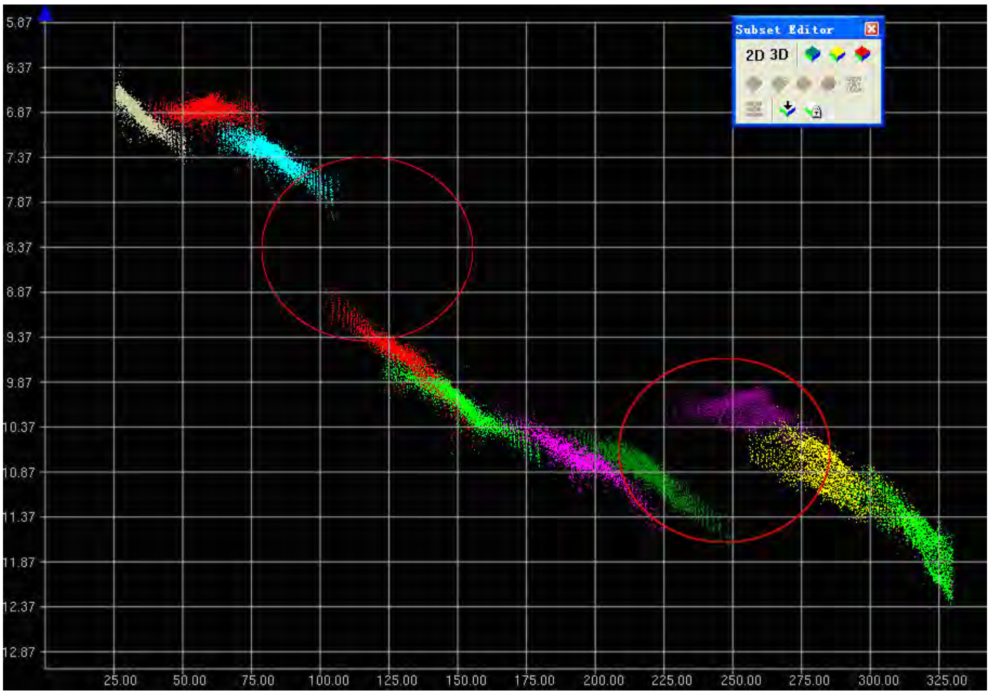


Figure 5: *The stitching faults between the swaths*

During multibeam sounding processing, tide corrections, sound velocity corrections and attitude corrections are applied to the sounding swathes. During this process, a "concave-convex" phenomenon can appear. These are more than "smiling" and "weeping" phenomenon and these errors are considered residual systematic errors relating to the instruments. (ZHAO JH et al., 2013).

Any malfunction or improper maintenance of the transducer will manifest themselves as other data quality problems. In ***Figures 6*** and ***7***, a systematic error is observed that illustrates the “W” phenomena and can be found in the center beam of certain swaths. Once identified, such a transducer hardware malfunction must be rectified as soon as possible.

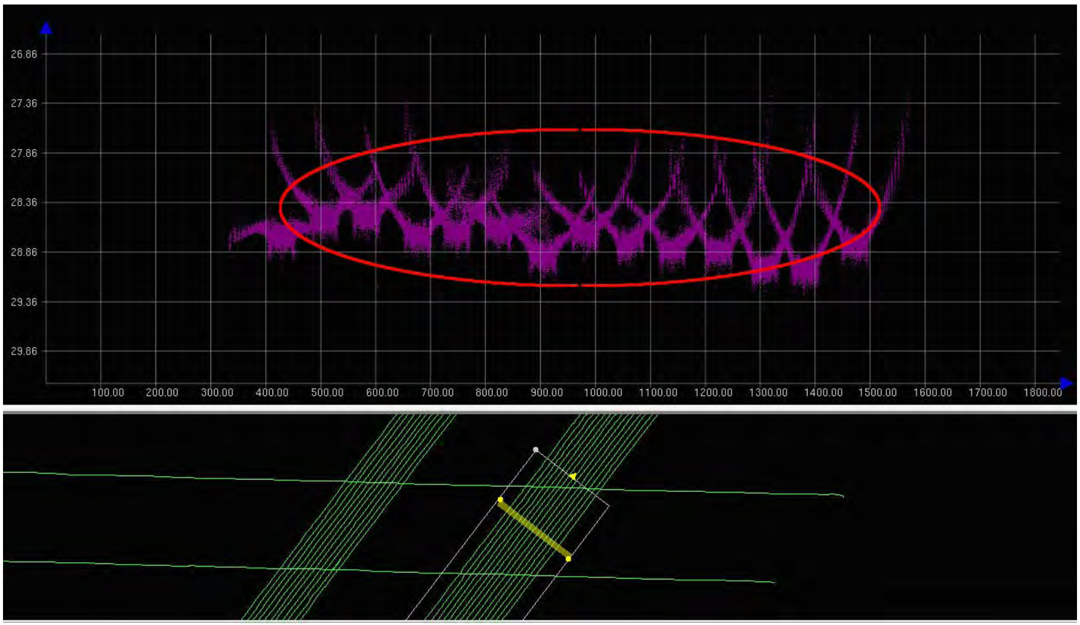
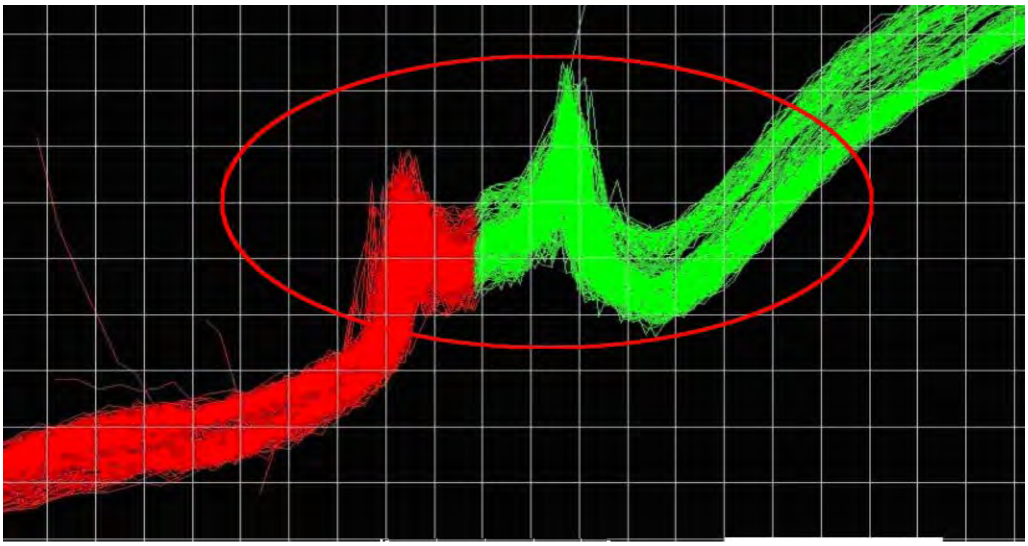


Figure 6: *The residual systematic errors in sounding swath*



7（a）Swath edition mode

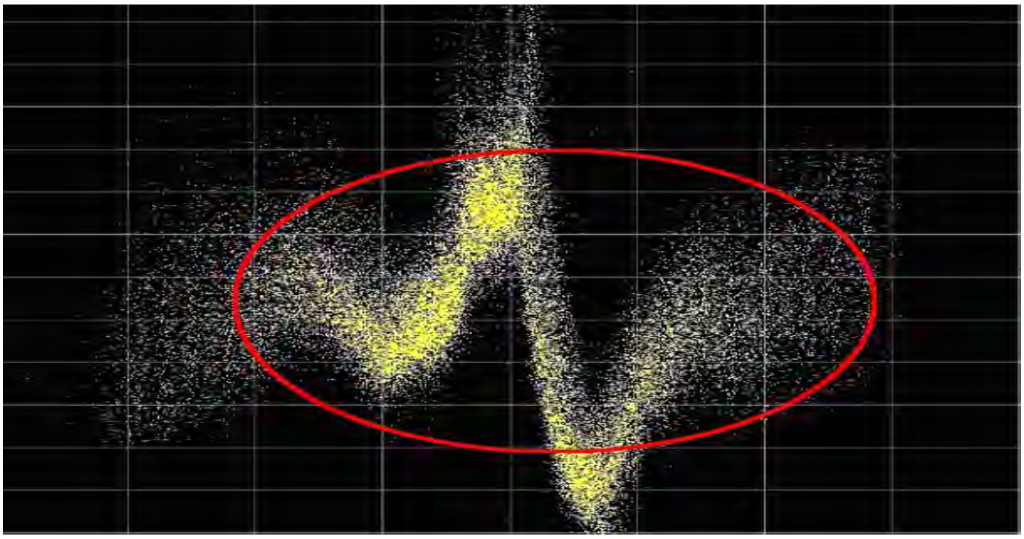


Figure 7（b）： Subset edition mode

Figure 7: *The "W" phenomena caused by the hardware problem in sounding swath (a) Swath edition mode and (b) Subset edition mode*

Internal ocean waves can affect sounding quality as shown in ***Figure 8***. The sound velocity is expected to be steady through stratified distributions in the water column. The presence of internal ocean waves results in the supposed horizontal layer containing peaks and troughs. The sea bottom will be distorted and the accuracy of the multibeam sounding will be affected (LIU SX et al., 2012). Furthermore, this kind of systematic error cannot be effectively reduced.

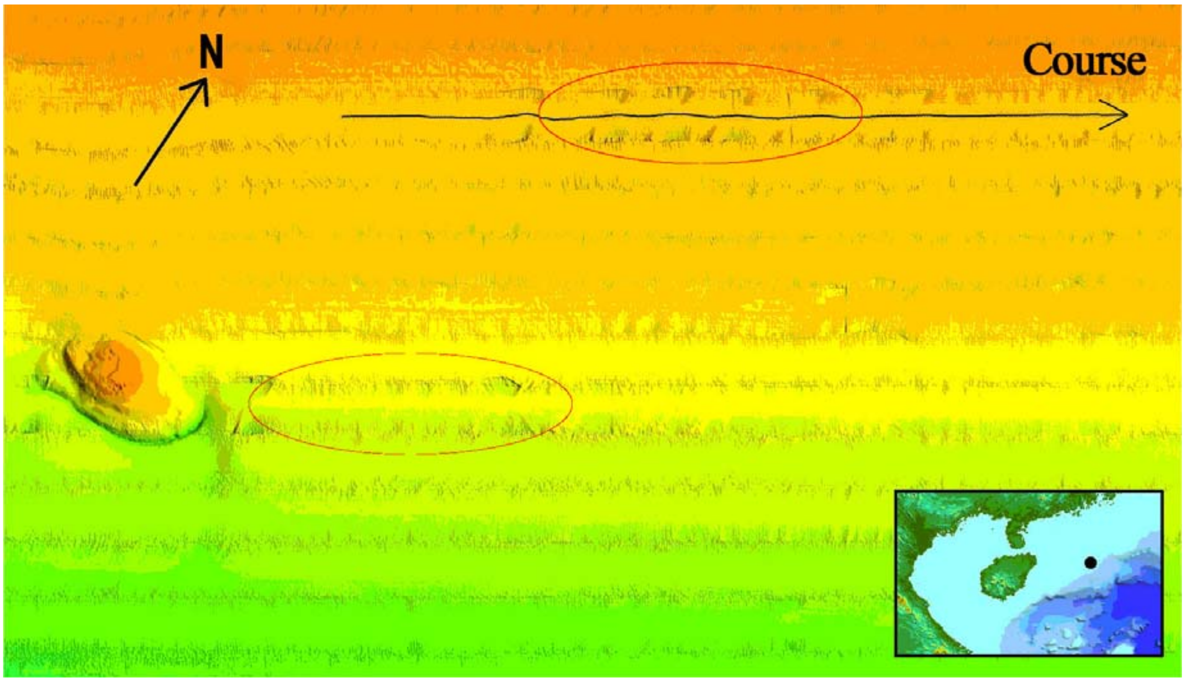


Figure 8: *The distortion of smooth sea bottom caused by ocean internal waves*

3. Quality Assessment of MBES Products

3.1 Quality Assessment Indexes

Similar to single beam sounding products, there are two quality assessment indexes for multibeam sounding products (GB, 1998 and CHB, 2011):

(i) the sounding limit error in different depths; and

(ii) the differences in depths between the main lines and cross-over check lines.

The precision of the sounding system is reflected by the sounding limit error shown in ***Table 1***. The accuracy of the survey data are reflected by the allowable depth differences of the cross points as shown in ***Table 2***. The survey specifications require the comparison between cross point depths to be less than the 15% of total calculation point depths.

Table 1: *The sounding limit error in different depths*

Depths（ z ）(m)	**The sounding limit error（2σ）(m)**
0< z ≤20	±0.3
20< z ≤30	±0.4
30< z ≤50	±0.5
50< z ≤100	±1.0
z >100	± z ×2%

Table 2: *The allowable difference in the comparison between cross points*

Depths（ z ）(m)	**Allowable difference in the cross point comparison (m)**
0< z ≤20	0.5
20< z ≤30	0.6
30< z ≤50	0.7
50< z ≤100	1.5
z >100	± z ×3%

For single beam soundings and according to the distribution characteristics of the sounding lines and sounding points, the surveying precision can be mainly evaluated by the correlative indices in Table 2. Therefore, the integrated dynamic effects of the marine environment are concealed in the indexes, as well as the effects of draft, ground swell, sounding velocity and the tide. In other words, the accuracy of each correction can not be reflected by the differences of the cross points.

For multibeam sounding collection, the sounding data provides full coverage of the seafloor. Apart from using the above two indexes, the surveying precision can also be evaluated through each step of the surveying operation including data acquisition, processing and product making. The refraction of the sound ray can be checked during the swath editing of the single survey lines. Likewise, other data can be independently evaluated using the neighboring swaths, observing stitching faults and the “concave-convex” phenomenon caused by the integrated dynamic effects of the marine environment (such as the draft, sound velocity, ground swell and the tide) as well as the calibration and the installation errors in the system as shown in Figures 1 to 8. These gross and systematic errors can be detected during the acceptance inspections of the multibeam sounding data. Therefore the single ping, single swath and neighboring swaths and sounding surface have been included in the acceptance inspection and quality assessment of multibeam sounding.

3.2 Acceptance Inspection and Assessment

Based on the analysis of the sources and impacts of gross and systematic errors in multibeam sounding products, a quality inspection scheme has been developed for data acquisition, processing, product making, inspection and assessment processes. During the inspection of the multibeam sounding products, gross and systematic errors (seen in ***Figures 1 to 8***) are identified. A full seafloor coverage inspection of the multibeam sounding capture and the variation in the marine topography is also undertaken.

When the "map sheet" area is selected as the basic unit for inspection, eleven primary Quality Elements are tested. Each Element has several Inspection Items leading to 120 items being checked in total. The Quality Elements and the more important Inspection Items are listed in ***Table 3***.

Table 3: *The Quality Elements and Inspection Items of multibeam sounding products*

Quality Element	Inspection Item
Positioning system	1. The accuracy of the stability test of the system and the results
Sounding system	1. The accuracy of the stability test of the system and the results
Auxiliary systems	1. Test of surface sound velocity probe 2. Test of POS 3. Test of sound velocity profiler 4. Test of current meter
System Calibration	1. The spatial position accuracy of the installation of the positioning system and sounding system 2. The calibrations and results of the positioning system and sounding system 3. The quality, precision and rigor of the calibrations of the transducer installation
Tide control	1. The rationale of the control range of the tide gauge 2. The accuracy of the datum 3. The accuracy of observed data 4. The rationale of the observed time period 5. The rationale of the tidal data editing 6. The rationale of the tide correction
Data acquisition	1. The overall quality of the transducer 2. The validity of the sound velocity at the surface 3. The rationale of the acquisition time and space density of the sound velocity profile 4. The validity of the attitude survey, such as Pitch, Roll and Yaw 5. The valid coverage of the swaths (meet the requirements of the full coverage) 6. The detection of the special depths (without missing measure)
Data processing	1. The gross error of the attitude have been completely deleted or not 2. The gross error of the sound velocity have been completely deleted or not 3. The gross error of the position have been completely deleted or not 4. The integration of the position, attitude, sound velocity and tide data being successful or not 5. The gross error of the depth has been deleted or not 6. The accuracy and rationality of the manual and auto editing of the depths 7. The selection of the cross points and the calculation of the differences are reasonable

Quality Element	Inspection Item
Map drawing	1. The method, interval and output of the data thinning are reasonable 2. The plane, height, depth and tide datum are correct 3. The depth interval on the chart are reasonable 4. The selection of the special depth are reasonable 5. The gross errors in 3D bathymetric map 6. The systematic errors in 3D bathymetric map 7. The consistency with the known depth map sheet

After completion of checks on all of the Quality Elements and Inspection Items, faults are sorted by quality element and graded by inspection element into:

- Serious Fault (Sort A): represents a fault which can result in the disqualification and rejection of the product for further use;
- Heavier Fault (Sort B): represents a fault which can influence the normal use of the products in a certain situation; or
- General Fault (Sort C): represents a fault which only has a slight influence on the normal use of the products.

The outcome of the assessment of the Quality Elements and Inspection Items are categorized into corresponding Fault Sorts (***Table 4***). According to the standards listed in ***Table 4***, the quality value *S* of the multibeam sounding system can be calculated by the following formula (1).

$$S = 100 - 41a_1 - k(6a_2+a_3) \qquad (1)$$

Where:

a_1, a_2, a_3 is the number of the Sort A, Sort B, and Sort C faults

k is the adjust parameter: $k=2$ for class I, $k=1$ for class II, $k=0.5$ for class III.

Table 4: *The Fault Sort (A, B, and C) of multibeam sounding products*

Quality Elements to be tested	Sort A	Sort B	Sort C
Positioning system	1. The positioning system has not been tested, the products are invalid, which can not be remedied. 2. The test results are unqualified, the products are invalid, which can not be remedied.	1. The test items are incomplete 2. The time of the test does not conform to the ordinary demands	1. The test precision is near to the tolerance
Sounding system	1. The sounding system has not been tested, the products are invalid, which can not be remedied. 2. The test results are unqualified, the products are invalid, which can not be remedied.	1. The test items are incomplete 2. The time of the test does not conform to the ordinary demands	1. The test precision is near to the tolerance
Auxiliary systems	1. Test of surface sounding velocity meter, POS system, sounding velocity profiler and automatic tide gauge have not been tested, the products are invalid, which can not be remedied.	1. More than 2 types of auxiliary system have not been tested, but has little influence to the products	1. Only one type of auxiliary system has not been tested, and has little influence to the products
System Calibration	1. Calibration of transducer installation errors have not been tested, the products are invalid, and can not be remedied. 2. Calibration of position installation errors of the systems have not been tested, the products are invalid, which can not be remedied.	1. Errors are found due to the irregular vibration in the instability of the transducer installation. 2. The transducer installation errors have not been calibrated 3. Calibration of transducer installation errors is incomplete, the systematic errors are introduced and observed between the swaths	1. Calibration of transducer installation errors is incorrect, the systematic errors are introduced and observed between the swaths, but the sounding precision has not exceeded the tolerance 2. Errors due to the irregular vibration has been observed due to the instability in the transducer installation, but the sounding precision has not exceeded the tolerance
Tide control	1. The vertical datum relation is faulty and the products are invalid, which can not be remedied.	1. The tidal correction is incomplete, and stitching faults exist between the swaths, and the sounding precision have exceed to the tolerance	1. The tidal correction is incomplete, and stitching faults exist between the swaths

Quality Elements to be tested	Sort A	Sort B	Sort C
Data acquisition	1. The datum is faulty and the products are invalid, which can not be remedied. 2. The surface sound velocity meter has been damaged	1. The stitching faults exceed the tolerance in more than 10% of the swaths, and the products are invalid, which can not be remedied 2. The sea bottom has not been fully covered by the effective beam points, which can result in missing an important navigation obstruction.	1. The other faults are within tolerance.
Data processing	1. The profile of the sound velocity does not meet requirements, which can reduce the inconsistent with the real marine topography in more than 20% of the swaths, which can not be remedied 2. The stitching faults have exceed the tolerance, which can not be remedied 3. The systematic errors exist in more than 20% of the swaths, which can not be remedied 4. The artificial sound ray correction must be applied, but has not been performed. 5. The internal accuracy of the cross points exceed the tolerance	1. The attitude correction is incomplete, which can reduce the consistency with the real marine topography in more than 10% of the swaths, which can not be remedied 2. The profile of the sound velocity does not accord with the requirements, which can reduce the consistency with the real marine topography in more than 10% of the swaths, which can not be remedied 3. The artificial sound ray correction must be effectively applied, which can reduce the consistency with the real marine topography in more than 20% of the swaths, which can not be remedied 4. The stitching faults or systematic errors exist in more than 10% of the swaths, which can not be remedied	1. The edit of the positioning data is incomplete 2. The sound velocity correction is incomplete, which impacts the systematic errors in specific swaths 3. The attitude correction is incomplete, which impacts the systematic errors in specific swaths 4. The edit of the sounding depth is incomplete, which reduce the spurious signal
Map drawing	1. The systematic errors exist in neighboring map sheets, which can not be remedied 2. The systematic errors exist in 3D marine topography in large area, which have exceed the tolerance 3. The spurious signal exist in 3D marine topography in large areas, which exceed the tolerance	1. The error impact on the special depth have exceed more than 10% 2. The systematic errors exist in 3D marine topography in some areas, which exceed the tolerance 3. The spurious signal exist in 3D marine topography in some areas, which exceed the tolerance	1. The error impact on the special depth are under 10% 2. The systematic errors exist in 3D marine topography which exceed the tolerance 3. The spurious signal exist in 3D marine topography in some areas, which exceed the tolerance

4. Conclusion and Recommendations

Differences exist between multibeam and single beam sounding systems during the data acquisition, processing and product generation processes. The nature and extent of gross and systematic errors also differ between these systems. For single beam sounding, resolving gross and systematic errors are more difficult. However, if each kind of quality issue can be resolved for multibeam sounding systems and processes, the quality problems in single beam sounding will be resolved accordingly. Meanwhile, where gross and systematic errors can been adequately recognized in the multibeam systems and processing, systematic problems can be resolved in multibeam sounding output data. The results of this paper provide reference to the system and environmental phenomena and the required inspection of the multibeam sounding products.

Multibeam sounding technology and methodologies will continue to be the mainstay of bathymetric surveying capability in the future, so the software and hardware technologies and processing capabilities for these sounding systems must continually improve. Meanwhile the correlative work processes and data inspections must be rigorously performed during surveying to identify and resolve data quality problems. By following a rigorous approach towards system installation, calibration, processing and inspection, it has been found to achieve twice the product output with half the effort.

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