Mapping the Depths Uncertainty by Comparison between Multibeam Regular and Crosscheck Lines

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This paper was prepared for presentation at the Twelfth International Congress of the Brazilian Geophysical Society, held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

Maps and graphics are useful to approach the total vertical uncertainty and to evaluate the quality of the hydrographic survey. They are created supported by the Standards for Hydrographic Surveys, from International Hydrographic Organization (2008), and according to the analysis of comparison between multibeam regular and crosscheck lines. Complementary, one will be able to identify some biases that were not removed during the sensors' calibration. The methodology is based on the results of the analysis of two distinct $-ASCII$ files generated after bathymetric data cleaning process; one from the regular lines and another from crosscheck lines. A script written in Matlab© language reads the files and produces some statistical results, such as maps, histograms and other graphics. That method was applied in two surveys performed at the Baía de Guanabara - Rio de Janeiro, in 2009-10. The results were satisfactory because it was able to give us a general idea on how the errors were distributed geographically and what kind of errors were recorded in raw data; even it was not capable to identify them quantitatively. Some positive aspects are related to the fact that, statistical graphics allow the analyst to identify and fix the problems that, unfortunately, are degrading the quality of the survey, such as, external bad beams, sound velocity, roll and pitch biases, etc.

Introduction

In order to guarantee the safe navigation and the quality of the nautical charts, the countries that follow the International Hydrographic Organization Standards classify their surveys in orders. As function of the area characteristics, such as: under-keel clearance; bottom features; port transit; etc., an unique chart might have different orders and that is the challenge for the hydrographic agencies.

To accomplish that task, Hare (1995) proposal applies the propagation of uncertainty through the terms of the reduced depth equation. Further more, Calder and Mayer (2003), based on statistical hypothesis, wrote an algorithmic that highlight doubtful data in which might be accepted or rejected by the hydrographer. Nowadays, those process have been widely used by many hydrographic softwares to help the data cleaning process. Alternatively, some hydrographics agencies have used the crosscheck lines to evaluate the quality of their works. That process consists in comparison of the depths that are supposed to be upon the same position of the two different cross track lines.

The techniques enumerated before, have their advantages and concerns. The concern about the two formers process is that they do not take into account the variability of the measure. On the other hand, the velocity of the data processing increases highly.

With the analysis of the crosscheck lines is possible to highlight mistakes that still remain in the data and to solve problems regarding to the variability of the measure. But the velocity of the process decrease and if the same equipment is used to perform the overlap lines, their analysis do not indicate absolute accuracy because there are numerous sources of potential common errors between main and check lines.

The task to calculate depths uncertainty by comparison between regular and crosscheck lines is not a new subject among the hydrographic communities. It was and still is widely used to evaluate the quality of single beam surveys. The problem with the multibeam data is the size of the depths recorded in a single file, but the high performance of new generation computer machines became the process executable.

Method

The methodology was tested in two different hidrographic surveys performed in the years 2009-10. The figure 1 spots the area surveyed. The green and the yellow boxes refer to the surveys of 2009 and 2010, respectively, and the tables 1 and 2 presents their corners. The Baía de Guanabara, in Rio de Janeiro, was chosen in order to minimize problems regarding the tide and the proximity between the vessel and the reference positioning station, both located at the Hydrographic Office.

Basically, there are two hypothesis that must be verified:

1. For the same survey, is it possible to evaluate its quality using overlap swaths collected by the same equipments?

2. By comparison between overlapping swaths, is it possible to classify the survey in orders and to identify errors that still remain in the raw bathmetric data?

Figure 1: Surveys performed in 2009 (green box) and 2010 (yellow box). Baía de Guanabara, Rio de Janeiro - Brazil. Source: Google Maps.

Corners	Latitude	Longitude
Lower left corner	$22°53'05,6544''S$	$043°08'54,0827''W$
Upper right corner	$22°52'21,6941''S$	$043°08'28,7002''W$

Table 1: Geographic corners of the area surveyed in 2009. Coordinates referred to WGS-84.

Corners	Latitude	Longitude
Lower left corner	$22°53'04,3865''S$	$043^{0}08'50,7239''W$
Upper right corner	$22°52'20,7080''S$	$043^{0}08'36,0006''W$

Table 2: Geographic corners of the area surveyed in 2010. Coordinates referred to WGS-84.

The table 3 spots the sensors installed in the resource vessel.

Sensors	Model (2009)	Model(2010)
Echosounder	EM3000	EM3000
Attitude sensor	MRU-5	MRU-5
Gyro	Seapath 20	Seapath 200
Positioning	RTG	RTG
SVP (profile)	SVPlus-V2	SVPlus-V2
SVP (surface)	Smart Sensor (AML Micro SV)	Smart Sensor (AML Micro SV)

Table 3: Sensors employed in 2009 and 2010.

After the data cleaning step, two different $-ASCII$ files, one from the regular lines and another from cross check lines, must be created. That files contain the follow amount of information: the geographic position of the reduced and acceptable depth; the depth; the beam number; and the ping counter or sequential counter. It is important warning that is not advisable to use sorted depths because it might probably hide the final result.

Basically, the process consists in:

1. Load the $-ASCII$ files;
2. To determine the geographic limits of each cross check line and to select a set of regular depths inside of that limits;
3. From the beginning until the end of the each cross check $-ASCII$ file, to read each depth and according to its geographic position, starting a search in a regular $-ASCII$ file, selecting all the depths inside of a specific circle; and
4. Perform the statistical analysis.

The first statistical process is to determine the standard deviation of the depths inside of the circle regarding to the i^{th} depth of the cross check line, equation (1). That value represents the random error of the i^{th} depth.

$$\sigma_{random} = \sqrt{\frac{\sum_{i=1}^{i=n} (Z_i - \overline{Z})^2}{n-1}} \tag{1}$$

Where Z_i is the i^{th} cross check depth; $\overline{Z}$ is the mean of the set of the regular depths; and n is the size of the regular depth sample. As big as the size of the sample n, more accurate is the result.

The next step is to estimate the systematic biases that was not removed by calibration or modeling. That is not a simple task to accomplish because some biases are difficult to identify or remove, such as temperature and salinity change, tide correction, and etc., *United States Army Corps of Engineers* (2002). The other problem is, in order to estimate the systematic errors is necessary to know the "true" measure depth (Z_{true}), equation (2), which is supposed be impossible.

$$\sigma_{systematic\_biases} = (Z_{true} - \overline{Z}) \tag{2}$$

To minimize that uncomfortable situation, the Z_{true} value is replaced by Z_i, equation (3).

$$\sigma_{systematic\_biases} = (Z_i - \overline{Z}) \tag{3}$$

Merging the systematic biases and the random errors, is possible to calculate the root mean square (RMS) of each measured depth. The RMS has often been used for comparing relative accuracies that differ substantially in bias and precision, *United States Army Corps of Engineers* (2002). The formula employed to estimate the vertical uncertainty, according to the SP-44 Standard Publication, equation (4), has the follow components: the a^2 term represents the systematic biases and does not vary with depth; and the term $(b \times d)^2$ represents the random errors and varies with depth d.

$$\pm\sqrt{a^2 + (b \times d)^2} \tag{4}$$

By analogy, the root mean square represents the vertical uncertainty and might be calculated, with 95% confidence level, equation (5).

$$TVU = 1,96\sqrt{\sigma^2_{systematic} + \sigma^2_{random}} \tag{5}$$

The vertical uncertainty, as described in (5), and the difference between overlap swaths is stored in a new

$-ASCII$ file for further analysis. Graphics and maps will help to interpret the quality of the survey and recognize possible faults.

Maps and Graphics

All the maps and graphics which will help on an analysis and evaluation of the hydrographic data is based on four statistical results:

1. The mean depth of the crosscheck line;
2. The standard deviation of the difference between the overlaps depths;
3. The difference between the overlaps depths; and
4. The root mean square.

To estimate the vertical uncertainty, the mean depth of the crosscheck line is applied on equation (4). The a and b values depends on characteristics of the area. That estimate does not represent the individual depth uncertainty, it only gives an general idea about the vertical uncertainty of the area.

The standard deviation of the difference between the overlaps depths express as spread the random errors are.

The difference between the overlap depths when plotted in a histogram, figure 2, help understanding the distribution of systematic biases errors. A displacement greater than $5,0cm$ from zero might highlight blunders errors which probably are relationship to bad data or problems regarding to the tide. In that situation the histogram becomes flatten, since the residuals were close to the mean. Generally, problems with the position of the transducer's head and sound velocity have the mean difference between the overlaps depths close to the zero, but with a huge histogram base.

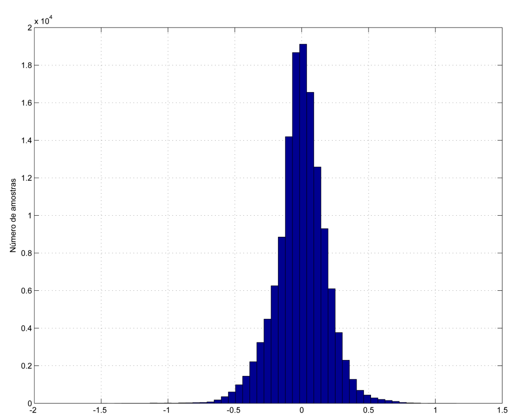

Figure 2: Histogram.

Finally, the root mean square represent the final value of the vertical uncertainty for each depth.

In complement to the previous information, some geographic maps help to interpret the results. The map 3 represents the difference between the overlaps depths and the map 4 the order of the survey.

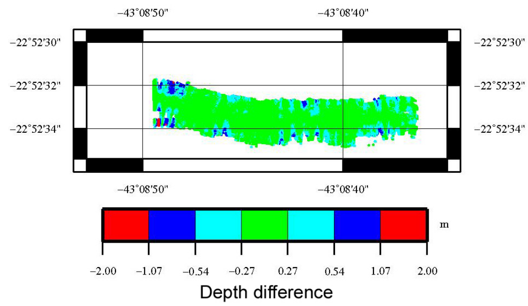

Figure 3: Depth difference between overlap swaths.

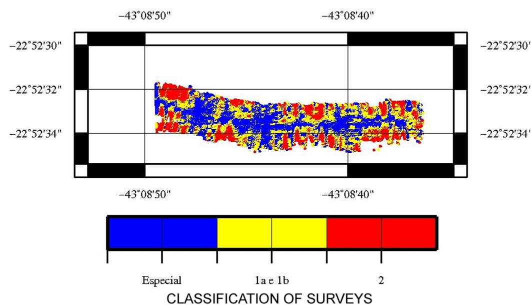

Figure 4: Distribution of the order of the survey.

The relationship between the mean of the difference of the depths per beam number is shown on figure 5. That information together with the histogram might help to identify problems with sound velocity and the position of the transducer head. For example, if the curve is fairly similar to the straight line, probably there might be problem with misalignment in transducer head or a constant heel of the vessel. Whether the curve was symmetric but with opposite sign regarding to center beam, the problem might be relationship with sound velocity profile.

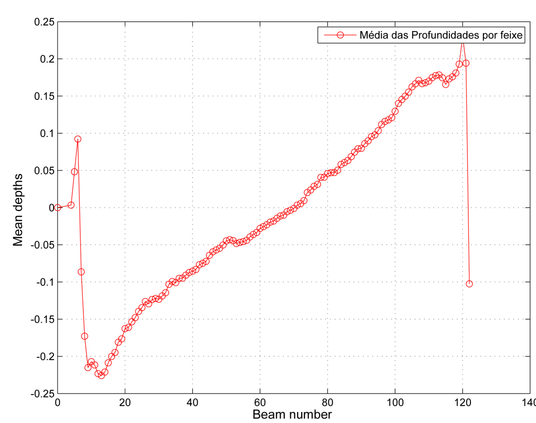

Figure 5: Relationship between the mean of the difference of the depths per beam number.

The value of the root mean square can be expressed in two different graphics. The first one relates the beam number with the absolute value of the root mean square; and the second on relates the beam number with the root mean square as a percentage of the depth or its normalized value. Both graphics carry on the same information, that is the variability of the RMS regarding to the nadir of the transducer. For most of the echosounders, the root mean square keeps low values for the central beams, but its value rise for external beams. Some echosounders try to minimize that problem using phase and amplitude beam detection. The figures 6 and 7 show that behavior.

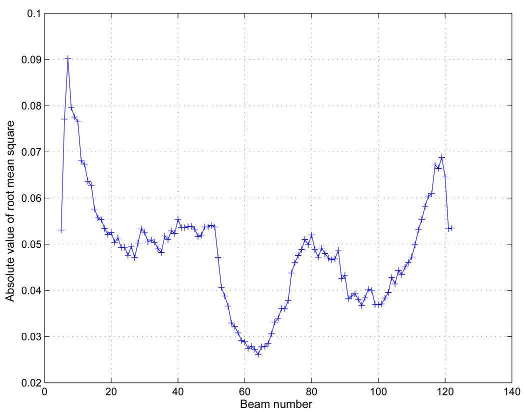

Figure 6: Absolute value of the root mean square per beam number.

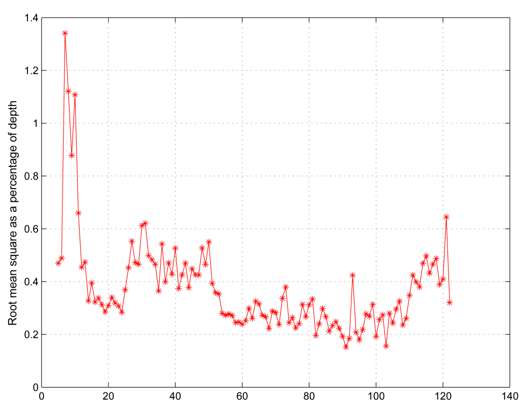

Figure 7: Root mean square, as a percentage of the depth, per beam number.

The last graphic is useful to confirm the misalignment in the transducer head. It shows the mean distance between several sets of ten successive swaths along the entire line. In general, if any misalignment is detected, the curve seems like a straight Line, otherwise, a catenary with positive or negative concavity might appear indicating the possibility of transducer misalignment. The figure 8, exemplify that situation.

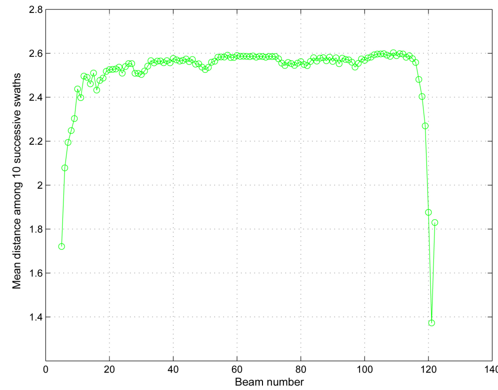

Figure 8: Mean distance between several sets of ten successive swaths along the entire line.

Result

The graphics, the maps and other amount of information necessary that allow the hydrographer build and describe the results that is going to be presented as follow are available on web site `www.hidrografia.xpg.com.br`.

Varying the variable d, on equation (4), between 5.77 and 21.41 meters, respectively the lowest and highest depth surveyed, and the variables a and b, according to each order of hydrographic survey, the graphic on figure 9 is reached.

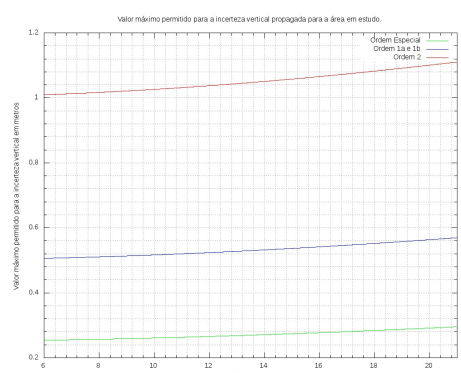

Figure 9: Maximum value allowed for the vertical uncertainty. The limits, in meters, for each curve are: especial order (green curve) $[0.254; 0.295]$; orders 1a and 1b (blue curve) $[0,506; 0.570]$; and order 2 (red curve) $[1.009; 1.111]$.

The classification of the depth in order is done according to the location of the root mean square on the graphic. If the depth is bellow the green curve, it will be classified as special order; if between the blue and red curves, as order 1a or 1b; otherwise if the value is above the red curve, as order 2. Thus, after processing the RMS, the result displayed on table 4 were reached.

Year	Line	Special Order	Order 1a e 1b	Order 2
2009	202	56.085	34.743	9.172
	204	60.447	32.830	6.723
	206	57.051	34.694	8.255
2010	038	54.858	31.119	14.023
	040	44.448	36.288	19.264
	042	50.196	32.224	17.5800
	044	46.984	35.766	17.250
	046	55.843	32.817	11.340
	048	47.645	33.998	18.357
	050	51.102	36.928	11.970
	052	51.954	33.537	14.510
	053	59.845	32.414	7.741

Table 4: Distribution of the vertical uncertainty per line and per year. All beams considered. Value in percentage.

On average, by the years 2009 and 2010, respectively, 57.861% and 51.431% of the depths were classified as special order; 34.089% and 33.899% as order 1a or 1b; and $8,050\%$ and $14,671\%$ as order 2. The table 5 and the histograms carry on the idea of the distribution of the difference between overlaps depths. As one can see, the mean is close to zero, that is probably a sigh that there are no problems regarding to blunder errors or systematic biases.

Year	Line	Mean	Standard Deviation
2009	202	-0.032	0.141
	204	0.014	0.163
	206	0.020	0.146
2010	038	0.027	0.186
	040	-0.040	0.222
	042	0.008	0.204
	044	0.003	0.208
	046	0.031	0.173
	048	-0.025	0.208
	050	0.009	0.163
	052	-0.004	0.185
	053	0.004	0.144

Table 5: Distribution of the difference between overlaps depths. Values in meters.

As related before, problems with sound velocity or transducer head misalignment cannot be detected only by analyzing those amount of information presented up to now. For that, the relationship between beam number and the mean of the differences of the depths is used. In general, the curves for the year 2009 are symmetric to the y-axis, which means that probably any problem with sound velocity profiles were recorded in the raw file. Otherwise, the curves for the year 2010 are fairly similar to the straight line, probably by problems with misalignment in transducer head or constant heel of the vessel. The latter option must be rejected because the echosounder used is roll compensated, so the main cause is regarding to the transducer misalignment.

The mean of the difference of the depth per beam is useful to detect a common problem among the multibeam echosounders, that is, the external beams have highest mean in comparison to the inner beams. This behavior is also detected when analyzing the root mean square graphics. In the case in study, it is possible to detect that the beams between the numbers 0-20 and 100-127, have high root mean square. This behavior hide the final quality of the hydrographic survey.

So, in order to verify the effects of those beams in the final result, they were removed from the analysis and the data reprocessed. After that, the distribution of the vertical uncertainty were as seen on table 6.

Year	Line	Special Order	Order 1a e 1b	Order 2
2009	202	57.351	34.094	8.555
	204	64.232	30.647	5.121
	206	62.186	32.329	5.485
2010	038	61,993	28,690	9.317
	040	50,216	37,190	12.594
	042	56.242	31.013	12.745
	044	55.091	35.482	9.427
	046	64.204	31.023	4.774
	048	53.147	33.742	13.111
	050	56.854	35.895	7.251
	052	59.030	31.732	9.238
	053	63.457	30.423	6.119

Table 6: Distribution of the vertical uncertainty per line and per year. Only the beams 21-99 considered. Value in percentage.

That is, when the external beams were removed, the quality improves, as can seen on figure 10.

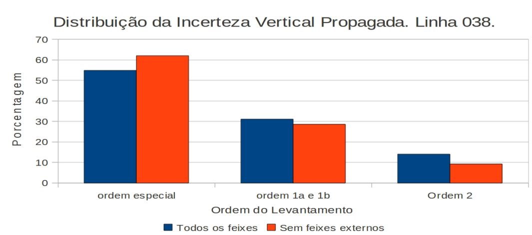

Figure 10: Distribution of the vertical uncertainty in two different times.

That graphic represents, in percentage, the distribution of the vertical uncertainty in two different times:

1. Blue bars - analysis the quality of the survey with all beams; and
2. Red bars - analysis the quality without the external beams.

After removing the external beams, on average, the percentage of depths regarding to special order were not greater than 95% of the total samples depths. It means that the survey cannot be classifyed as special order. Otherwise, if the percentage regarding to special and 1a/1b orders were added, table 7, sometimes was possible to reach an amount superior 95% of the total samples depths. Thus, it can be stated that due to problems that happened during data acquisition process the hydrographic surveys were classified as order 2.

Table 7: Percentage regarding to special and 1a/ 1b orders added. Values in percentage.

Year	Line	Special Order	1a and 1b Order	Sum
2009	202	57.351	34.094	91.445
	204	64.232	30.647	94.879
	206	62.186	32.329	94.515
2010	038	61.993	28.690	90.683
	040	50.216	37.190	87.406
	042	56.242	31.013	87.255
	044	55.091	35.482	90.573
	046	64.204	31.023	95.227
	048	53.147	33.742	86.889
	050	56.854	35.895	92.749
	052	59.030	31.732	90.762
	053	63.457	30.423	93.880

Conclusions

As one can observe along the article, if special actions were done before starting the hydrographic survey some unpleasant or dangerous mistakes would be avoided. The methodology presented, widely used to evaluate the quality of single beam surveys, is another option to the actual processes available that is based on the propagation of uncertainty through the terms of the reduced depth equation. Unless it requires more time and a good computers, it is able to detect and highlight mistakes that happened during the period of data acquisition. The other positive aspect is that the process takes into account the variability of the measures.

The process might also be used to detect any modification in an area surveyed along the time, when compared with different surveys performed in distinct periods of time. It is advisable, in order to avoid numerous sources of potential common errors, the overlap lines should be collected by different equipments in order to indicate absolute accuracy.

Regarding to the survey in analysis, some undesirable errors, such as bad sound velocity profiles loaded in 2009, misalignment on the transducer head in 2010, etc., were detected after analysis of graphics, maps and tables. The final quality also was affected function of the less accuracy of the external beams - a common problem among multibeam echosounders. But the graphics that relate the beam number with the value of the root mean square could detect precisely which beams were affecting the quality of the survey.

Finally, in order to mapping the depths uncertainty by comparison between multibeam regular and crosscheck lines is necessary to analyze the set of graphics, maps, tables and other addition information together. A simple map or graphic, by itself, is not able to spot the errors and classify correctly any hydrographic survey performed by multibeam echosounders.

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