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Crossover Adjustment Applied in Marine Gravity Data Processing: an example of a Dataset Surrounding Bach Long Vi Island, Vietnam

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ABSTRACT

Marine gravity anomalies have usually been being used for a number of scientific purposes such as geodesy, geophysics, geology and so on. After surveying, gravity anomaly measurements are normally calculated and adjusted to detect and reduce some error sources, including gross and systematic errors, and/or to remove blunders. After detecting and removing possible blunders, data processing will be continued with the application of crossover adjustment to the remaining measurements. This paper presents the result of applying crossover adjustment to process marine gravity dataset surrounding Bach Long Vi island, Vietnam. The crossover adjustment reduced the standard deviation of the 291 crossover points detected from 62 ship tracks from 2.38 mgal to 1.89 mgal.

1. Introduction

As mass distribution of the Earth can be determined and interpreted by the gravity field, gravity data plays an important role in Earth Science. As a consequence, the Earth's size and shape can be determined by gravity measurements (Tomoda, 2010). In addition, if the change of gravity anomalies has been determined, we have researched not only inside-structure but also the outside-movement of the Earth. For this reason, scientists, who work on geodesy and geophysics, consider the gravity (or gravity anomaly) data to be a potential data resource used to study the Earth's characteristics (Pham *et al.*, 2017).

Various methods can be used to determine gravity or it's changes that are divided into surface gravimetry, i.e., land and shipborne gravimetry, airborne and space-based gravimetry (Stelkens-Kobsch, 2005). In case of sea and ocean, gravity is normally measured by shipborne gravimetry (e.g., Ishihara *et al.*, 1999; Strang Van Hees, 1983), airborne gravimetry (e.g., Hwang *et al.*, 2006; Hwang *et al.*, 2007) or by satellite altimetry (e.g., Andersen & Knudsen, 1998; Hwang *et al.*, 2002), or by the combination of these methods (e.g., Forsberg *et al.*, 2004; Hwang & Parsons, 1995). Due to the instability of gravimeters in shipborne

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gravimetry, gyro stabilized platform is used in sea gravity equipment (Le *et al.*, 2017; Torge, 1989). Different error sources existed in marine gravity data, e.g., due to instrumental errors, navigational errors, lead to significant inconsistencies in crossover points between two ship tracks (Wessel & Watts, 1988). This problem could partly be overcome by crossover adjustment, where offsets and tilts can be modelled and measured in each track, that has been successfully applied with global dataset (Wessel & Watts, 1988) or regional dataset (Amos *et al.*, 2005; Strang Van Hees, 1983; Wenzel, 1992).

Before applying crossover adjustment, possible blunders need to be detected and removed. The theory and algorithm related to gross-error detection applied specially in gravity data are well known (for more details, we refer the reader to Sproule *et al.* (2006); Tscherning (1991a, 1991b); Xavier and Rolim (2012) and some others). With the same dataset, i.e., marine gravity data around Bach Long Vi island, Vietnam, Bui and Nguyen (2015) has carried out the gross error detection using statistical residuals between marine gravity data and those computed by the interpolation from surrounding points, and those calculated by the use of normalized spherical harmonics coefficients of the Earth Gravitational Model 2008 (EGM2008) (Pavlis *et al.*, 2008, 2012).

This paper shows a general description of crossover adjustment and the result of applying this technique to blunder-removed marine gravity dataset surrounding Bach Long Vi island, Vietnam, i.e., the dataset after gross-error detection and removal conducted by Bui and Nguyen (2015). From the dataset, duplicate data points are first removed, then tracks and available crossover points between any two tracks are detected along with the computation of their differences in gravity anomaly. For the crossover adjustment, a model with a bias per track is applied. The result shows that the crossover adjustment reduced standard deviation from 2.38 mgal to 1.89 mgal, corresponding to unadjusted and adjusted gravity anomalies.

2. Study area and experimental data

2.1. Study area

Bach Long Vi island locates in the center of Gulf of Tonkin (Figure 1), which has fish and oil resources. It plays an important role in marine economy, travelling, safety and national defense. Bach Long Vi is the furthermost island of Vietnam in the Gulf of Tonkin. The island is from 20^{0}07'35'' to 20^{0}08'36'' North latitude and from 107^{0}42'20'' to 107^{0}44'15'' East longitude. The island plays a vital role in extending and determining the region of beaches in the Gulf of Tonkin because of its location.

2.2. Experimental data

The data used in this research is provided by Vietnam institute of Geodesy and Cartography, Ministry of Natural Resources and Environment of the Socialist Republic of Vietnam, based on the

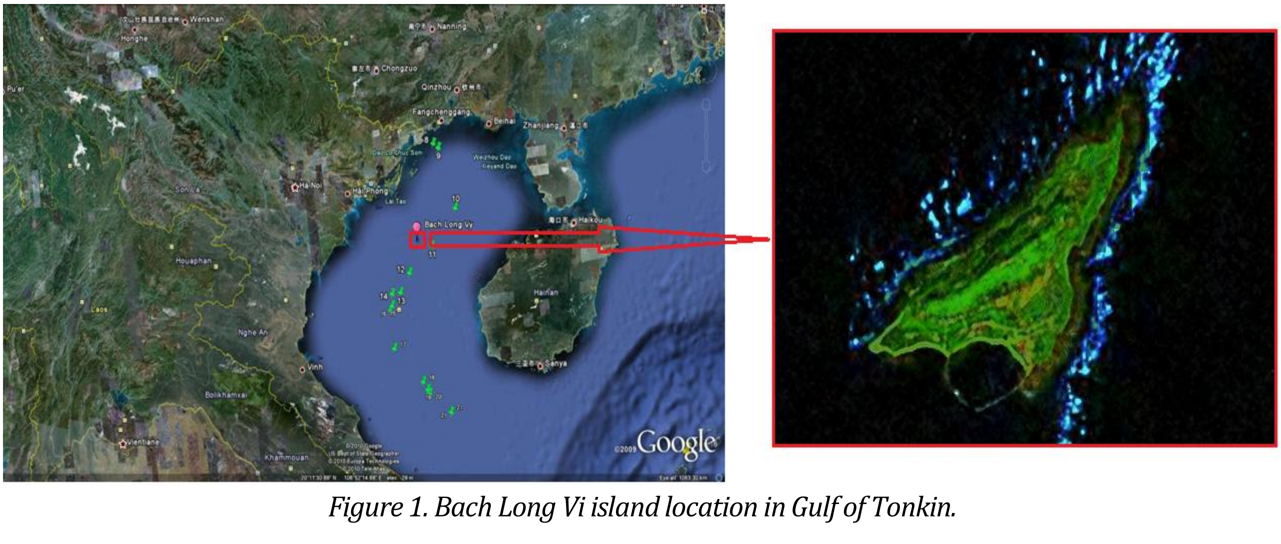


Figure 1. Bach Long Vi island location in Gulf of Tonkin.

Project "Marine gravity surveying and establishment of gravity anomaly map at main sea area of Bach Long Vi".

The data was measured using ZLS Dynamic Gravity Meter D60 produced by ZLS Corporation (USA) in 2005. The marine gravity observations were collected based on 4 horizontal and vertical-control points measured by GPS technology at the coastal regions of Hai Phong, Quang Ninh, and 4 inshore gravity-tie points, from August to December 2007. The total length of cruise is 944 km covering the area of about 345 km^2. The experimental area is limited to $20^0 03'45''N \le \phi \le 20^0 12'30''N$ and $107^0 37'10''E \le \lambda \le 107^0 50'45''E$ (Figure 2).

The average distance between adjacent points in each track is approximately 20 m and the spacing between horizontal and vertical surveying lines (tracks) are 1,100 m and 600 m respectively. The total number of 28,164 ship-track gravity observations was collected throughout the survey period as depicted in Figure 2.

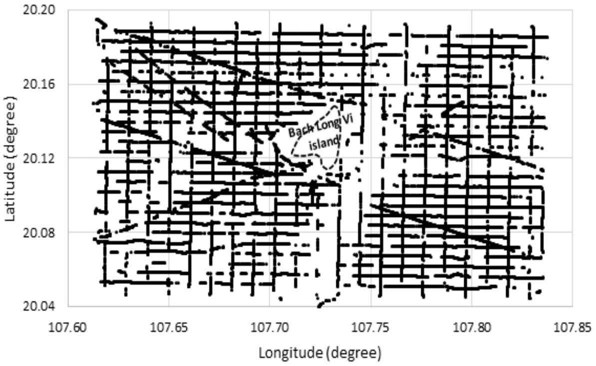


Figure 2. The gravity survey lines in the vicinity of Bach Long Vi island.

3. Methodology

3.1. Crossover adjustment

Various factors can negatively affect marine gravity observations, that vary from instrumental errors, e.g., off-levelling, cross-coupling, nonlinear drift, etc., to the quality of navigational system used for determining ship's position and others error sources, such as incorrect connection to harbor tie-stations or inconsistent use of reference system. The navigational errors, resulting in incorrect computation of Eötvös corrections and ship's position, can be easily overcome by the use of GNSS technology that has been used in this experimental survey. The connection to harbor tie-stations has been performed at the beginning and at the end of each cruise, and this is assumed to be correct in this study.

It is, actually, difficult to quantify separate sources of error to correct marine gravity data. Therefore, they are combinedly analyzed by the discrepancies in gravity anomaly at intersecting ship lines (tracks). In each track, a model of bias (intercept) and drift (tilt) is normally used (e.g., Wessel & Watts, 1988). However, the drift parameter is only valuable for long tracks (Denker & Roland, 2005). Thus, a model with bias only is used in this research.

The basic theory of crossover adjustment is that gravity anomaly value at a crossover point, i.e., intersecting ship tracks, is considered to be identical in both survey lines. Let us suppose that track i intersects track j at an intersecting point M, a_i and a_j are biases of the two tracks respectively. The gravity anomaly value at M is dg_M and is calculated by the following equation (Denker & Roland, 2005):

$$\begin{cases} dg_i + v_i + a_i = dg_M \\ dg_j + v_j + a_j = dg_M \end{cases} \tag{1}$$

Where dg_i, dg_j are the gravity anomalies at the crossover point M that are linearly interpolated from track *i* and *j* respectively using four points around the cross over point, v_i, v_j are the gravity anomaly residuals for track i and j respectively.

From equation (1), the difference in gravity anomaly at the crossover point from the two tracks is calculated by the following equation:

$$\begin{gathered} (dg_i - dg_j) + (v_i - v_j) + (a_i - a_j) = 0 \Leftrightarrow \\ dg_{ij} + v_{ij} = a_j - a_i \end{gathered} \tag{2}$$

The equation (2) is then re-written as:

$$v_{ij} = a_j - a_i - dg_{ij} \tag{3}$$

The equation (3) is established for one crossover point. For n crossover points, the equation (3) is used to form a system of equations that is expressed in matrix as:

$$V = Ax - L \tag{4}$$

By the use of standard least-squares principle, the observation equations (4) is represented by the set of normal equations:

$$Rx - b = 0 \qquad (5)$$

Where:

$$\begin{cases} R &= A^T A \\ b &= A^T L \end{cases} \qquad (6)$$

The biases a_i, a_j are determined based on the standard least-squares principle applied in free network adjustment by adding a matrix of datum/data conditions (e.g., Koch, 1999):

$$x = \tilde{R}.b \qquad (7)$$

Where $\tilde{R}$ is the pseudo-inverse matrix of the matrix R. For the sake of convenience in computer-based computation, the pseudoinverse matrix $\tilde{R}$ in equation (7) is calculated by (Vu, 2011):

$$\tilde{R} = (R + CPC^T)^{-1} \qquad (8)$$

Where C is the control matrix established based on the aforementioned matrix of datum/data conditions. In crossover adjustment applied in marine gravity data, the gravity datum is normally constrained so that the track bias for one track is set to be a given value, or the sum of all track biases is fixed to zero (Denker & Roland, 2005). In this study, the former approach is applied where the bias of the first track is set to the average value of the differences in gravity anomalies of its crossover points. $C = [1 \quad 0 \quad \ldots \quad 0]^T$. P is the diagonally weighted matrix having the size of $d \times d$, and d is the deficiency. The matrix P is expressed by the following equation:

$$P = \begin{bmatrix} 10^m & & \\ & 10^m & \\ & & \ddots \end{bmatrix}_{d \times d} \qquad (9)$$

It is well known that if m is set to be greater than or equal to 6 then the matrix $\tilde{R}$ is determined accurately enough (e.g., Vu, 2011).

After the biases of all tracks are determined, the adjusted gravity anomaly of the point k, $dg'_{k,m}$, belonging to track m will be calculated from the corresponding unadjusted value, $dg_{k,m}$, by the following equation:

$$dg'_{k,m} = dg_{k,m} + a_m \qquad (10)$$

3.2. Crossover adjustment result

All the dataset with the total of 28,164 observations has been used with the procedure of duplicate removal applied first, where 6 duplicate observations were found. The remaining 28,158 observations, without duplicate points, were then analyzed with 291 crossover points determined from 62 detected tracks.

The crossover adjustment was applied with the model of bias only applied with 291 crossover points, and the biases of all tracks are depicted in Table 1.

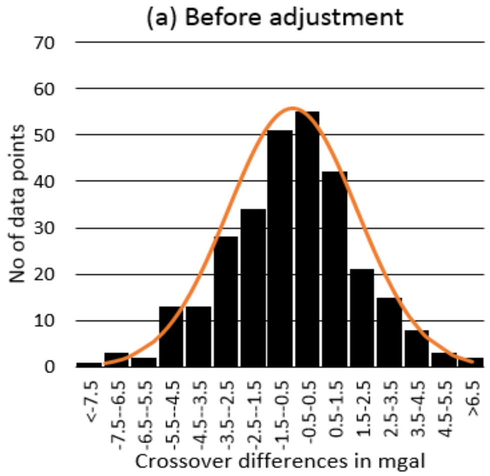
Table 1. The result of biases of 62 tracks computed from crossover adjustment for the whole dataset. Unit: mgal.

Track	Bias	Track	Bias	Track	Bias	Track	Bias	Track	Bias
1	0.30	14	-0.56	27	-0.63	40	-1.88	53	2.83
2	1.62	15	-2.66	28	0.35	41	-1.69	54	1.75
3	-1.42	16	-2.14	29	-0.46	42	-0.60	55	1.73
4	1.41	17	0.27	30	0.66	43	-1.12	56	-1.07
5	-0.62	18	0.19	31	0.35	44	-2.44	57	0.80
6	-0.34	19	-3.53	32	-0.41	45	0.37	58	-1.90
7	-1.31	20	-0.74	33	-0.83	46	-2.19	59	0.14
8	-2.11	21	-0.82	34	1.25	47	1.10	60	-0.89
9	-1.01	22	-0.12	35	-0.83	48	-1.81	61	-0.46
10	-0.36	23	-0.04	36	-0.13	49	-0.27	62	1.50
11	0.12	24	-0.59	37	1.09	50	1.83		
12	0.39	25	-0.76	38	-1.38	51	2.87		
13	1.54	26	0.06	39	-1.97	52	-1.81		

The maximum and minimum values of biases are 2.87 mgal and -3.53 mgal, respectively. The result of the differences in gravity anomaly at crossover points is shown in Table 2, and the corresponding histograms are given in Figure 3. The result shows that the maximum and minimum values are 6.04 mgal and -7.51 mgal before crossover adjustment, and 5.35 mgal and -5.76 mgal after crossover adjustment respectively, while the standard deviation reduces from 2.38 mgal to 1.89 mgal corresponding to ~20% reduction (Table 2).

Table 2. The statistics of differences in gravity anomalies at crossover points before and after crossover adjustment. Unit: mgal.

Case	Max	Min	Mean	Std. dev	RMS
Before adjustment	6.04	-7.51	-0.59	2.38	2.45
After adjustment	5.35	-5.76	0.00	1.89	1.89


(a) Before adjustment

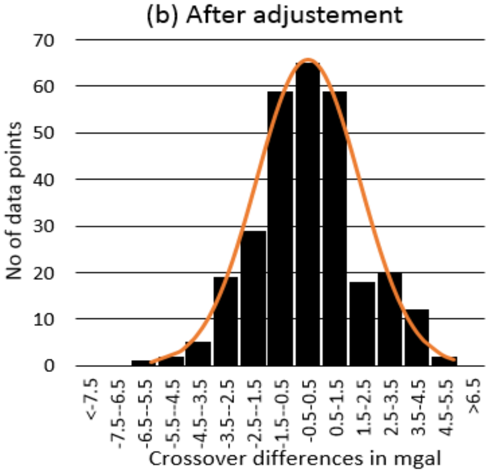

(b) After adjustement

Figure 3. Histograms of crossover differences before (a) and after (b) crossover adjustment.

This small improvement in standard deviation between the datasets before and after adjustment might be attributed to the small area of experiment, which is constituted by only 944 km in cruise length covering ~345 km^2, and the identicalness in the gravimeter, i.e., only one equipment was used. In reality, this crossover adjustment method has been demonstrated to have a great improvement in crossover differences in gravity anomalies in larger experiment areas, especially the case where gravimetry measurements were collected by different gravimeters, with wide ranges of accuracy, over various measuring time periods (e.g., Amos *et al.*, 2005; Denker & Roland, 2005; Strang Van Hees, 1983; Wessel & Watts, 1988). In Vietnam, the results shown in the paper is promising, and we believe that a better improvement can be obtained if this crossover adjustment is applied to larger datasets of maritime gravity. These datasets, if any, are inaccessible to the authors to date. In addition, this is a good approach that can also be applied to upcoming data in sea areas of Vietnam.

4. Conclusion

This paper shows the compilation of 944-km-length of ship track gravity observations locating in the vicinity of Bach Long Vi island, Vietnam, measured in 2005 using ZLS D60 Dynamic Gravity Meter. The procedure of duplicate removal was conducted first with 28,164 original points, where 6 duplicate points were detected. Within the remaining 28,158 points, after duplicate removal, 291 crossover points were determined from 62 detected tracks. The crossover adjustment was then applied with these 291 intersecting tracks, and the result shows that the standard deviation reduces from 2.38 mgal before adjustment to 1.89 mgal after adjustment. The maximum and minimum discrepancies at crossover points are 6.04 mgal and -7.51 mgal corresponding to the dataset before adjustment, and the corresponding values of 5.35 and -5.76 mgal were computed based on the adjusted dataset.

The small improvement of ~20% in standard deviation of crossover differences in gravity anomalies might be blamed for the small experimental area plus the identicalness in measuring equipment. The procedure applied in this research is believed to be able to be further developed with a wider range of marine gravity anomalies dataset in Vietnam, i.e., the one covering a larger area, and can be applied with other types of gravity data as well, e.g., altimetry-derived or airborne gravity data. The marine gravity dataset after crossover adjustment can subsequently be used for the purpose of merging with other types of marine gravity data, e.g., the data determined by airborne gravimetry or altimetry, or even with land gravity data. The unified dataset after merging from these types of data will be useful for various applications in Vietnam, such as the determination of the local geoid model.

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