Article

Methods for Underwater Gravity Measurement Error Compensations Based on Correlation Analysis

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Abstract: The measurement of Earth’s gravitational field is important in geophysics, geodynamics, geodesy, oceanography, and space science. The ocean covers 71% of the earth’s surface; therefore, measuring the ocean’s gravitational field is crucial. Compared with shipborne gravimetry, underwater gravimetry near the seafloor is closer to gravity sources and can obtain short-wavelength gravity information that is useful for small-scale deposit detection and seawater intrusion monitoring. This article focuses on gravimetric errors caused by the poor dynamics of the carrier; an error compensation method for underwater gravimetry based on correlation analysis is proposed. By analyzing the error sources that affect the dynamics of the carrier, the relationship between the gravimetry error and impact factors related to the dynamics was established, and the model’s parameters were estimated by the least-squares fitting method. The experimental data show that this method can effectively compensate for gravimetric errors caused by carrier dynamics and provide the theoretical basis and algorithm model for underwater gravimetry in the bottom-tracking mode.

Keywords: underwater gravimetry; correlation analysis; error compensation; empirical mode decomposition; carrier dynamic

1. Introduction

The traditional methods of marine gravimetry include ship load gravimetry, aerial gravimetry (offshore), and satellite height measurement. These methods have high measurement efficiency and can cover a large measurement area. However, the observation space is located at or above the water surface, and the acquisition of gravity signals close to the seabed is limited. Keeping the gravimeter close to the seabed allows more precise measurements of gravitational anomalies. Although the development of underwater dynamic gravimetry is relatively late, the measurement space is closer to the seabed, which fills medium and short wavelength information in ocean gravity information and greatly improves the resolution of the gravimeter. It is necessary to carry out relevant research on underwater dynamic gravimetry.

According to the measurement carrier classification, the mainstream underwater dynamic gravimetric measurement carrier includes tow carriers, manned underwater vehicles, and autonomous underwater vehicles. The underwater gravimetric measurement method based on the two-stage towed carrier is adopted in our study. Compared with the underwater gravimetric measurement method based on the AUV, the towed carrier system has the advantages of low cost, strong endurance, reliable communication and synchronization, and accurate positioning, and its attitude stability is also better than the other two methods. Although the towed carrier has relative advantages, its motion is still affected by fluid resistance. Furthermore, underwater gravity measurements using the bottom-tracking mode require maintaining the gravimeter at a constant height above the seabed, which induces high dynamic depths.
The carrier dynamic is one of the important factors that affect the measurement accuracy of strapdown gravimeters. In general, the worse the dynamics of the carrier, the lower the accuracy of the gravity measurement. Carrier dynamics are mainly influenced by changes in depth. The more intense the depth changes and the greater the fluctuation, the worse the carrier dynamics. Because the acceleration of the carrier is obtained by the depth’s second-order difference, the dynamics of the carrier will affect the estimated acceleration, thereby indirectly affecting the accuracy of the gravity measurement. Underwater gravity measurements using the bottom-tracking mode require maintaining the gravimeter at a constant height above the seabed; keeping the gravimeter close to the seabed allows more precise measurements of gravitational anomalies.

However, because of the variability of the seabed’s topography, this measurement method will lead to frequent changes in the depth of the gravimeter, the carrier dynamics will deteriorate, and the quality of gravity-measurement data will also decline. In order to improve the quality of underwater gravity measurements, gravity surveyors all over the world have performed extensive work on error compensation methods for gravity measurements for many years. The errors of airborne gravimetry systems were analyzed in [1], and the errors of different grades were compensated. A deep-learning method was employed by [2] to compensate for errors of the gravimeter, and some good results were obtained. The error sources of underwater gravity measurements were analyzed in [3], and a general model for compensating the errors of marine gravity measurement was proposed, which is applicable to highly dynamic environments. In the present work, we use a correlation analysis method to compensate for gravity-measurement errors caused by poor dynamics and ensure the accuracy of gravity measurements in the bottom-tracking mode. Our work is carried out in the following order: the first section briefly introduces the problem background, the second section introduces the error compensation method, the third section describes the experimental process and experimental results, and the fourth section discusses the experimental results and provides the conclusion.

2. Materials and Methods

The errors related to dynamics are mainly caused by changes in depth. A drastic change in depth will change the pitch angle of the carrier; the upward acceleration of the carrier will also fluctuate greatly, and the upward-specific force error will increase. The upward-specific force error can be expressed as follows [4]:

\[ \delta f = k \cdot f + \tau \cdot df + \nabla \]

where \( \delta f \) is the upward-specific force error; \( k \) is the scale factor error; \( df \) is the derivative of the upward-specific force; \( \tau \) is the time delay coefficient; \( \nabla \) is Gaussian white noise.

Therefore, errors related to dynamics mainly include the motion acceleration of the upward-specific force, the upward-specific force itself, the derivative of the upward-specific force, changes in the pitch angle, and depth changes (sky velocity). In order to suppress the influence of dynamics-related error terms on gravity measurement, it is necessary to model and compensate for each error term.

The data flowchart of the error compensation method based on correlation analysis is shown in Figure 1. Firstly, the gravity-measurement results on the survey line are empirically mode decomposed to obtain a group of intrinsic mode functions and residual signals. Secondly, intrinsic mode functions that have no correlation with the gravity-measurement results, the upward-specific force, the upward-specific force derivative, the upward velocity, the upward acceleration, and the pitch angle change are removed; the remaining intrinsic mode functions and residual signals are then reconstructed. Thirdly, the difference between the reconstructed gravity-measurement result and its fitting curve is calculated. According to the least-squares fitting method, an error model is established.
between the difference and the upward-specific force, the upward-specific force derivative, the upward velocity, the upward acceleration, and the pitch angle change. Finally, the reconstructed gravity-measurement results are compensated according to the error model. The specific data-processing steps are summarized as follows:

1. Obtain the depth curve of each survey line in the survey area, and calculate the standard deviation of the depth value of each survey line. The larger the standard deviation, the more drastic the depth change with respect to the survey line, and the worse the dynamics of the carrier on the survey line. Select the survey line with the largest standard deviation of the depth curve as the target survey line.

2. Calculate the upward-specific force, depth, pitch-angle change, and gravity measurement results of the gravimeter on the target survey line. The upward-specific force derivative is obtained by differentiating the upward-specific force, the upward velocity is obtained by differentiating the depth, and the upward acceleration is obtained by differentiating the upward velocity. The results of the gravity measurement, the upward-specific force, the derivative of the upward-specific force, the upward velocity, the upward acceleration, and the change in the pitch angle are taken as the influence factors.

3. Empirical mode decomposition (EMD) is performed on the gravity-measurement results of the target survey line to obtain a set of intrinsic mode functions from low frequency to high frequency and a residual signal. Correlation coefficient $r$ is obtained by analyzing the correlation between intrinsic mode functions and gravity-measurement results, the upward-specific force, the derivative of the upward-specific force, the upward velocity, the upward acceleration, and the change in the pitch angle.

When $|r| \geq 0.7$, the correlation between the intrinsic mode functions and the influence factor is strong; when $0.2 \leq |r| < 0.7$, the correlation between the intrinsic mode functions and the influence factor is weak; when $|r| < 0.2$, the correlation between the intrinsic mode functions and the influence factor is weak.

4. Remove the intrinsic mode functions that have no correlation with the gravity-measurement results, the upward-specific force, the upward-specific force derivative, the upward velocity, the upward acceleration, or the pitch angle change and accumulate the remaining intrinsic mode functions and the residual signals to obtain the reconstructed gravity-measurement results. Curve fitting is performed on the reconstructed gravity-measurement result to obtain the fitted gravity-measurement curve. Taking the fitting curve as the standard value, the difference between the reconstructed gravity-measurement result and the fitting curve is obtained; this is the gravity-measurement error of the target survey line.

5. Establish the relationship between the gravity-measurement error and the upward-specific force, the upward-specific force derivative, the upward velocity, the upward acceleration, and the pitch angle change, as shown in formula 2:

$$
\delta g_{\text{fitting}} - \delta g_1 = k_1 f + k_2 \dot{v} + k_3 df + k_4 dp + k_5 dh + k_6 f^2 + k_7 \dot{v}^2 
+ k_8 df + k_9 dp^2 + k_{10} dh^2 + k_{11} f \ddot{v} + k_{12} df \ddot{v} + k_{13} f dp 
+ k_{14} df dh + k_{15} \dot{v} df + k_{16} \dot{v} dp + k_{17} \dot{v} dh + k_{18} df dp + k_{19} df dh + k_{20} dp dh, \tag{2}
$$

where $\delta g_{\text{fitting}}$ is the gravity-measurement result after fitting; $\delta g_1$ is the reconstructed gravity-measurement result; $\dot{v}$ is the upward acceleration; $dp$ is the change in pitch angle; $dh$ is the upward velocity; $k_\alpha (\alpha = 1, 2, \ldots, 20)$ is the error model parameter.
(6) Each model parameter in Formula (2) is estimated by the least-squares fitting method to obtain the specific form of the error equation. According to the error model, reconstructed gravity-measurement results are error-compensated to obtain compensated gravity-measurement results. The error compensation equation is shown in Formula (3):

\[
\delta g_{\text{compensate}} = \delta \hat{g}_1 + k_1 f + k_2 \hat{v} + k_3 df + k_4 dp + k_5 dh + k_6 f^2 + k_7 \hat{v}^2 \\
+ k_8 dP^2 + k_9 dh^2 + k_{10} f \hat{v} + k_{12} f df + k_{13} f dp \\
+ k_{14} f dh + k_{15} \hat{v} df + k_{16} \hat{v} dp + k_{17} \hat{v} dh + k_{18} df dp + k_{19} df dh + k_{20} dp dh,
\]

(3)

where \(\delta g_{\text{compensate}}\) is the gravity-measurement result after compensation.
(7) Other survey lines are selected in the survey area with the same type of gravity-measurement result fitting curve as the target survey line. For example, if the gravity-measurement-result fitting curve of the target survey line is a quadratic curve, the gravity-measurement result fitting curve of the other selected survey lines should also be a quadratic curve. The reconstructed gravity-measurement results are obtained from the gravity-measurement results of other measuring lines according to steps (3) and (4), and error compensation is performed according to the error model formula of step (6) to obtain the compensated gravity-measurement results.

3. Results

In order to test the performance and technical indices of the towing system and the underwater dynamic gravimetry system mounted on the towed body, our research group conducted an underwater gravimetry test in a deep-sea area of the South China Sea in 2019. The area is challenging and has a variety of topographic and geomorphic features. The water depth in the test area is about 2200 m, and underwater gravimeter performs gravity measurements at a depth of about 2000 m with an average speed of 2.5 knots. The round-trip measurement of the test line SHEW1 produced two repeated test lines SHEW1-1 and SHEW1-2, and the round-trip measurement of the test line SHEW2 also produced two repeated test lines SHEW2-1 and SHEW2-2. The experimental results show that the inner coincidence accuracy of SHEW1 is 1.06 mGal/180 m. The consistency accuracy of SHEW2 in two repeated lines is 1.15 mGal/180 m. For the detailed introduction of the experiment, please refer to [5]. The error analysis and compensation involved in this paper are carried out on the basis of gravity anomaly processing; for the specific processing process of gravity anomaly, please refer to [6], which will not be repeated in this paper. The statistical results of depth standard deviation along survey line SHEW1 and survey line SHEW2 are 12.8 m and 24.4 m, respectively. The depth curve of one east–west survey line SHEW2-2 and the gravity-measurement results after 300 s finite impulse response (FIR) low-pass filtering are shown in Figures 2 and 3, respectively.

![Figure 2. Depth curve of SHEW2-2.](image-url)
Figure 3. Gravity-measurement results of SHEW2-2.

It can be seen from Figure 2 that there are two peaks in the depth curve of survey line SHEW2-2; these were caused by the project team continuously retracting and releasing the cable during the acquisition of survey line SHEW2-2 to prevent the towing body from being too close to the bottom. The drastic change in depth also leads to two spikes in gravity-measurement results; these are gravity-measurement errors caused by dynamics (Figure 3). Since the depth standard deviation of survey line SHEW2-2 is the largest and its dynamic property is the worst, it was used as the target survey line to fit the reconstructed gravity-measurement result curve, as shown in Figure 4.

Figure 4. Fitting curve of gravity-measurement results of survey line SHEW2-2.

The parameters of each model in Formula (3) were estimated by the least-squares fitting method, and parameters of the fitting model are shown in Table 1.
Table 1. Statistics of error fitting parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$</td>
<td>0.05</td>
<td>$k_{11}$</td>
<td>160.98</td>
</tr>
<tr>
<td>$k_2$</td>
<td>-0.03</td>
<td>$k_{12}$</td>
<td>2068.08</td>
</tr>
<tr>
<td>$k_3$</td>
<td>0.82</td>
<td>$k_{13}$</td>
<td>-1.89</td>
</tr>
<tr>
<td>$k_4$</td>
<td>-7.45 × 10^{-5}</td>
<td>$k_{14}$</td>
<td>0.72</td>
</tr>
<tr>
<td>$k_5$</td>
<td>-1.96 × 10^{-4}</td>
<td>$k_{15}$</td>
<td>-2807.23</td>
</tr>
<tr>
<td>$k_6$</td>
<td>-55.13</td>
<td>$k_{16}$</td>
<td>3.78</td>
</tr>
<tr>
<td>$k_7$</td>
<td>-171.08</td>
<td>$k_{17}$</td>
<td>-1.07</td>
</tr>
<tr>
<td>$k_8$</td>
<td>2492.97</td>
<td>$k_{18}$</td>
<td>24.52</td>
</tr>
<tr>
<td>$k_9$</td>
<td>-0.01</td>
<td>$k_{19}$</td>
<td>-2.70</td>
</tr>
<tr>
<td>$k_{10}$</td>
<td>-1.76 × 10^{-4}</td>
<td>$k_{20}$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Since the fitting curves of gravity-measurement results of all survey lines in the survey area are primary curves, the reconstructed gravity-measurement results according to the error model are compensated according to Formula (4) to obtain the compensated gravity-measurement results. Figure 5 is a comparison diagram of gravity-measurement results (300 s low-pass filtering) before and after the compensation of repeated survey line SHEW2; Figure 6 shows gravity-measurement results (300 s low-pass filtering) before and after the compensation of the SHEW1-repeated survey line.

\[
\delta g_{\text{compensate}} = \delta g_1 + 0.05f - 0.03\dot{v} + 0.82df - 7.45e - 05dp - 1.96e - 04dh - 55.13f^2 - 171.08\dot{v}^2 \\
+ 2492.97df^2 - 0.01dp^2 - 1.76e - 04dh^2 + 160.98f\dot{v} + 2068.08fdf - 1.89fdp \\
+ 0.72fdh - 2807.23\dot{v}df + 3.78\dot{v}dp - 1.07\dot{v}dh + 24.52fdwp - 2.70fdh + 0.01dpdh
\]  

(4)

Figure 5. Gravity-measurement result curves for survey line SHEW2 before and after compensation (300 s filtering). (a) Gravity-measurement results for survey line SHEW2-1 before and after compensation; (b) gravity-measurement results for survey line SHEW2-2 before and after compensation.
Figure 6. Gravity-measurement result curves for survey line SHEW1 before and after compensation (300 s filtering). (a) Gravity-measurement results for survey line SHEW1-1 before and after compensation; (b) gravity-measurement results for survey line SHEW1-2 before and after compensation.

The statistics of gravity-measurement accuracy before and after compensation of the two repeated measuring lines are shown in Table 2. The coincidence accuracy of the compensated repeated measuring lines improved. It can be seen that the error-compensation method based on the correlation analysis can compensate for gravity-measurement errors caused by dynamics and thereby improve the accuracy of gravity measurements.

Table 2. Statistics of gravity-measurement accuracy of repeated survey lines before and after compensation (300 s filtering).

<table>
<thead>
<tr>
<th></th>
<th>SHEW1 (mGal)</th>
<th>SHEW2 (mGal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before comp.</td>
<td>1.06</td>
<td>1.15</td>
</tr>
<tr>
<td>After comp.</td>
<td>0.99</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Figures 7 and 8 show the gravity-measurement results (300 s low-pass filtering) of the north–south survey lines SHNS1 and SHNS2 after compensation according to Formula (4). It can be seen from the figure that the fluctuation of the gravity-measurement results after the compensation is smaller and smoother.

Figure 7. Gravity-measurement results for survey line SHNS1 before and after compensation.
4. Discussion and Conclusions

The accuracy of gravity measurement is not only related to the errors that can be modeled but also to non-model errors caused by different dynamics. In general, the worse the dynamics, the worse the gravimetric results. The survey line SHEW2-2 in the experiment kept retracting the cable due to the sea state to prevent the depth of the towed body from touching the bottom, which was difficult to accept in high-precision dynamic gravity measurements. If only the influence of model error is considered, the accuracy of gravity results will relatively decrease. Via the non-model error compensation correction method proposed in this paper, the fluctuation of the gravity measurement results is smaller, and the inner coincidence accuracy of the measurement line SHEW2 improved from 1.15 mGal to 0.73 mGal.

For measuring line SHEW1, the overall motion process is relatively stable, and the inner conformity accuracy is slightly improved after compensation, but the effect is not very obvious, and the accuracy increased by 0.07 mGal. This is because our method only deals with the non-model error caused by the dynamic, and the worse the dynamic, the better the effect will be. Compared with traditional methods that only consider model errors, the method in this paper further considers methods for confronting non-model errors caused by high dynamics, which is common in underwater gravimetry. The accuracy of the two survey lines improved regardless of whether the dynamics is good or bad. This also provides us with ideas for dealing with other measure environments such as aerial, vehicular, and shipborne gravity measurements. Similar results can be obtained by our method for each measure environment.

Aiming at gravity measurement errors, which cannot be modeled due to poor carrier dynamics in underwater gravimetry, our paper proposes an underwater gravimetry error compensation method based on correlation analysis. Experimental data show that this method can well compensate gravity measurement errors related to dynamics and improve the accuracy of gravimetry. In terms of engineering, our research largely compensated for the dynamic error of underwater gravity measurements caused by men or the environment and improved the experimental efficiency.

5. Patents

Error compensation method for underwater gravity measurement based on correlation analysis, invention patent, 2020 (application number: 202010970205.8).

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