# Correction Method with Multi-beam Bathymetric Constraints for False Strata Undulation of Sub-Bottom Profile Data Collected by Deep-Tow System

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**Abstract.** The deep-towed sub-bottom profiling method is widely used in deep-sea engineering geological surveys due to its high resolution and low noise characteristics. However, due to the cable-towing operation method, the collected profile data cannot reflect the actual geological conditions, and post-processing is required to correct the false fluctuations in the strata. The surge correction methods commonly used for shipborne sub-bottom data are ineffective for correcting false fluctuations caused by cable-towing operations. This paper analyzes the feasibility of correcting false fluctuations based on bathymetric data, starting from the working characteristics of deep-towed multi-sensor integrated detection and the measurement principles of sub-bottom profiling. The effectiveness of the correction method based on multi-beam bathymetric constraints is verified through actual data.

**Keywords:** Deep-Tow system, Sub-bottom profile, Multi-beam echo sounder, False fluctuations in strata, Water depth constraints.

## 1 Introduction

Sub-bottom profilers identify strata by analyzing the characteristics of sound waves passing through different media layers. In shallow waters, shipborne methods can collect high-quality data that meet the requirements of marine engineering geological surveys [1]. However, in deep-water areas, due to the absorption of sound waves by water, the data collected cannot meet the survey requirements [2]. The deep-towed sub-bottom profiling method reduces the loss of sound wave energy during propagation by bringing the equipment closer to the seabed, thereby obtaining high-resolution profile data. This technology has been widely used in deep-sea engineering surveys.

During operations, the height of the towbody above the seabed changes due to vessel speed changes and obstacle avoidance maneuvers. The sub-bottom profiler records the travel time of sound waves and converts it into distance based on sound speed. This distance represents the distance from the reflection layer to the instantaneous position of the instrument. Since the height of the sub-bottom profiler changes constantly, the


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recorded fluctuations in the strata do not match the actual geological conditions, resulting in false fluctuations. These false fluctuations can interfere with profile interpretation, leading to misjudgments or omissions of geological anomalies, and increasing the risks in marine engineering design and construction.

For shipborne equipment, surge filtering methods are commonly used to eliminate high-frequency, small-amplitude fluctuations caused by sea waves. In deep-towed mode, corrections are based on the depth of the towbody, with pressure sensors recording the real-time depth and transmitting it to a central processing unit for real-time compensation of sub-bottom profiling data. Internationally, Triton's SB-Logger software uses this compensation method [3]. This paper analyzes the feasibility of correcting profile data based on depth constraints and proposes specific correction methods, addressing the issue of false fluctuations in sub-bottom profiling data caused by deep-towed operations. Finally, the practicality of the process is verified using collected profile data.

## 2 Correction For False Strata Undulation Based on Multi-Beam Bathymetric Constraints

### 2.1 Principle of Sub-bottom Profiling

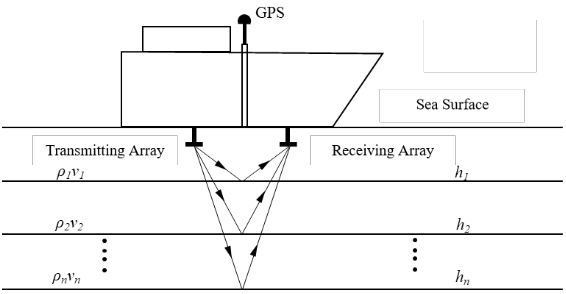



**Fig. 1.** The working principle diagram of a sub-bottom profiler

As shown in Figure 1, the principle of sub-bottom profiling is to simplify seawater and strata into layered propagation media [4]. Seawater is the first medium that sound waves encounter after emission, with an assumed density of $\rho_1$ and a sound wave propagation speed of $v_1$. The seabed is assumed to have n layers of different properties, with densities and sound wave propagation speeds of ($\rho_2, \rho_3, ..., \rho_n$) and ($v_2, v_3, ..., v_n$), respectively. During sound wave propagation, part of the sound wave is reflected to the receiver at the interface between media. Another part continues to propagate through the interface to the next layer, where it is either transmitted or reflected again. The intensity of the reflected sound wave depends on the reflection coefficient R:

$$A_r = R*A_i \tag{1}$$

In the formula (1), Ar is the amplitude of the reflected wave, Ai is the amplitude of the incident wave, and $R$ is the reflection coefficient, determined by the following equation:

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{2}$$

During operation, the sub-bottom profiler emits high-power, low-frequency acoustic pulses vertically into the water, and then records the returning acoustic information at fixed time intervals [5]. Profiler calculates the position and properties of each stratum by recording the travel time and reflection intensity of the reflected waves from each interface [6].

## 2.2 Analysis of the Causes of False Strata Undulation

During deep-tow sub-bottom profiling surveys, the towbody is typically connected to the mother ship via a neutrally buoyant Ethernet umbilical cable and a 10,000-meter armored cable [7]. To ensure safe operation, the towbody must be maintained at a certain height above the seabed. When the seabed is uneven, the length of the armored cable must be continuously adjusted during operation to raise or lower the towbody, causing the height of the sub-bottom profiler's transducer to change with the towbody's movement constantly.

Figure 2 shows the effect of towbody movement on sub-bottom profile data. Assuming the seabed is flat, the real terrain is $L_1$. At a given instant, the towbody is at position $A$, and the travel time of the reflected wave from point $A_1$ on the seabed is t. The depth of the seabed reflection layer is calculated, using the horizontal plane at the current position of the towbody as the reference plane, the depth of point $A_1$ recorded by the sub-bottom profiler is $h_1$, located at $A_1$. If the towbody rises to position $B$ next moment, the vertical height difference between $A$ and $B$ is $\Delta h$. Due to the rise of the towbody, the travel time of the reflected wave from point $B_1$ on the seabed increases by $\Delta t$. The depth of point $B_1$ recorded by the sub-bottom profiler is $h_2$, located at $B_2$ instead of $B_1$. The vertical height difference between $A_1$ and $B_2$ is $\Delta h$ and the terrain recorded by the sub-bottom profiler is $L_2$. Similarly, the echoes from the reflection layers below the seabed will be affected by the change in towbody height, leading to similar false undulation of the strata.

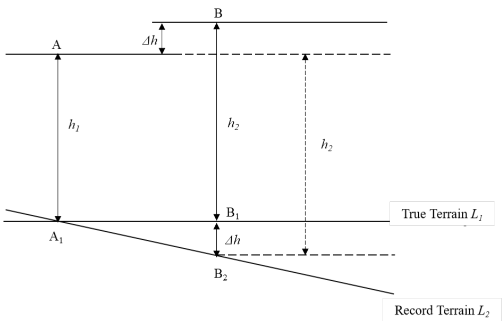



**Fig. 2.** The impact diagram of towbody heave on sub-bottom profiling data

### 2.3 Correction Method for False Strata Undulation Based on Multi-beam Bathymetric Constraints

When using Deep-Tow System for sub-bottom profiling, single-beam or multi-beam bathymetric surveys are usually conducted simultaneously. Since the seabed topography in the same area does not change significantly in a short period, the water depth values are relatively stable. Therefore, it is proposed to use the sea surface as reference plane to correct the false undulation of the strata in sub-bottom profiles using bathymetric data from the same area. Compared to single-beam and pressure sensor linear measurement methods, multi-beam bathymetric systems can obtain hundreds of depth points perpendicular to the direction of travel with each emission and reception [8]. The multi-beam bathymetric system mounted on the Deep-Tow System has the characteristics of high efficiency and accuracy in obtaining seabed topography data, and it is not constrained by time synchronization conditions, resulting in high data utilization.

Therefore, this paper proposes a method to calibrate sub-bottom profile data (time domain) using multi-beam bathymetric data (depth domain) in deep-tow mode. The correction of false strata undulation in sub-bottom profiles based on multi-beam bathymetric data first requires tracking the seabed in the sub-bottom profile data to obtain the false seabed, and then correcting the false seabed to the actual seabed position based on the multi-beam bathymetric data. The specific process is:

**Seabed tracking in sub-bottom profile data.** Extract the plane coordinates and the two-way travel time of the seabed reflection wave for each trace in the sub-bottom profile data.

**Bathymetric data matching.** Match the multi-beam bathymetric data based on the plane coordinates extracted in the last step to obtain the corresponding multi-beam water depth.

**Calculate the time correction value for each trace.** Convert the obtained multi-beam water depth from the depth domain to the time domain based on the sound speed, and calculate the time correction value for each trace of the sub-bottom profile data. Seabed tracking of sub-bottom profiling data provides two-way travel time of the seabed reflection wave. Time derived from the depth-to-time conversion of multi-beam bathymetric data corresponds to the one-way travel time of the seabed reflection wave in the multi-beam data [9].

$$t_{1i} = \frac{h_i}{v} \tag{3}$$

$$\Delta T = 2t_{1i} - t_i \tag{4}$$

In the formula (4), $t_{1i}$ is the one-way travel time of the seabed reflection wave in the multi-beam data, $t_i$ is the two-way travel time of the seabed reflection wave record by the sub-bottom profiler, $\Delta T$ is the time compensation value for referencing the datum plane of each sub-bottom profiler trace to the sea surface.

**Modify the sub-bottom profile data record.** Rewrite each trace of the sub-bottom profile data based on the time correction value calculated in the last step.

# 3 Experimental Analysis

## 3.1 Experimental Area and Survey Line Design

As shown in Figure 3, the experiment covers 3*3 $km^2$ with water depths ranging from 1,200 to 1,300 meters. 2400 DT-1 Deep-Tow system with a maximum operating depth of 3,000 meters was used in the experiment, equipped with: EdgeTech 2400 side-scan sonar/sub-bottom profiler system; Kongsberg EM 2000 multi-beam system and Ranger 2 Gyro USBL acoustic positioning system. Four primary survey lines (101, 102, 103, 104) and one secondary line (101A) were deployed (Figure 4). The primary lines followed north-south (102, 104) and east-west (101, 103) orientations, while the secondary line 101A shared the same direction as line 101 but was surveyed at a different time. Each primary line spanned approximately 3 km, and the secondary line 101A was 1.4 km long. The intersections of the four primary lines formed four crosspoints, with the primary and secondary lines depicted in blue and red, respectively.

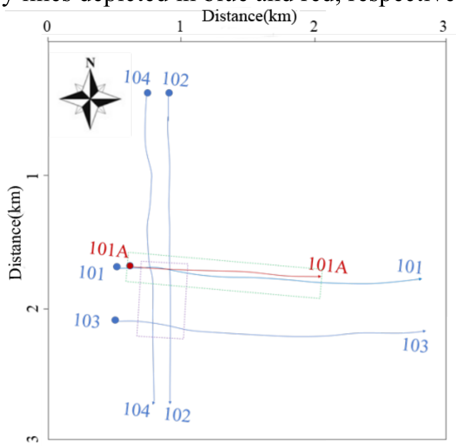



**Fig. 3.** Layout diagram of deep-tow survey lines in the experimental area

## 3.2 Correction of False Strata Undulation

**Single Survey Line Correction.** Lines 101 and 101A were analyzed. Despite sharing the same orientation, their survey dates differed. A segment of 1,400 traces from line 101A was spatially aligned with line 101. We tracked the seafloor of the two survey line's sub-bottom profile data before and after correction. compared obtained seabed reflection layers (Figures 4a–4f). Due to the vibration of the towbody, significant discrepancies in strata undulation and seabed positions were observed between the two lines before correction (Figures 4a–4c). The undulation patterns and seabed positions are basically consistent after correction, with minor deviations due to the position deviation of lines (Figures 4d–4f).

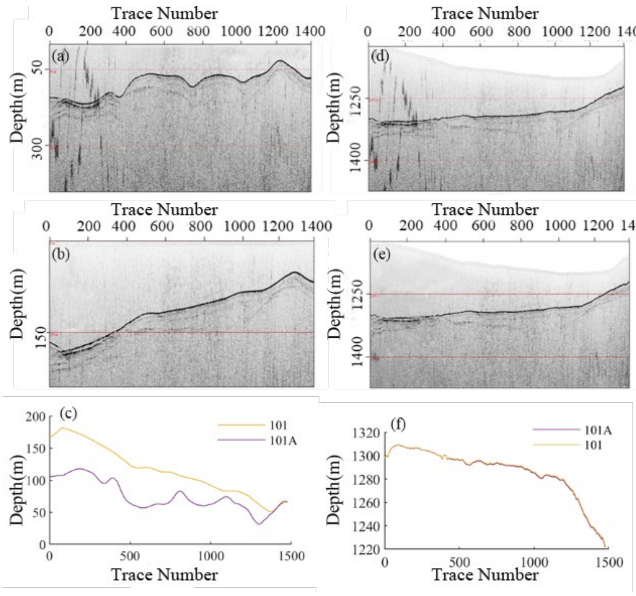



**Fig. 4.** Comparison diagram of seabed reflection layers before and after correction

**Crosspoint Correction.** To validate the effectiveness of the proposed method in correcting false strata undulation in sub-bottom profile data at survey line crosspoints, sub-bottom profile data from survey lines 101–104, delineated by the purple dashed box in Figure 5, were spliced at their intersection points.

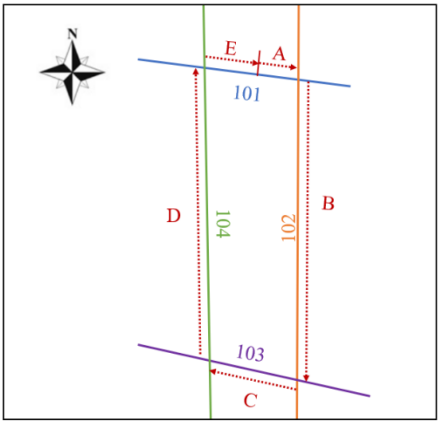
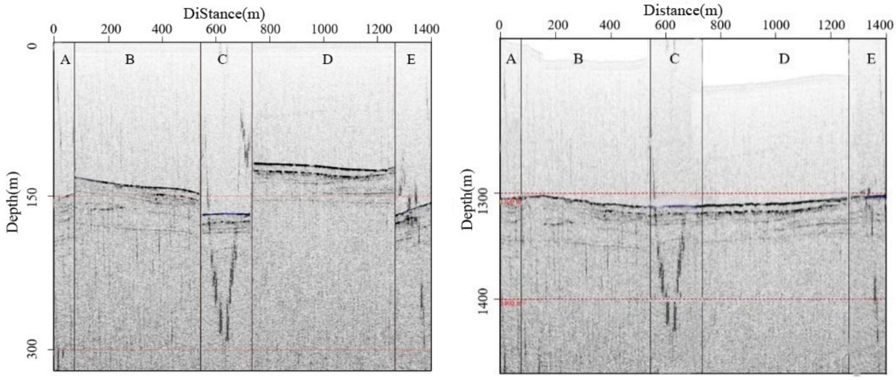



**Fig. 5.** Schematic of survey line crosspoints

To splice the sub-bottom profile images of the four primary survey lines, the data were divided into five sections (A, B, C, D, and E). The profile images before and after correction were then sequentially spliced in order (Figures 6a–6b).




(a) (b)

**Fig. 6.** Crosspoint profile mosaic before (a)and after(b) correction

To quantitatively analyze the performance of the correction method, 100 sampling points with identical timestamps were selected from two intersecting survey lines at each crosspoint before and after correction. The precision of this method was evaluated by comparing the amplitude consistency of the sampling points at the crosspoints. The following evaluation metrics were employed:

*Maximum Amplitude Difference (MAXΔA).* MAXΔA refers to the maximum absolute value of the amplitude differences between corresponding sampling points from two intersecting survey lines at the crosspoint.

*Minimum Amplitude Difference (MINΔA).* MINΔA refers to the minimum absolute value of the amplitude differences between corresponding sampling points from two intersecting survey lines at the crosspoint.

*Root Mean Square Error (RMSE).* RMSE is defined as the square root of the ratio of the sum of squared amplitude differences between corresponding sampling points from two intersecting survey lines at the crosspoint to the number of sampling points *N*. A smaller RMSE value indicates better consistency between the two intersecting survey lines at the crosspoint after correction.

*Spearman Correlation.* Proposed by Spearman in 1904, Spearman Correlation is a non-parametric measure of the strength and direction of association between two variables (Lehmann and D'Abrera 1998). It is suitable for analyzing correlations involving ordinal variables or interval data that violate the normality assumption. To calculate Spearman Correlation, the raw data must first be ranked in descending order. The correlation coefficient is then computed using the following formula:

$$Rs = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{5}$$

In the formula (5), $d_i$ represents the rank difference of amplitudes between corresponding sampling points from the two intersecting survey lines at the crosspoint, and $n$ denotes the number of selected sampling points. Quality assessments were conducted separately for each of the four crosspoints using the aforementioned metrics, as shown in Figure 7 and Table 1.

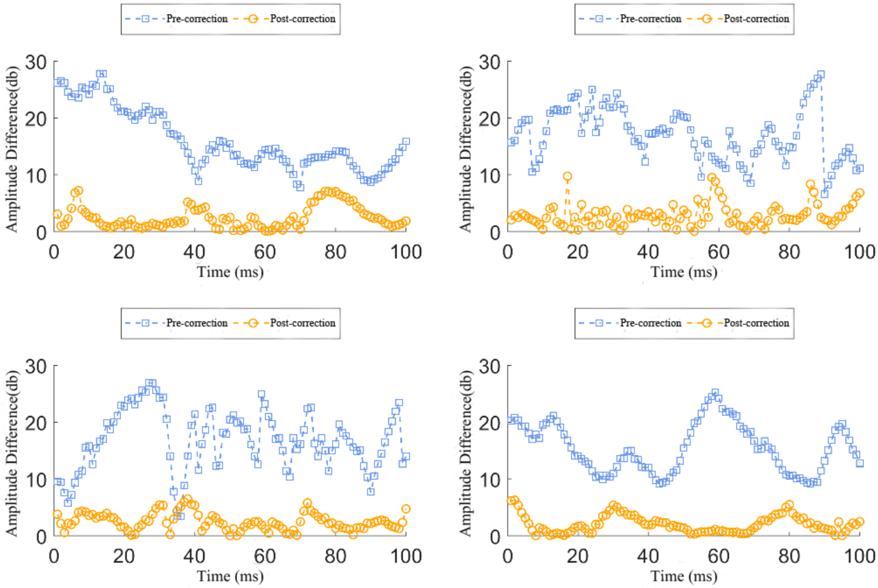



**Fig. 7.** Amplitude differences at crosspoints

**Table 1.** Performance index of intersection data before and after correction.

| Index | A-B Intersection | B-C Intersection | C-D Intersection | D-E Intersection |
|---|---|---|---|---|
| MAXΔA | 27.77 → 7.22 | 27.67 → 9.73 | 26.92 → 6.49 | 25.26 → 6.28 |
| MINΔA | 7.73 → 0.05 | 6.60 → 0.062 | 3.42 → 0.04 | 9.12 → 0.03 |
| RMSE (dB) | 16.96 → 3.16 | 17.68 → 3.48 | 17.63 → 2.89 | 16.07 → 2.53 |
| CORR | 0.525 → 0.921 | 0.501 → 0.916 | 0.497 → 0.921 | 0.557 → 0.932 |

### 3.3 Analysis of Results

The experimental results demonstrate that:

The strata interfaces in sub-bottom profiles exhibited significant non-closure at crosspoints before correction. All crosspoints showed well-aligned strata interfaces after correction.

Amplitude values at identical positions across crosspoints varied considerably, with an average root mean square error (RMSE) of approximately 17 dB before correction. The RMSE decreased significantly to ~3 dB after correction.

A weak correlation was observed between amplitude values at crosspoints before correction. The corrected survey lines exhibited a strong amplitude correlation after correction.

Comparative analysis of single survey lines and crosspoint profiles, both pre-and post-correction, confirms that the proposed water depth-constrained method effectively corrects false strata undulation in sub-bottom data acquired under deep-tow conditions. Post-correction profiles demonstrate enhanced consistency in reflection layers, accurately reflecting the real geological structure of the seabed.

## 4 Conclusions

In recent years, the engineering geophysical survey method employing Deep-Tow System integrated with sub-bottom profilers has gained widespread application in deep-sea engineering projects. Compared with traditional pressure sensor-based corrections methods for sub-bottom profiler data, the multi-beam bathymetry-constrained correction method proposed in this study demonstrates significant advantages. Conventional approaches rely on real-time acquisition of towed pressure sensor data to calculate depth parameters, which carries the risk of data chain interruption due to sudden sensor failures. In contrast, multibeam bathymetric data possesses retrospective characteristics, enabling spatial stratum repositioning through historical high-precision 3D topographic data from the same area even when pressure sensors malfunction, thereby ensuring the continuity of deep-sea exploration operations. However, this method is notably constrained by multibeam data quality, particularly in areas with dramatic seabed topographic variations. It requires preprocessing procedures including manual anomaly screening and interpolation algorithm optimization to enhance bathymetric model accuracy, resulting in reduced time-efficiency when applied in complex terrains. Notably, current spatial matching between large-scale bathymetric data and sub-bottom profiler data still depends on empirical threshold settings, limiting batch processing capabilities. With the advancement of artificial intelligence technology, deep neural network models could be developed to achieve automatic feature extraction and intelligent matching of multi-source data. By implementing transfer learning strategies to enhance model adaptability to complex terrains, data preprocessing efficiency could be substantially improved, offering new technological pathways for real-time monitoring in deep-sea engineering and large-scale seabed exploration.

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