SOUND VELOCITY PROFILE (SVP) INVERSION THROUGH CORRECTING THE TERRAIN DISTORTION

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Abstract

In this paper, mode vectors are obtained via the Empirical Orthogonal Function (EOF) based on real Sound Velocity Profiles (SVP) measurements. Through correcting the terrain distortion, reconstructed coefficients of SVPs are determined by Genetic Algorithm (GA) and then the inversion result of the SVP is obtained. The conclusions show that the terrain distortion caused by sound velocity errors can be effectively corrected by the inversion result of the SVP. Using this process, the accuracy and processing efficiency of multi-beam bathymetry data can be significantly improved.

***Key Words*:** sound velocity profile; SVP; EOF; GA; inversion; accuracy

Résumé

Cet article décrit la décomposition en vecteurs propres via les fonctions empiriques orthogonales (EOF) des mesures des profils de vitesse du son (SVP). La correction des distorsions de terrain permet de déterminer des coefficients reconstruits des SVP à l'aide d'un algorithme génétique (AG), puis le résultat de l'inversion du SVP est obtenu. Les conclusions montrent que les distorsions de terrain causées par les erreurs de vitesse du son peuvent être effectivement corrigées par le résultat de l'inversion du SVP. A l'aide de ce processus, la précision et l'efficacité du traitement des données bathymétriques multifaisceaux peuvent être améliorées de façon importante.

Mots clés: profil de vitesse du son, SVP, EOF, AG, inversion, précision.

Resumen

En este artículo, se obtienen los vectores de forma a través de la Función Empírica Ortogonal (EOF) basada en mediciones reales de los Perfiles de la Velocidad del Sonido (SVP). Mediante la corrección de la distorsión del terreno, los coeficientes reconstruidos de los SVPs son determinados por el Algoritmo Genético (AG) y posteriormente se obtiene el resultado de la inversión del SVP. Las conclusiones muestran que la distorsión del terreno causada por errores de velocidad del sonido puede corregirse eficazmente mediante el resultado de la inversión del SVP. Utilizando este proceso, la exactitud y la eficiencia del procesado de los datos de batimetría multihaz pueden mejorarse significativamente.

Palabras clave: perfil de la velocidad del sonido; SVP; EOF; GA; inversión; exactitud.

1. Introduction

During multi-beam bathymetric data processing, the speed of sound varies with depth and can cause the oblique sounding ray paths to bend, introducing significant and systematic biases in soundings which leads to terrain distortion. The accuracy of bathymetric survey can be greatly improved by using corrected Sound Velocity Profile (SVP) data.

SVP sampling is the major method of obtaining sound velocity during a multi-beam bathymetric survey. (Herman, et al. 1998). Current survey practice requires that sound velocity measurements are taken near the extreme times of water temperature changes during the day, being 08:00 am, 02:00 pm and 08:00 pm. Rather, it is preferred that sound velocity measurements are taken nearer the time of the bathymetric data collection. (ZHU, 2011). Due to the variability in time and space, the ray trace solutions of multi-beam bathymetry collected using current methods won't necessarily meet the accuracy requirements for all bathymetric data. Thus, the distortion in the resultant seafloor terrain can be the result of sound velocity differences (errors) between the SVPs. During the multi-beam bathymetric data processing, the terrain distortion caused by sound velocity differences, can be corrected, by adjusting the Coefficients parameter of Refraction in commercial processing software.

Based on the measurement characteristics discussed, mode vectors can be obtained by EOF using real SVPs obtained in the survey area. Correcting the terrain distortion, the inversion result of the SVP can be determined by Genetic Algorithm (GA). Finally, these methods have been tested using observed data.

2. Terrain Distortion Caused by Sound Velocity Errors

Changes in temperature and salinity throughout the water column affect sound velocity. Changes in the physical properties of the medium causes deflection of the acoustic direction. If the ray traced solutions are computed using the incorrect sound velocity profile, the incorrect ray paths will lead to a lower accuracy in the bathymetry measurement and increased terrain distortion. (LI, et al. 1999, DONG, et al. 2007, LI, et al. 2001, ZHAO, LIU 2009).

When the sound velocity at the surface is less than the sound velocity at lower depths, the terrain distortions are concave. Where the above is reversed, the terrain distortions are convex. (DONG, et al. 2007, DONG, et al. 2011). If the adjacent two swaths are both distorted, there is a "ridge" or "groove" in the along-track direction. As shown in ***Figure 1***, both of the multi-beam swaths are concave and there is a "ridge" in the along-track direction. Hence it can be determined that the SVP used to compute the ray traced solutions of the multi-beam bathymetry is wrong in this area.

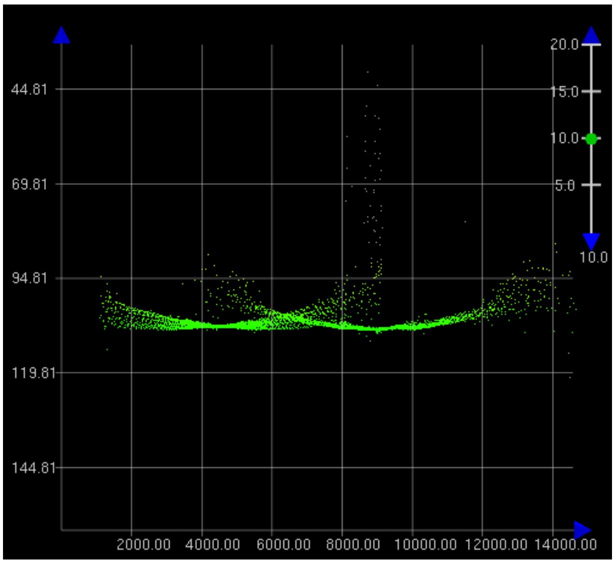


Figure 1*. Terrain Distortion caused by the Sound Velocity Errors*

3. Sound Velocity Profiles (SVPs) by EOF Modeling

A SVP is the vertical distribution of a velocity structure and can be estimated by some regularity in coastal and ocean areas. (Cartwright, 2003, Kammerer, 2000, ZHU, 2011). They can also be described by a parametric model. (ZHANG, et al. 2011). Currently, there are two parametric models for determining SVPs: Analytic Function (AF) and Empirical Orthogonal Function (EOF).

According to LeBlanc and Middleton (1980), it is a valid method to describe the SVP using an EOF parametric model based on the spatio-temporal correlation of the profiles. (DING, et al. 2007, LeBlanc and Middleton, 1980, SHEN, et al. 1999, PENG, et al. 2003, HE, et al. 2006). First, mode vectors via EOF are obtained based on real, measured SVPs. When combined with the sample data, reconstructed modeled SVPs can then be obtained.

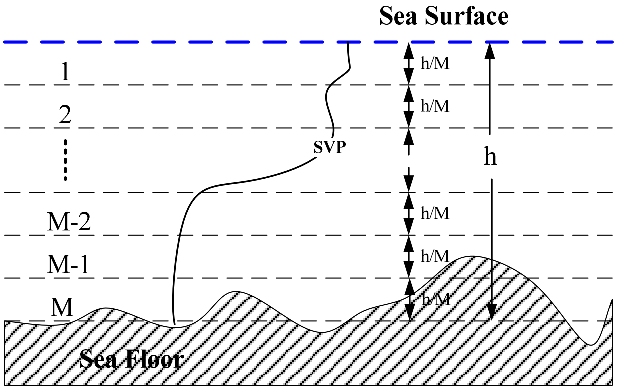


***Figure 2**. Regular Intervals of the Sound Velocity Profiles (SVPs)*

The modeling process follows:

As is shown in ***Figure 2***, N is the number of SVPs in the survey area. Interpolating M equally spaced vertical measurements to a standard floor, the SVP standardization matrix C with a size $M \times N$ of can be obtained:

$$
\mathrm{C} = \begin{bmatrix} c_{11} & c_{21} & \cdots & c_{N1} \\ c_{12} & c_{22} & \cdots & c_{N2} \\ \vdots & \vdots & \vdots & \vdots \\ c_{1M} & c_{2M} & \cdots & c_{NM} \end{bmatrix} \quad (1)
$$

The average SVP can be obtained after each row of the standardization matrix is averaged. The SVP disturbance matrix $\Delta\mathrm{C}$ is obtained by subtracting each column C and $\overline{C}$ and $R = \Delta C \Delta C^T$ is the covariance matrix of the SVPs disturbance matrix $\Delta\mathrm{C}$. As shown below, the covariance matrix R eigenvalue decomposition:

$$
RF = DF \quad (2)
$$

$D = \mathrm{diag}\begin{bmatrix} \lambda_1 & \lambda_2 & \cdots & \lambda_n \end{bmatrix}$ is the matrix consisting of characteristic values and F is determined from the feature vectors from the matrix R .

$$
F = \left[f_1(z) \; f_2(z) \cdots f_M(z) \right]^T \quad (3)
$$

λ_i is the eigenvalue corresponding to the feature vector $f_i(z)$ (EOF mode). Thus, each SVP in the survey area can be represented with K dimension vectors:

$$
c(z) = \bar{c}(z) + \sum_{i=1}^{K} a_i f_i(z) \quad (4)
$$

Where $a_i = \left[a_i(1) \; a_i(2) \cdots a_i(K) \right]$ are the coefficients of SVP reconstruction.

Once obtained they are used for inversion of the SVP.

Moving $\bar{c}(z)$ to the left side of the equation （4）:

$$
c(z) - \bar{c}(z) = \sum_{i=1}^{K} a_i f_i(z) \quad (5)
$$

$$
\Delta C_{M \times N} = \mathrm{C}_{M \times N} - \overline{C}_{M \times N} = F_{M \times K} A_{K \times N} \quad (6)
$$

According to least squares theory:

$$
A = (F^T P F)^{-1} F^T P \Delta C
= \begin{bmatrix} a_1(1) & a_2(1) & \cdots & a_N(1) \\ a_1(2) & a_2(2) & \cdots & a_N(1) \\ \vdots & \vdots & \vdots & \vdots \\ a_1(K) & a_2(K) & \cdots & a_N(K) \end{bmatrix} \quad (7)
$$

4. Inversion of the SVP by correcting the terrain distortion

The inversion of the SVP is a method whereby the acoustic properties of the ocean can be estimated by using observed data. Many scholars have proposed methods associated with this problem (HE, et al. 2011, JIN, et al.

1996, Lindsay and Chapman, 1993, Vaccaro, 1998, ZHANG, et al. 2002). This section discusses how mode vectors obtained via EOF are used for the inversion of the SVP. By correcting the terrain distortion, reconstruct coefficients of the SVP are determined by Genetic Algorithm (GA) using MATLAB (2005) software to compute the SVP inversion result.

4.1 The fitness function based on the terrain distortion

As discussed in section, the terrain distortion appears when the incorrect SVP is used for the ray traced solutions of the seabed bathymetry. As shown in ***Figure 3***, depth gradually increases from the edge to the center when the terrain distortion is concave.

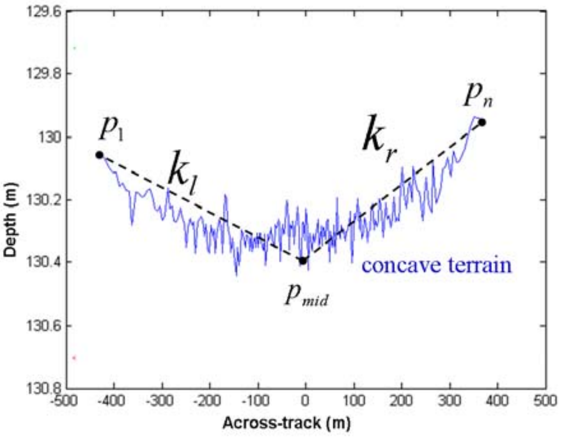


Figure 3. *Composition Principle of the Fitness Function*

In order to measure the extent of the terrain distortion, a fitness function should be constructed as follows:

$$fit(a) = C_{\max} - |k_l - k_r| \tag{8}$$

$$k_l = \frac{(depth_{mid} - depth_1)}{(x\_across_{mid} - x\_across_1)} \tag{9}$$

$$k_r = \frac{(depth_n - depth_{mid})}{(x\_across_n - x\_across_{mid})} \tag{10}$$

Where :

$depth_i$ is the depth of beam i ;

x_across_i is the across-track distance of beam i ;

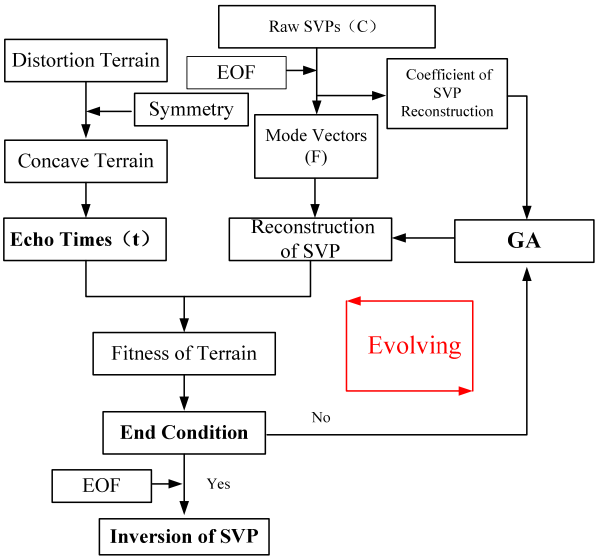
k_l , k_r are the slope of the left measured depths respectively from the mid-point P_{mid};

$C_{\max}$ is a constant;

When the degree of deformation decreases, the value of fitness function $fit(a)$ becomes larger while the $|k_l - k_r|$ becomes smaller. The actual observed measurements, provide more rigor and are retained when determining the solution.

4.2 Process of SVP Inversion

Figure 4 shows the SVP inversion process by GA.



First, the echo times (travel-times) of the terrain distortion are collected while the mode vectors and reconstruct coefficients ranges of the profiles are obtained by EOF in the survey area. Second, the SVP is reconstructed based on the above two elements and is used for the ray traced solutions for the bathymetry. By evolving with GA, the best individual measurements are preserved. Finally, the best reconstitution coefficient of the SVP is computed and the inversion result of the SVP is obtained.

5. Experiments

5.1 Inversion of the Sound Velocity Profile (SVP)

In this experiment, 11 SVP measurements were taken over 3 days are selected in during the survey area (***Figure 5***).period. The data of 70 pings arewere selected. One of the 11 measured SVPs is selected and inverted by the others. The process is measured SVPs and the EOF modeling results are shown in ***Figures 6*** and 75 and ***Table 1*** shows the 6. The computed ranges of the reconstruct coefficients are shown in ***Table 1***.

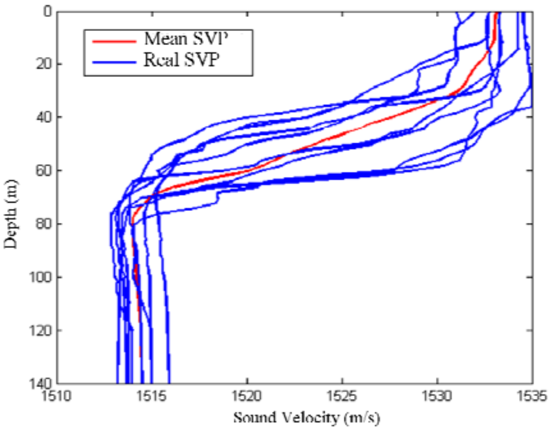


Figure 5. *The measured SVPs*

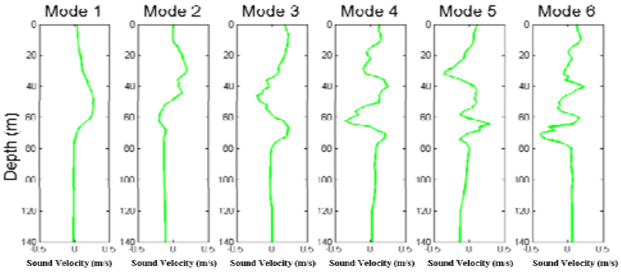


Figure 6. *Mode Vectors via EOF Based on measured SVP's*

Based on the vectors and the 22nd ping of the bathymetry measurement, the SVP can be obtained by the method described in Section 4 (The energy of the SVP represented by the first six-dimensional vectors can reach above 96%).(HE, et al. 2011, ZHANG, et al. 2010).

According to the coefficient ranges in ***Table 1,*** the population can be initialized. The parameters for the GA method are:

Population Size: 50, Hybrid Probability: 0.8, Mutation Probability: 0.15, $C_{\max} = 100$

Coefficients of EOF	**ID of Coefficient**	**Lower Bound**	**Upper Bound**
Coefficient 1	a_1	-85.232068	87.875102
Coefficient 2	a_2	-27.131524	28.083683
Coefficient 3	a_3	-14.213039	13.785649
Coefficient 4	a_4	-11.402809	11.203382
Coefficient 5	a_5	-9.080608	11.533016
Coefficient 6	a_6	-8.664668	7.817749

Table 1. *The Ranges of Reconstruct Coefficients*

After an evolution process of 2000 iterations, the optimal reconstruct coefficients are computed and listed in ***Table 2***.

Coefficient	a_1	a_2	a_3	a_4	a_5	a_6
Value	16.901	9.145	11.350	-6.023	-5.350	-5.319

Table 2. *Computed Reconstruct Coefficients*

In Figure 7, the real, measured SVP is shown as a black line whereas the inversion result for the SVP is shown by the red line. The blue line shows the SVP which is nearest to the real SVP in time.

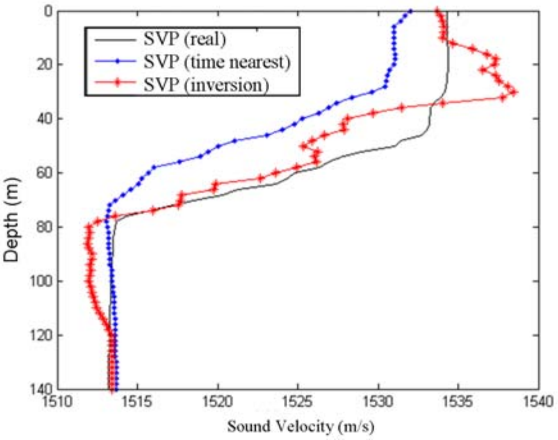


Figure 7*. Comparison of Sound Velocity Profiles*

Comparing the error statistics (listed in ***Table 3***) and the graphical results (***Figure 7***), it appears that the SVP obtained by inversion (red line), more closely estimates the real SVP (black line).

	Max （m）	Min (m)	Means (m)	RMS (m)
SVP (time nearest)	11.1000	0.0222	-3.1179	3.6447
SVP (inversion)	6.0699	0.0337	-0.6938	2.1904

Table 3*. Velocity Error Statistics*

In ***Figure 8***, the black line shows the actual seabed topography and this corresponds closely with the red line that shows the seabed topography derived from the inversion result of the SVP. The blue line shows the seabed topography which is nearest to the real SVP in time.

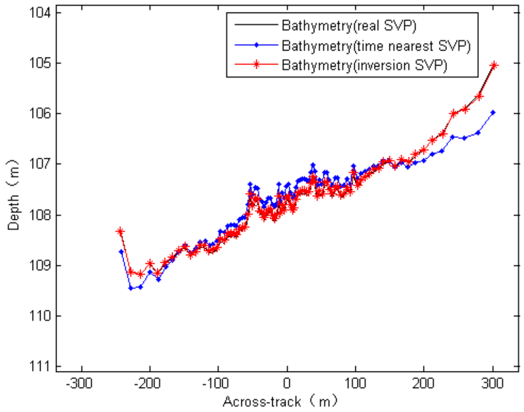


Figure 8. *Comparison of Bathymetries*

Statistical results shown in ***Table 4***, indicates centimeter-level errors in the bathymetry based on the inversion SVP modeling.

	Max （m）	Min (m)	Means (m)	RMS (m)
SVP (time nearest)	11.1000	0.0222	-3.1179	3.6447
SVP (inversion)	6.0699	0.0337	-0.6938	2.1904

Table 4*. Bathymetry Error Statistics*

5.2 Correction of Terrain Distortion by the Inversion SVP

In ***Figure 9,*** the inversion SVP is used forleft hand image shows the ray traced solutions of two adjacent swaths:

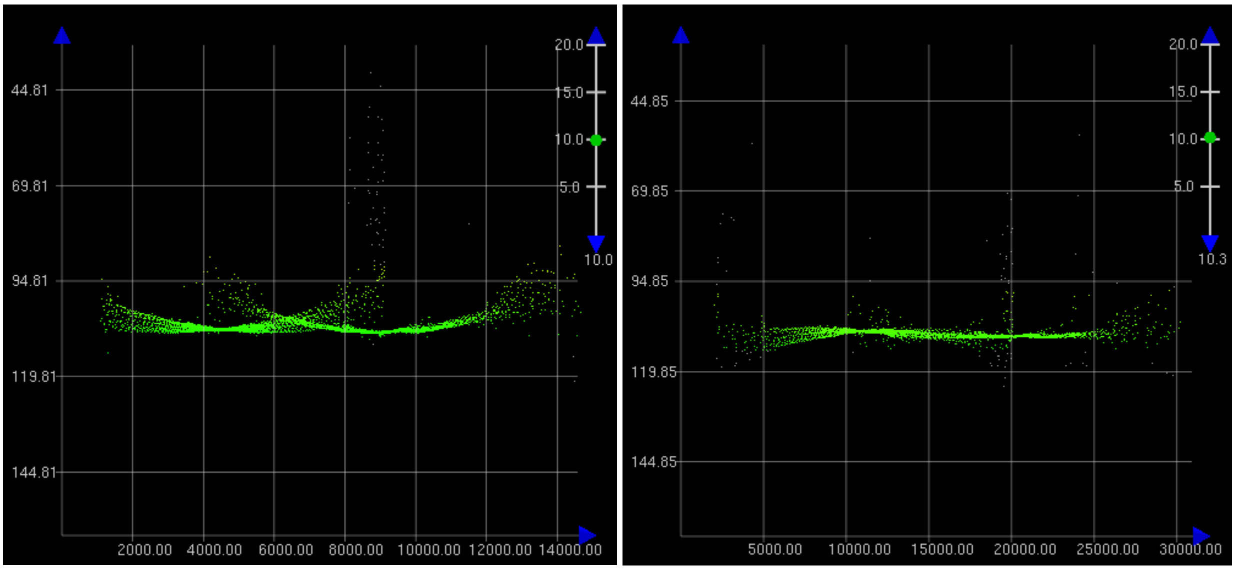


***Figure 9**. Original distorted terrain (left) and the corrected terrain (right)*

6. Conclusions

In this paper, the influence of sound velocity error in determining seabed terrain is analyzed. According to the degree of the terrain distortion, a method for inverting the sound velocity profile (SVP) is proposed by combining EOF and GA methods. The design of a fitness function based on the terrain distortion provides the contents of the kernel to be used in the inversion process. The test results demonstrate that the terrain distortion caused by sound velocity errors can be effectively corrected by the SVP inversion results. Meanwhile, the accuracy of the multibeam bathymetry data has been significantly improved.

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