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Travel-time approximation of acoustic ranging in GPS/Acoustic seafloor geodesy

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ABSTRACT

Previous studies have proposed methods to reduce the effect of sound-speed variation in the water column on the precision of GPS/Acoustic positioning. However, the fit of temporal travel-time variation makes reference to sound-speed profiles without considering depth-dependent variation. Accordingly, the goal of this study is to provide a simple and precise approximation for a given sound-speed profile considering its depth-dependent variation. We propose two synthetic models for sound-speed profiles, one linear and the other bilinear, for better travel-time approximations of acoustic ranging in GPS/Acoustic seafloor geodesy. The linear and bilinear models are tested on three types of sound-speed profiles derived from conductivity–temperature–depth (CTD) casts made at water depths of 300, 1000, and 2000 m, respectively. The change in error of the best acoustic travel-time approximation resulting from the change in break depth of the bilinear model is investigated for the three types of sound-speed profiles. Furthermore, the performance of the linear and bilinear models is evaluated using the data collected from a GPS/Acoustic survey. The evaluation results demonstrate that both the linear and bilinear models can effectively reduce the effect of sound-speed variation on the precision of GPS/Acoustic positioning.

1. Introduction

GPS/Acoustic seafloor geodesy has recently received considerable attention as a method for monitoring tectonic plate motion, especially after the 2011 Tohoku Earthquake in Japan (Fujii et al., 2011; Sato et al., 2011b; Tadokoro et al., 2012). Research on GPS/Acoustic geodesy began in the 1980s when Dr. Fred N. Spiess and other researchers at Scripps Institution of Oceanography (SIO) developed a strategy to combine seafloor transponders with GPS measurements (Spiess et al., 1980; Spiess, 1985a, 1985b). Since then, the SIO research group has conducted a series of expeditions with GPS/Acoustic geodesy in the Pacific Northwest region of North America (Chadwell et al., 2002; Spiess et al., 1998, 2000), in the Peru-Chile Trench (Gagnon et al., 2005), and in the Kilauea Volcano (Hildebrand et al., 2000; Phillips and Chadwell, 2005). In addition to the SIO group, research teams in Japan have investigated oceanic crustal deformation for years using the GPS/Acoustic approach. Numerous transponder arrays have been deployed along the Japan Trench and the Nankai Trough, where huge earthquakes are anticipated (Fujita et al., 2006) and continuous long-term monitoring of plate deformation is carried out (Ikuta et al., 2008; Kido et al., 2006; Osada et al., 2012; Sato et al., 2011a; Tadokoro et al., 2006).

GPS/Acoustic seafloor geodesy uses the measurements of GPS, acoustic travel times, and sound-speed profiles in the water column to estimate the position of a seafloor reference point. The measurements of acoustic travel time are converted to geometric ranges by ray tracing technique through the observations of sound-speed profiles. Therefore, a successful positioning of seafloor reference points requires detailed knowledge of sound speed and its variability in the water column. In a GPS/Acoustic survey, sound-speed profiles are measured by CTD (conductivity, temperature, and depth) or XBT (expendable bathythermograph) casts, which is time consuming, especially for deep-sea profiling. To measure a sound-speed profile for every single acoustic ranging shot, however, is impractical. In addition, sound speed varies with time and space. Significant variations in sound speed can occur in a short time because of internal wave oscillations, and the variation can be equivalent to a maximum of 20 cm in range (Spiess et al., 1998). Yamada et al. (2002) found that the error of positioning a seafloor transponder at a depth of 1500 m can reach 18 cm, even when CTD casts are obtained frequently. According to Osada et al. (2003), the daily variation of sound speed is approximately ±0.7 m on an acoustic ranging of 4–7 km with a fixed velocity structure. Though various empirical formulas have been used to calculate sound-speed structures from CTD/XBT observations (Chen and Millero, 1977; Del-Grosso, 1974; Mackenzie, 1981; Medwin, 1975; UNESCO et al., 1981; Wilson, 1960), each yields different results. Apparently, measurements of sound-speed profile in a GPS/Acoustic survey cannot

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provide accurate enough knowledge of sound speed and its variability in the water column.

Previous studies have proposed methods for reducing the effect of sound-speed variation on the precision of GPS/Acoustic seafloor geodesy. Fujita et al. (2006) indicated that the measurement of acoustic travel time implies not only information on range, but also information on the sound-speed structure. Fujita et al. (2006) therefore used a quadratic polynomial to model the temporal variations in the averaged sound speed. Assuming that the sound speed is horizontally stratified, Ikuta et al. (2008) used a B-spline function to approximate the temporal variations of a referenced CTD-derived sound-speed profile. Ikuta et al. (2008) also used the tomographic method to estimate the position of a seafloor transponder and the sound-speed structure simultaneously. Based on a reference sound-speed profile, Kido et al. (2008) presented two models, the travel-time residual and the travel-time ratio, to express sound-speed variations in acoustic ranging. The methods in these studies fit the temporal travel-time variation with reference to some sound-speed profiles without considering depth-dependent variation. However, we believe that depth-dependent variation of the sound speed should be considered in order to provide the most precise GPS/Acoustic positioning.

The goal of this study is to provide a simple and precise approximation for a given sound-speed profile considering its depth-dependent variation. Many acoustic propagation studies attempt to outline simplified assumptions in the mathematical modeling of complicated environmental phenomena, such as modeling the sound speed with a relatively simple profile. Therefore, instead of frequently measuring sound-speed profiles in GPS/Acoustic seafloor geodesy, in this study we seek to model a simple vertical structure of sound speed to approximate acoustic travel-time measurements. Considering depth-dependent variation of sound speed structure, two simple synthetic models, the linear and bilinear profiles, are proposed for approximating the travel times of acoustic ranging.

The remainder of this paper is organized as follows. In Section 2, the optimization method used to design the linear and bilinear profiles for approximating acoustic travel times is introduced. The methods of travel-time residual and travel-time ratio proposed by Kido et al. (2008) for the expression of sound-speed variations are also presented in Section 2 for comparison purposes. Numerical results and comparisons are given in Section 3 to demonstrate the effectiveness of the linear and bilinear models for three distinct types of sound-speed profiles. The performance of the linear and bilinear models is further evaluated in Section 4 according to the data collected from a field GPS/Acoustic survey. Concluding remarks are presented in Section 5.

2. Methods

In this section, we present the linear and bilinear models for sound-speed profiles to approximate the acoustic travel times measured in a GPS/Acoustic seafloor geodetic survey. An assumption in both models is that sound-speed profiles are horizontally stratified and no lateral variation is considered. The aim of travel-time approximation is to minimize the sum of squared deviations between the real and approximated acoustic travel times. In addition, for comparison purposes, the methods of the travel-time ratio and the travel-time residual proposed by Kido et al. (2008) to express sound-speed variations are presented.

2.1. Linear model

Let Z be the water depth of the seafloor transponder, measured downward along the z axis from $z=0$ at the sea surface. The sound-speed profiles $C_i(z)$ $(i=0\text{–}m)$ in the water column are measured periodically during the period of the GPS/Acoustic geodetic survey. The first proposed model to approximate the acoustic travel times is a linear profile (Fig. 1(a)). The linear profile assumes that the sound speed varies linearly as a function of water depth:

$$C_L(z)=c_s+gz \tag{1}$$

where c_s is the surface sound speed and g is the gradient of sound speed over the whole depth. To fit the acoustic travel times generated by the linear model to those generated by the specified sound-speed profile $C_i(z)$, the values of the surface sound speed c_s and the gradient of sound speed g must be determined.

The values of c_s and g are determined by the optimization method with the observations of travel time at several horizontal ranges from the transceiver to the seafloor transponder. As shown in Fig. 2, suppose that the seafloor transponder is located at a depth of Z and the surface transceiver interrogates the transponder at different horizontal ranges of x. With the sound-speed profile $C_i(z)$, the acoustic round-trip travel time $t_j^{(r)}$ along the direct path between the seafloor

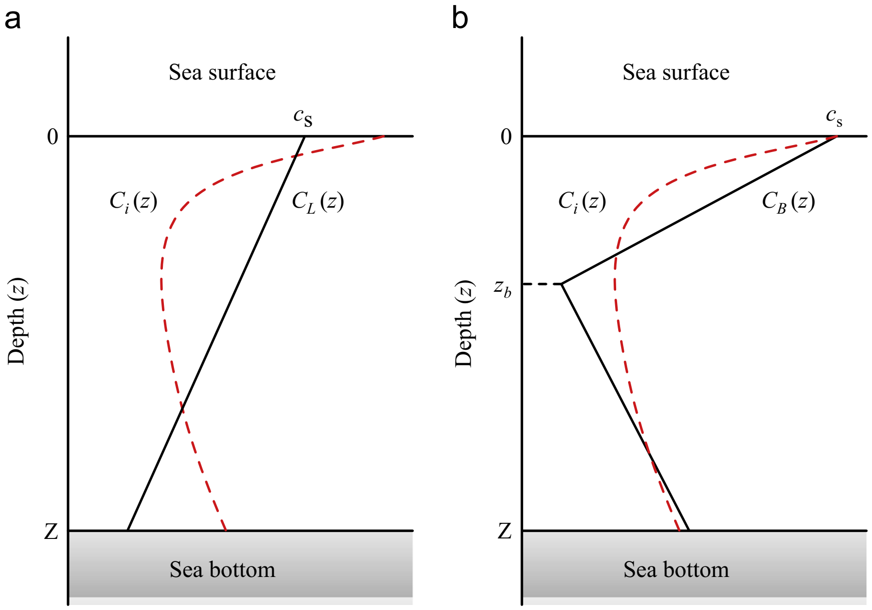

Fig. 1. Two proposed sound–speed structures (solid lines) for the approximation of acoustic travel times obtained from a GPS/Acoustic seafloor geodetic survey. The dashed lines represent a real sound-speed profile. (a) Linear model. (b) Bilinear model.