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Optimal localization of a seafloor transponder in shallow water using acoustic ranging and GPS observations

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Abstract

This study utilized circular and straight-line survey patterns for acoustic ranging to determine the position of a seafloor transponder and mean sound speed of the water column. To reduce the considerable computational burden and eliminate the risk of arriving at a local minimum on least-squares inversion, the position of a seafloor transponder was estimated by utilizing optimization approaches. Based on the implicit function theorem, the Jacobian for this inverse problem was derived to investigate the constraints of employing circular and straight-line survey patterns to estimate the position of a transponder. Both cases, with and without knowledge of the vertical sound speed profile, were considered. A transponder positioning experiment was conducted at sea to collect acoustic and GPS observations. With significant uncertainties inherent in GPS measurements and the use of a commercial acoustic transponder not designed for precise ranging, experimental results indicate that the transponder position can be estimated accurately on the order of decimeters. Moreover, the mean sound speed of the water column estimated by the proposed optimization scheme is in agreement with that derived from conductivity, temperature, and density (CTD) measurements.

Keywords: Transponder; Acoustic ranging; GPS; Sound speed; Circular survey; Straight-line survey; Localization; Optimization

1. Introduction

Since the 1970s, acoustic time-of-flight navigation systems, such as long baseline (LBL) and ultra-short baseline (USBL), have been employed in oceanographic instruments and vehicles (Milne, 1983; Caiti et al., 2005). A LBL system has an array of acoustic transponders deployed on the seafloor. The absolute location of a fixed seafloor transponder is first estimated from observations of acoustic ranges and GPS positions. Then, vehicles or oceanographic instruments can be tracked based on measurements of round trip travel ranges between seafloor transponders and an onboard transceiver. For USBL positioning, although a seafloor transponder is not needed, recent studies have shown that range and bearing measurements based on a known fixed seafloor transponder improve USBL positioning accuracy (Opderbecke, 1997; Philips, 2003).

The absolute position of a fixed transponder is usually estimated by the least-squares inversion based on acoustic and GPS observations (Shiobara et al., 1997; Yoerger et al., 2000; Osler and Beer, 2000; Kussat et al., 2005). However, one shortcoming of least-squares inversion is the significant computational burden incurred by accumulation of several hundred observations (Sweeney et al., 2005). Another shortcoming is that the nonlinear least-squares procedure can fall into local minima in the solution space. To estimate the position of a seafloor transponder, this study utilizes optimization approaches. This scheme facilitates the use of global optimization methods, such as genetic algorithms, to obtain the global minimum without a good initial guess. Additionally, the survey pattern used to collect observations is critical to the success

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of localizing a seafloor transponder (Shevenell, 1984; Shiobara et al., 1997). Often, when estimating the position of a seafloor transponder, acoustic and GPS observations are collected by utilizing a straight-line survey pattern (Obana et al., 2000; Yamada et al., 2002) or circular survey pattern (Osada et al., 2003; Kussat et al., 2005). In fact, an improper survey path yields either non-unique solutions or false solutions which never converge; however, few studies have mentioned the feasibility of survey patterns on the inverse problem solution. In this study, the implicit function theorem (Hildebrand, 1976) is used to investigate constraints on circular and straight-line surveys for acquiring a unique solution.

Precise acoustic ranging requires accurate travel time measurement and knowledge of sound speed along the acoustic path. At present, travel time resolution of a few microseconds is possible (Sweeney et al., 2005), meaning that slant range measurement can be accurate to centimeters when sound speed is known. However, surveys generally last for hours when gathering a sufficient number of observations for estimating transponder position. Measuring sound speed profiles frequently during data collection is inappropriate as this is very time consuming. Since sound speed profiles of the water column are temporarily and spatially varied in the upper ocean, a small number of measured sound speed profiles cannot exactly represent the sound speed field through which the acoustic ray traveled. That is, the position estimate of a transponder is subject to errors due to spatial-temporal variations of sound speed. Additionally, ray-tracing calculations are typically performed when estimating the position of a transponder; however, this process is complex and time-consuming. Yamada et al. (2002) employed simulations to estimate the horizontal position of a transponder located on the seafloor at a depth of 1500 m. The sum of squared travel-time residuals was assessed by assuming that sound speed is uniform throughout the ocean. Yamada et al. located the seafloor transponder with only an 18-cm discrepancy. This simulation result indicates that it is possible to estimate the transponder position accurately within centimeters by assuming sound speed is uniform throughout the water column. Therefore, this study treats mean sound speed as an unknown parameter, which is estimated by optimization analysis. The estimate of mean sound speed will be verified by comparison to data from CTD measurements.

The remainder of this paper is organized as follows. In Section 2, objective functions for optimization of transponder position estimation with and without knowledge of sound speed are presented. In Section 3, circular and straight-line survey patterns are introduced. In Sections 4 and 5, the constraints for obtaining a unique solution from circular and straight-line surveys are derived, respectively. Section 6 presents and interprets the estimation results of the field experiment. Finally, conclusions are given in Section 7.

2. Position estimation

Recovering the position of a fixed transponder based on acoustic ranges and GPS positions is an inverse problem. Ideally, observations collected at three independent locations can determine the position of a fixed transponder. However, measurement noise deleteriously affects the estimates when only three observations are used for estimation. Therefore, in this study, numerous observations are collected at different locations and then the position of a fixed transponder is estimated by numerical optimization algorithms.

2.1. Estimation when sound speed is observed

Assume the global position of a fixed transponder is $\mathbf{P}_\mathrm{T}$:

$$\mathbf{P}_\mathrm{T} = [P_{\mathrm{T}x},\ P_{\mathrm{T}y},\ P_{\mathrm{T}z}]^\mathrm{T}. \tag{1}$$

The observed slant range and the vessel's GPS position at the ith location are SR_i and $\mathbf{P}_i$, respectively, where

$$\mathbf{P}_i = [P_{ix},\ P_{iy},\ 0]^\mathrm{T}. \tag{2}$$

Theoretically, when the sound speed is known and the ray bending effect is ignored, the measured slant range equals the calculated range between points $\mathbf{P}_\mathrm{T}$ and $\mathbf{P}_i$:

$$\mathrm{SR}_i = \sqrt{(P_{\mathrm{T}x} - P_{ix})^2 + (P_{\mathrm{T}y} - P_{iy})^2 + (P_{\mathrm{T}z})^2}. \tag{3}$$

However, due to measurement errors, Eq. (3) is not likely to be true. Let the difference between measured and calculated ranges be ε_i:

$$\varepsilon_i = \mathrm{SR}_i - \sqrt{(P_{\mathrm{T}x} - P_{ix})^2 + (P_{\mathrm{T}y} - P_{iy})^2 + (P_{\mathrm{T}z})^2}. \tag{4}$$