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Numerical modeling and simulation technique in time-domain for multibeam echo sounder

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Abstract

A Multibeam Echo Sounder (MBES) is commonly used for rapid seafloor mapping. We herein present a time-domain integrated system simulation technique for MBES development. The Modeling and Simulation (M&S) modules consist of four parts: sensor array signal transmission, propagation and backscattering modeling in the ocean environment, beamforming of the received signals, and image processing. Also, the simulation employs a ray-theory-based algorithm to correct the reconstructed bathymetry, which has errors due to the refraction caused by the vertical sound velocity profile. The developed M&S technique enables design parameter verification and system parameter optimization for MBES. The framework of this technique can also be potentially used to characterize the seabed properties. Finally, typical seafloor images are presented and discussed.

Keywords: Image position; MBES; Multibeam echo sounder; Multibeam sonar

1. Introduction

A Multibeam Echo Sounder (MBES) is a device used in seafloor mapping along with a Single Beam Echo Sounder (SBES). The application of these devices fostered a new generation of hydrographic survey techniques, which first appeared in the 1960s (de Moustier, 1986; Farr, 1980; L-3 Communications SeaBeam Instruments, 2000; Burdic, 1984). SBES has advantages such as their ease of manufacturing and low cost; however, they require considerable time to process a wide range of bathymetry jobs and have limited accuracy. Therefore, to overcome these limitations, MBES has been researched intensively. Similar to a SBES, a MBES emits sound waves in a fan shape beneath a ship's hull. The amount of time taken by the sound waves to bounce off the seafloor and return to the receiver is used to determine the water depth. However, in contrast with a SBES, a MBES can measure a wider range of water depths and can acquire high-resolution images simultaneously through the beamforming process. In recent years, substantial research has focused on obtaining high-precision bathymetry data using high frequencies, classification and monitoring of sediments using high-resolution backscatter data (Yu et al., 2015).

In this paper, we performed numerical modeling and simulations in the time domain. The main principles of MBES are also presented herein; these can be used in numerical analysis and evaluation during MBES design and development. The contribution of this paper is to model and simulate the integrated sensor array and physical system of ocean environment for image construction of MBES.

The remainder of this paper is organized as follows. In Section 2, the sonar equation and the basic principles of MBES are explained. In Section 3, the fundamentals of the

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modeling simulation structure to be used for numerical analysis are discussed. In Section 4, the simulation results of transmitted signals and seabed shapes are compared, and images created using the received signals are shown. Finally, the conclusions are presented in Section 5.

2. Background theory

2.1. Sonar equation

The sonar equation is used to study the detection capability and performance of an echo sounder; it represents the diffusion and absorption of the sound waves and the reflecting ability of the target object by using a variety of sonar parameters. The MBES sonar equation (Farr, 1980; L-3 Communications SeaBeam Instruments, 2000) is based on the Echo Excess (EE) and can be expressed as

$$\mathrm{EE} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{S_s} + \Phi - \mathrm{NL} \tag{1}$$

where SL is the source level, TL is the one-way transmission loss, NL is the noise level, S_s is the backscattering strength, and Φ is the scattering area, which can be obtained by integrating the beam pattern:

$$\Phi = 10\log\int_{\Omega} b(\theta,\phi)b'(\theta,\phi)R_pR_r d\Omega \tag{2}$$

where $b(\theta,\phi)$ and $b'(\theta,\phi)$ are the beam widths of each receiver and projector, θ is the horizontal angle, ϕ is the elevation angle, R_p and R_r are the slant ranges from the projector and receiver to the point on the seafloor. S_s is assumed to follow Lambert's law. It is defined as

$$S_s = 10\log\left(s_{v_0}\sin^2\beta\right) \tag{3}$$

where s_{v_0} is the backscattering coefficient and β is the grazing angle to the reflection or scattering surface.

2.2. Principles of MBES

2.2.1. Beamforming

A beam pattern represents the variation in the intensity of a beam as a function of direction and distance. Beamforming is a technique used to send signals in or receive signals from a specific direction. It is also called spatial filtering and is conducted using a sensor array or through signal processing.

Beamforming using a sensor array involves summing the phases of the sensors by considering the constructive and destructive interference of signals at a specific angle. The array directivity is caused by interference in accordance with the array geometry, and the array response varies depending on the signal direction due to the beam pattern in the array.

When the one-dimensional line array of omnidirectional sensors is as shown in Fig. 1, assuming that the receiver's position is in the far field, the received signal $s(t+\tau)$ at an arbitrary point x is given by

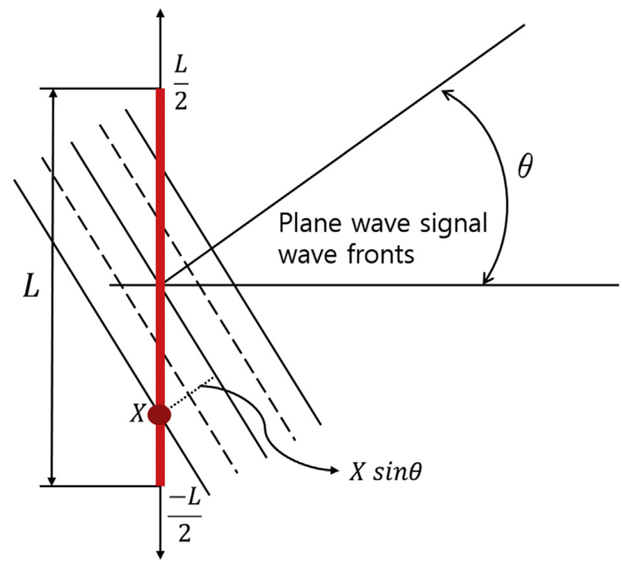

Fig. 1. Plane wave incident on line array.

$$s(t+\tau) = s(t + x\sin\theta/c) \tag{4}$$

The output of the line array can be obtained by integrating its response to the signal along its length (Burdic, 1984). Thus, if $g(x)dx$ is the array response to a unit signal at x, the total output resulting from a plane wave at angle θ is

$$\begin{aligned} S_{out}(t) &= \int_{-L/2}^{L/2} g(x)s(t + x\sin\theta/c)dx \\ &= \int_{-L/2}^{L/2} g(x)\left[\int_{-\infty}^{\infty} s(f)\exp\left(\frac{i2\pi fx\sin\theta}{c} + i2\pi ft\right)df\right]dx \\ &= \int_{-\infty}^{\infty} s(f)\left[\int_{-L/2}^{L/2} g(x)\exp\left(\frac{i2\pi fx\sin\theta}{c}\right)dx\right]\exp(i2\pi ft)df \end{aligned} \tag{5}$$

where c is velocity of sound and g(x) is an aperture function or a tapering function. In general, the aperture function is a product of the weighting (shading) function and the rectangular function with respect to the line array.

The inner integral in Eq. (5) has the form of the Fourier transform of the aperture function g(x) from the x-domain to a domain represented by the variable $u = (\sin\theta)/\lambda$, where $\lambda = c/f$, and the integral is called a beam pattern. If g(x) is constant over length L, the beam pattern is given by

$$\begin{aligned} B(\theta) &= \int_{-L/2}^{L/2} g(x)\exp(i2\pi xu)dx \\ &= \frac{1}{L}\int_{-\infty}^{\infty} rect\left(\frac{x}{L}\right)\exp(i2\pi xu)dx \\ &= \mathrm{sinc}(uL) \end{aligned} \tag{6}$$

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