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Validation of a high-resolution acoustic imaging sonar method by estimating the biomass of submerged plants in shallow water

Katsunori Mizuno[a,*], Akira Asada[b], Syuhei Ban[c], Yoshitoshi Uehara[d], Takuya Ishida[d], Noboru Okuda[d]

[a] Graduate School of Frontier Sciences, The University of Tokyo, Kashiwanoha, Kashiwa-city, Chiba 277-8563, Japan
[b] Institute of Industrial Science, The University of Tokyo, Meguro-ku, Tokyo 153-8505, Japan,
[c] Department of Ecosystems Studies, The University of Shiga Prefecture, Hassaka-cho, Hikone-City, Shiga 522-8533, Japan
[d] The Research Institute for Humanity and Nature, Motoyama, Kamigamo, Kita-ku, Kyoto, 603-8047, Japan

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ABSTRACT

Acoustic sensing is often used for mapping and monitoring aquatic plants in shallow waters. Recently, high-resolution imaging sonar was applied to study a variety of aquatic organisms. This method can provide high-resolution, three-dimensional (3D) acoustic data on the spatial distribution of submerged plants. However, no commercial software packages are available to digitalize the images of submerged plants generated from imaging sonar data, and the high-resolution imaging sonar method has not been standardized because of a lack of empirical data. In this study, we measured the biomass of submerged plants in the north basin of Lake Biwa using high-resolution acoustic imaging sonar and compared the results to directly measured biomass values to validate the utility of high-resolution acoustic imaging sonar as a quantitative method. Biomass was calculated in 10 randomly selected quadrats (1 × 1 m) in Lake Biwa. The analysis of the resulting data indicated a strong correlation between the number of pixels in the digital images of submerged plants and their directly calculated biomass ($R^2 = 0.91$, $p < .0001$). The results suggest that the high-resolution imaging sonar method is a promising tool for estimating the biomass of submerged plants. Thus, this method is expected to contribute to a better understanding of aquatic ecology.

1. Introduction

Aquatic plants play an important role in underwater ecosystems and affect biological diversity throughout the world (Hooper et al., 2005). However, the distributions and population dynamics of plant species are affected by environmental factors such as eutrophication, predation, introduced species, and anthropogenic interventions, particularly in shallow waters, which are strongly affected by human-induced eutrophication (Duarte, 1995). Therefore, the sustainable management of underwater environments often includes the preservation, restoration, and/or growth of aquatic plants (Vis et al., 2003), and accurate maps are required to monitor the state of aquatic plants (Kirkman, 1996).

Several remote sensing methods are used to map and monitor aquatic plants, including optical (e.g., satellite-based) and acoustic (Zainal and Dalby, 1993; Dekker et al., 2005; Abukawa et al., 2013; Mizuno et al., 2017) methods. While optical methods (e.g., aerial surveys and underwater camera systems) provide relatively large-scale surveys of submerged plants, the results depend on the transparency of the water and the roughness of the water surface (Hewitt et al., 2004; Madsen, 1993). In addition, it is difficult to determine the spatial distribution of submerged plants in a three-dimensional (3D) underwater space using optical methods.

On the other hand, acoustic systems such as side-scan sonar (Pasqualini et al., 1999), echo sounders (Bučas et al., 2016; Han et al., 2007; Lefebvre et al., 2009; Sabol et al., 2002), and multibeam sonar (Abukawa et al., 2013; Komatsu et al., 2003) do not depend on the transparency of the water and have been successfully applied to study aquatic plants (Winfield et al., 2007).

Recently, the high-resolution imaging sonar termed Dual-frequency IDentification SONar (DIDSON) has produced near-video-quality images by simultaneously transmitting and receiving multiple acoustic beams (Belcher et al., 2002). Accordingly, high-resolution imaging sonar has been adopted by many fishery scientists for a wide range of purposes, including the observation of fish behavior (Moursund et al., 2003), fish size detection (Boswell et al., 2008), fish counting (Holmes et al., 2006), and fish shape classification (Burwen et al., 2007; Mizuno

* Corresponding author.
E-mail address: kmizuno@edu.k.u-tokyo.ac.jp (K. Mizuno).

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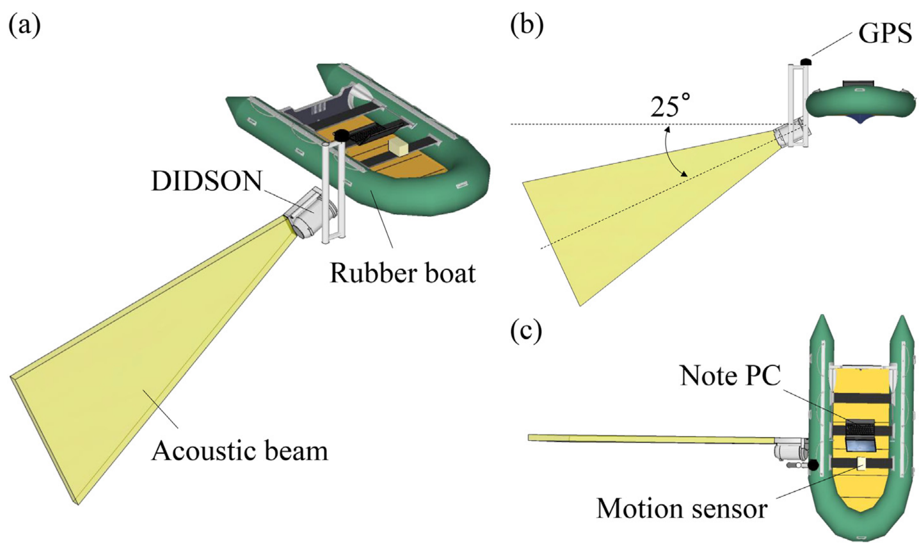

Fig. 1. Experimental setup: (a) overhead view, (b) front view, and (c) top view. The inflatable survey boat was equipped with a standard DIDSON unit, a GPS unit, and a motion sensor. The DIDSON unit was mounted on a pole with a concentrator lens angled 25° downward from the horizontal surface of the lake.

et al., 2015; Zhang et al., 2016). High-resolution imaging sonar can also provide high-resolution, 3D acoustic data in water and has been applied to the survey of aquatic plants in shallow lakes (Chunhui et al., 2013; Mizuno et al., 2013, 2016; Mizuno and Asada, 2014). However, no commercial software packages are available to digitalize the images of submerged plants generated by imaging sonar, and the methodology has not been standardized because of a lack of empirical data (Bučas et al., 2016).

This study aimed to validate a high-resolution imaging sonar method for biomass estimation.

2. Materials and methods

2.1. Field experiments

2.1.1. System configuration

An inflatable survey boat was equipped with the high-resolution imaging sonar DIDSON (Sound Metrics, Bellevue, WA, USA), a motion sensor (OS-5000US, OceanServer Technology, MA, USA), and a global positioning system (GPS; GPS 16×, Garmin, Olathe, KS, USA; Fig. 1). The DIDSON unit was mounted on a pole with a 1° concentrator lens tilted downward at an angle of 25° from the horizontal surface of the lake. The lens concentrated the beam width from the default 14° lens to 1°, which is suitable for shallow-water tasks such as lake surveys (Chunhui et al., 2013; Mizuno and Asada, 2014). Data were collected at 1.8 MHz (high-frequency mode) within 2.5 m of the imaging sonar. The two-dimensional (2D) frame consisted of 96 horizontal beams × 512 range samples. The resolution was approximately 5 mm/pixel, and the frame rate was 10 fps. Continuous slice images were captured while the boat moved at slow speed. Acoustic data were collected on September 12, 2016.

2.1.2. Study site

The field survey was conducted in the north basin of Lake Biwa, which is the largest freshwater lake in Japan (Fig. 2). Many studies have focused on the distribution of submerged plants in Lake Biwa, and at least 53 kinds of submerged macrophytes have been recorded (Ohtsuka et al., 2004; Haga et al., 2006, Haga and Ishikawa, 2011; Kawanabe et al., 2012). Thus, Lake Biwa is relatively rich in submerged plants, making it suitable for validating the acoustic sensing system. First, a total of ten quadrats (1 × 1 m; L1, …, L10) were established in shallow coastal waters (depth < 2 m) and marked with 1 m stainless-steel pipes at the four corners of each quadrat (Fig. 3). Acoustic measurements were designed to collect data from the square quadrats.

2.2. Processing and analysis of acoustic images

2.2.1. 3D view generation

The DIDSON frame represents the backscatter echo information from aquatic plants and the lake bottom in 2D space. Thus, to generate 3D views of the submerged plants, coordinate transformation from 2D to 3D space was required for each frame. Information from the motion sensor and GPS unit was used to correct for the effect of the boat's motion and generate the 3D coordinates in the global coordinate system. Detailed information on the 3D visualization method is provided by Chunhui et al. (2013).

2.2.2. Pixel counting for submerged plants

In the 3D view, the pixels appearing above the lake bottom represent the backscatter echo information from the submerged plants and other particles in the water. In this case, echoes from the particles were regarded as noise and separated from the echoes of the submerged plants. The number of pixels of submerged plants was considered to be strongly related to the volume of plants in the water. In general, the pixel intensity (brightness of pixel in the image: 8bit, 0–255) reflects the strength of backscatter echo from the target relative to the material and shape of the target. Therefore, we attempted to separate the noise and the echoes of the submerged plants automatically using discriminant analysis, which is generically called the Otsu method (Otsu, 1979). The Otsu method is often used to binarize 2D optical images; in this study, we applied the Otsu method to 3D acoustic images. First, we recorded the intensities of all pixels above the lake bottom in the objective space (1 m × 1 m × height) and constructed the probability distribution from the normalized gray-level histogram of the pixels. The pixels in the histogram were dichotomized into two classes, C_1 and C_2, using a threshold k; that is, C_1 denotes pixels with levels $[0{\sim}k]$, and C_2 denotes pixels with levels $[(k+1){\sim}255]$. The value of k was determined using the degree of separation σ_B as an indicator, where σ_B is the ratio of between-class variance σ_w to within-class variance σ_b. σ_w is given by.

$$\sigma_w^2 = \frac{\omega_1\sigma_1^2 + \omega_2\sigma_2^2}{\omega_1 + \omega_2} \tag{1}$$

where ω_1 and ω_2 are the numbers of pixels in classes C_1 and C_2, respectively, and σ_1 and σ_2 are the variances in classes C_1 and C_2, respectively. On the other hand, σ_b is given by.