Remote Sensing of Environment 206 (2018) 260–274

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Bottom characterization by using airborne lidar bathymetry (ALB) waveform features obtained from bottom return residual analysis

Firat Eren[a,*], Shachak Pe'eri[b], Yuri Rzhanov[a], Larry Ward[a]

[a] University of New Hampshire, Center for Coastal and Ocean Mapping, 24 Colovos Road, Durham, NH 03824, USA
[b] National Oceanic and Atmospheric Administration (NOAA), 1315 East West Highway, Silver Spring, MD 20910, USA

ARTICLE INFO

Keywords:
Lidar
Bathymetry
Waveform
Classification
Acoustic backscatter

ABSTRACT

Airborne Lidar Bathymetry (ALB) surveys are traditionally used for measuring depths in shallow nearshore and back-bay areas. In this paper, we present a novel ALB waveform processing procedure, namely bottom return residual analysis, for bottom characterization. Waveform features obtained from the bottom return residual analysis are used in a supervised classification approach, i.e. Support Vector Machine, to differentiate between: 1) sand and rock bottoms and subsequently, 2) fine and coarse sand bottoms. The classification procedure was tested on ALB survey data collected with an Optech SHOALS-1000T ALB system that covers a $\sim$7 km^2 area within 1 km from shore in the western Gulf of Maine, USA. The bottom classification results, when compared to ground-truth measurements, indicate a 96% overall accuracy for sand and rock classification and 86% overall accuracy for fine and coarse sand classification. Results of ALB-based bottom classification are compared with interpretations of a multibeam echosounder acoustic backscatter mosaic collected from the survey area.

1. Introduction

Bottom characterization of shallow nearshore and back-bay areas is important for a variety of applications, such as ship navigational safety, anchoring, dredging, marine construction, fisheries and habitat management (Bosnic et al., 2017; Guenther, 2007; NOAA, 2012). Bottom characterization by seafloor mapping is typically used to assess bathymetric changes at the entrance of the navigation channels for up-to-date charts for safe navigation and anchoring (Lippmann and Smith, 2008). In addition, identification and characterization of protected habitats (e.g., seagrass or corals) is important for fishing, recreational boat activity, or other anthropogenic effects (Hochberg and Atkinson, 2003; Hochberg et al., 2003; Mumby et al., 1998; Mumby and Edwards, 2002; Pittman et al., 2009). However, the resources needed for bottom characterization with traditional techniques (e.g., drop cameras, acoustic surveys and diving operations) can be demanding and expensive.

In the past few decades, optical remote sensing (ORS) from aerial or satellite platforms has become more accessible through public data archives and received significant attention as a potential survey technology for bottom characterization. ORS provides rapid surveys of coastal areas that extend over land and shallow waters (Mumby et al., 1998). In addition, the use of ORS avoids potential hazards that can occur when conducting acoustic surveys from boats in shallow nearshore regions (Costa et al., 2009). The main ORS technologies evaluated to date for bottom characterization are primarily passive remote-sensing systems such as multispectral and hyperspectral imagery (Brando and Dekker, 2003; Gould and Arnone, 1997; Lyzenga, 1980). These passive remote-sensing technologies provide high spatial resolution (ranging from centimeter to several meters) and spectral resolution (ranging from tens to hundreds of nanometers) (Mumby and Edwards, 2002). However, water penetration depth of passive remote-sensing systems is severely limited by water turbidity and is restricted to a depth equivalent to one Secchi depth (Hochberg et al., 2003; Mumby, 2001; Mumby and Edwards, 2002; Pe'eri et al., 2016; Stumpf et al., 2003).

Airborne Lidar Bathymetry (ALB) is an active ORS technology that uses pulsed-lasers to directly measure the water depth (Billard et al., 1986). In comparison to passive ORS, ALB can penetrate up to three Secchi depths and provide improved depth coverage (Guenther et al., 2000). ALB measurements use short, green laser pulses (on the order of sub-nanoseconds to nanoseconds) transmitted from an aircraft into the water (Guenther, 1985; Hickman and Hogg, 1969; Nagle and Wright, 2016; Pe'eri and Philpot, 2007). Once transmitted from the aircraft, the laser pulse interacts with the environment, i.e., the atmosphere, water surface, water column and seafloor, and returns to the receiver in the aircraft. These interactions can be observed in an ALB waveform as surface return, water-column volume backscatter and bottom return in the recorded waveform (Fig. 1).

* Corresponding author.
E-mail addresses: firat@ccom.unh.edu (F. Eren), shachak.peeri@noaa.gov (S. Pe'eri), yuri.rzhanov@unh.edu (Y. Rzhanov), lgward@ccom.unh.edu (L. Ward).

https://doi.org/10.1016/j.rse.2017.12.035
Received 22 June 2017; Received in revised form 22 December 2017; Accepted 27 December 2017

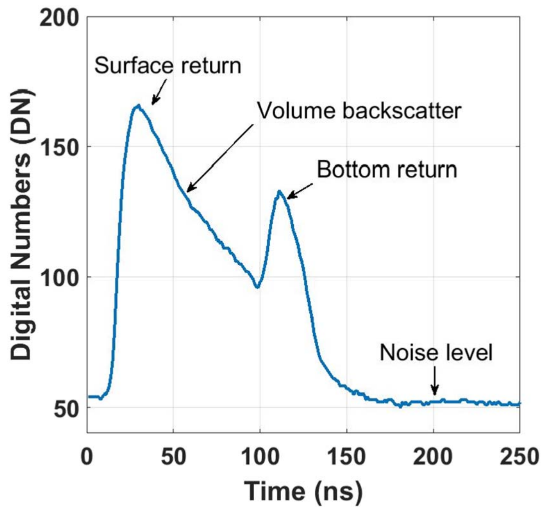

Fig. 1. An ALB observation from a full-waveform system (SHOALS-1000T) with indicated environmental interactions from the water surface, water column and the bottom.

The bottom return in an ALB waveform can provide bottom morphology information and thus has been used for bottom characterization (Collin et al., 2008; Collin et al., 2011; Tulldahl et al., 2007; Tulldahl and Wikström, 2012). Previous studies investigated ALB bottom returns to predict the seafloor reflectance characteristics and applied rigorous radiometric calibration algorithms to auxiliary sensors, such as hyperspectral cameras (Chust et al., 2010; Kim et al., 2016; Kopilevich et al., 2005; Tuell and Park, 2004; Tuell et al., 2005; Wang and Philpot, 2007). However, it is very difficult to reproduce the results of these studies because these approaches are specific to the hardware and survey site. One reason for the difficulty is that for each system, the laser-beam interactions with the environment manifest differently on the waveform because of different system hardware and processing algorithms (Brock et al., 2006; Nayegandhi et al., 2009; Wedding et al., 2008). In addition, rigorous radiometric-calibration procedures and ALB-waveform simulation models may not be practical and available for mapping agencies that require short turn-around times (Parrish et al., 2016). The concept of using only ALB waveforms for bottom characterization without radiometric calibration has been demonstrated several studies that use waveform parameters, such as pulse amplitude, pulse width, mean, variance, standard deviation, skewness, kurtosis, area under curve and slope (Collin et al., 2008; Collin et al., 2011; Parrish et al., 2014; Rogers et al., 2015; Tulldahl and Wikström, 2012). These features have been used to identify salt marsh vegetation biomass properties (Parrish et al., 2014; Rogers et al., 2015) and to classify the seafloor into rocky areas, macroalgae and sand through an unsupervised (Collin et al., 2008) and a supervised classification method, namely Support Vector Machine (SVM) (Collin et al., 2011). A more restricted version of these waveform features, namely slope, standard deviation of depth, pulse width and pulse area, are used by (Tulldahl and Wikström, 2012) to classify the seafloor into hard bottom, soft bottom, and soft bottom with high vegetation using a maximum likelihood approach. Although these features can provide satisfactory classification performance, there remains a variety of waveform features that could be extracted from the waveforms to enhance the bottom classification accuracy.

In this study, an ALB-waveform-based bottom characterization approach is developed without conducting rigorous radiometric calibrations or using external data from auxiliary sensors. The main novel aspect of this study is the development of bottom return analysis procedure that results in new waveform features for bottom classification. The most prominent of these new waveform features is the residual signal that is obtained from the bottom return. Specifically, shape change in the peak region of the bottom return, i.e. the strongest portion of the signal, is investigated and compared to a modeled signal. The shape change of the bottom return due to interactions with different sediments, i.e. fine sand, coarse sand and rocky areas, is assessed. The developed procedures result in a total of 11 waveform features which are used in a two-step supervised classification procedure using the SVM algorithm. First, the seafloor is classified as either sand or rock (the dominant seafloor types in the study area). Subsequently, the sandy areas are classified as fine sand or coarse sand. The results are then merged to produce a final bottom map with fine sand, coarse sand, and rock bottoms. ALB survey data used in this study was collected with an Optech SHOALS-1000T ALB system over Merrimack Embayment off the New Hampshire and Massachusetts coast in the western Gulf of Maine, USA (Fig. 2). ALB classification results are compared to an acoustic multibeam echosounder (MBES) survey that overlapped with the study area.

2. Methods

2.1. Survey site

The study area is in the western Gulf of Maine, USA, in the nearshore area just north of the Merrimack River near the New Hampshire - Massachusetts state border (Fig. 2). The survey site covers an area of approximately 7 km^2 (7.4 km × 0.95 km). A comprehensive geological study that used MBES acoustic surveying and grab samples was conducted in the same waters offshore of Massachusetts by the United States Geological Survey (USGS) (Barnhardt et al., 2009). The results from the USGS study revealed that the survey site consists of three different physiographic zones: 1) Ebb-Tidal Delta at the Merrimack River mouth characterized by fine to medium sand (grain size ranges from 0.062 to 0.5 mm); 2) Nearshore Ramp with a generally sandy seafloor consisting of fine to medium sand, coarse sand and fine gravel (grain size ranges from 0.062 to 8 mm); and 3) Rocky Zones characterized by high relief rocky outcrops with vegetation. The seafloor in the Rocky Zones is dominated by ledges and coarse-grained sediment (grain size larger than 8 mm).

2.2. Ground truth

The study site has three distinct bottom types that include fine sand, coarse sand, and rock. Ground-truth data (bottom sediment samples and bottom video) was collected at a total of 25 stations in the survey site during two different periods (Fig. 2). Using the University of New Hampshire (UNH) R/V *Cocheco*, sediment samples and video were collected from 13 stations in July 2009 (Ackerman et al., 2011; Morris et al., 2012; Pe'eri et al., 2011a; Pe'eri et al., 2013;). Additional ground-truth data were collected from 12 stations in November 2016 using the UNH R/V *Gulf Surveyor*. The grab samples from both surveys were obtained with a Shipek sampler. It should be noted that the Shipek sampler obtains sediment samples from the upper several centimeters of the seafloor while the laser pulse only interacts with the surface. Therefore, the size distribution of the grab samples is assumed to be uniform and homogeneous for at least several centimeters below the surface. The grain-size distributions of the sediment samples were determined by standard sieve and pipette techniques (Folk, 1980). The grain-size statistics were calculated using Gradistat software (Blott and Pye, 2001). The seafloor images were taken with an Ocean Systems Delta Vision High Definition camera that was hand-deployed in a fixed-cage system from the research vessels (Pe'eri et al., 2013) (Fig. 3). During collection of the seafloor images, the camera cage was placed vertically on the bottom and then tilted to observe an oblique view to provide information about the homogeneity of the bottom sediment. Taking into account the ship GNSS navigation and the uncertainty of the camera-frame positioning, the uncertainty (2σ) of the ground-truth coordinates is estimated to be < 25 m. It should also be noted that at each ground-truth station, the camera cage touched down on the bottom a minimum of four times and grab samples were collected at