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COASTAL CHANGE ANALYSIS OF LOVELLS ISLAND USING HIGH RESOLUTION GROUND BASED LIDAR IMAGERY

A Thesis Presented

by

JENNIFER K. LY

Submitted to the Office of Graduate Studies,
University of Massachusetts Boston,
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2014

School for the Environment

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COASTAL CHANGE ANALYSIS OF LOVELLS ISLAND USING HIGH RESOLUTION GROUND-BASED LIDAR IMAGERY

A Thesis Presented

by

JENNIFER K. LY

Approved as to style and content by:

_____
Allen M. Gontz, Associate Professor
Chairperson of Committee

_____
Crystal Schaaf, Professor
Member

_____
Steven Grey, Assistant Professor
Member

_____
John Duff, Program Director
College of Science and Mathematics

_____
Robyn Hannigan, Dean
School for the Environment

ABSTRACT

COASTAL CHANGE ANALYSIS OF LOVELLS ISLAND USING HIGH RESOLUTION GROUND-BASED LIDAR IMAGERY

August 2014

Jennifer K. Ly, B.S., The George Washington University
M.S., University of Massachusetts Boston

Directed by Dr. Allen Gontz

Many methods have been employed to study coastline change. These methods range from historical map analysis to GPS surveys to modern airborne LiDAR and satellite imagery. These previously used methods can be time consuming, labor intensive, and expensive and have varying degrees of accuracy and temporal coverage. Additionally, it is often difficult to apply such techniques in direct response to an isolated event within an appropriate temporal framework. Here we utilize a new ground based Canopy Biomass LiDAR (CBL) system built at The University of Massachusetts Boston (in collaboration with the Rochester Institute of Technology) in order to identify and analyze coastal change on Lovells Island, Boston Harbor. Surveys of a bluff developing in an eroding drumlin and beach cusps on a high-energy cobble beach on Lovells Island were conducted in June, September and December of 2013. At each site for each survey,

the CBL was set up and multiple scans of each feature were taken on a predetermined transect that was established parallel to the high-water mark at distances relative to the scale of the bluff and cusps. The scans from each feature were compiled, integrated and visualized using Meshlab. Results from our surveys indicate that the highly portable and easy to deploy CBL system produces images of exceptional clarity, with the capacity to resolve small-scale changes to coastal features and systems. The CBL, while still under development (and coastal surveying protocols with it are just being established), appears to be an ideal tool for analyzing coastal geological features and is anticipated to prove to be a useful tool for the observation and analysis of coastal change. Furthermore, there is significant potential for utilizing the low cost ultra-portable CBL in frequent deployments to develop small-scale erosion rate and sediment budget analyses.

ACKNOWLEDGEMENTS

I would like to express my great appreciation to my committee members, Dr. Gontz, Dr. Schaaf and Dr. Gray for their support and guidance with this thesis. I would also like to extend many thank to those who helped with data collection in the field, including the National Park Service, the University of Massachusetts - Boston Marine Operations crew, various students in the School for the Environment and a special thanks to Ian Paynter for help with data collection and analysis. Thank you to the University of Massachusetts Boston and the National Science Foundation REU program for funding for this project. And finally, I would like to thank my family and friends for their support during this process.

TABLE OF CONTENTS

ACKNOELEDGMENT vi

LIST OF FIGURES..... viii

LIST OF TABLES viii

CHAPTER Page

I. INTRODUTION 1

II. THE BLUFF ON LOVELLS ISLAND 13
II.I Study Area..... 18
II.II The Bluff..... 21
II.III Methods 22
II.IV Canopy Biomass LiDAR..... 23
II.V Experimental Setup..... 25
II.VI Data Processing 26
II.VII Results..... 29
II.VIII Discussion..... 31
II.IX Methodology Discussion..... 34
II.X Conclusion 38

III. BEACH CUSPS 39
III.I Background Information..... 39
III.II Experimental Set Up..... 40
III.III Discussion 43
III.IV Future Work 45

VI. CONCLUSION..... 46

REFERENCE LIST 52

LIST OF FIGURES

Figure Page

2.1. Map of Boston Harbor Islands 19

2.2. Study Locations on Lovells Island 20

2.3. The Canopy Biomass LiDAR set up for scanning 23

2.4. Bluff Transect Line 26

2.5. Methodology Flow Chart 27

2.6. Bluff photo, pointcloud and GIS interpolation..... 28

2.7. Sensitivity test set up..... 32

2.8. Sensitivity test pointcloud and GIS interpolation 32

2.9. Change analysis of the bluff..... 36

3.1. Beach cusp transect line 42

3.2. Beach cusp analysis..... 44

LIST OF Tables

Table Page

2.1. Erosion totals and erosion rates..... 29

2.2. Sensitivity test analysis manual calculation and results..... 33

CHAPTER I

INTRODUCTION

Observation and analysis of changes in shoreline position is an important field of study. The quantification, with high resolution information, of coastal elevation is necessary for resource management and planning (Bailey and Nowell, 1996; Klein et al., 2001 ; Bowen and Riley, 2003), the establishment of political and jurisdictional boundaries (Adger, 1999), navigation (Day et al., 2001; Brock and Purkis, 2009), and scientific research (Brock and Purkis, 2009). Accurate and up-to-date topographical maps are needed to establish building setbacks, inventory wetland and agricultural resources and to identify flood and hurricane hazard zones (Liu, Sherman, and Gu, 2007). Management and engineering design rely on the location of the shoreline at the present, in the past and in the future (Boak and Turner 2005).

Approximately 53% of the population of the US resides on the vulnerable coastal margin (Coastal, 2000) and thus shoreline information is necessary in order to analyze designs of coastal protection (Coastal Engineering Research Center, 1984). Additionally,

shoreline location is necessary to calibrate and to verify numerical models such as GENESIS (GENErelized model for SImulating Shoreline change)(Hanson, Gravens, and Kraus, 1988). Shoreline position is also important in order to monitor and assess sea-level rise (Leatherman, 2001), which is a focus of many studies as global climate change is considered. As we deal with global climate change, variations in weather patterns and sea level, it is important to develop hazard zones (Bellomo, Pajak, and Sparks, 1999; Douglas, Crowell, and Leatherman, 1999) to formulate policies and regulate development on the coast (National Research Council, 1990).

Many methods used have been to investigate, observe and measure of coastal change. Methods for observation vary depending on the features and scale and include sequential aerial photography, historic maps, and ground surveys (Jones and Williams, 1991; Kirk, 1975; Lajoie and Mathieson, 1985; Carter and Guy, 1988; Sunamura and Horikawa, 1972; and Hampton and Dingler, 1988). Similarly, the most common source for long-term, large-scale measures of shoreline position have been topographic maps, rectified aerial photographs, and traditional beach profiles (Dolan et al. 1980).

Though there are many ways of observing coastal change most methods are time consuming, expensive, limited in scope, tedious and labor intensive (Moore, 2000;Perroy et. al. 2010; Sallenger et. al. 2003; Shrestha et. al. 2005). As new technologies have emerged, creating data sets that are spatially dense over specific scales have become instrumental in identifying patterns and magnitudes of beach and cliff change as well as understanding the large-scale coastal behavior (Sallenger et. al. 2003).

The oldest available record of shoreline change is historical maps. The United States Geological Survey (USGS) quadrangles and National Ocean Service (NOS) Topographic (T) Sheets are most commonly used for shoreline mapping (Moore, 2000). As maps were not produced frequently they are considered to be better for the analysis of long-term shoreline change rather than short-term change (Stockdon et al, 2002). Errors arise during shoreline analysis using maps and are mostly attributed to errors made by the surveyors in identifying shoreline features, in the distortion of maps due to folding, tearing and shrinking over time, and due to changes in the reference datum (Anderson and Byrnes, 1991). According to Thieler and Danfoth (1994), as long as historical maps are used in shoreline change analysis, there will be a considerable amount of technological error, on the order of several meters, present in shoreline position and rate-of-change calculations. Although maps are a great source of historical shoreline change data they are not practical for high-resolution modern shoreline analysis.

Another source for studying coastal change involves the analysis of aerial photographs. Aerial photography has been used since the 1920s to document shoreline position and change (Anderes and Byrnes, 1991). Because much of the coastal areas of the United States have extensive aerial photographs, they are a valuable record of shoreline position (Moore, 2000). Aerial photographs are more appropriate for studying centennial-scale shoreline variability rather than historical maps (Stockdon et al., 2002). Some errors that are associated with aerial photographs can be excluded before features are identified within the image by using some recent techniques, which involve

softcopy photogrammetry where digital stereo images are used to georeference the image and remove distortion (Hapke and Richmond, 2000). Although using accurate digital images do minimize some of the errors associated with aerial photographs, the process of identifying shoreline features and then extracting it from images is quite labor intensive and makes the analysis of lager areas more complicated (Stockdon et al, 2002).

Ground-based surveys of cross-shore profiles of beach elevations (Stockdon et al, 2002) are accurate sources of shoreline information (May, Hayden and Hayden 1983; Goldsmith and Ortel, 1978). These surveys are affordable and short-term variation in shoreline change over a limited region can be studied (Morton, 1991). Although this is a good method for acquiring accurate measures of shoreline location, these measurements are limited in scope due to the labor-intensive nature of the method (Stockdon et al, 2002). More recent forms of ground-based surveys are based on GPS, where GPS antennae are mounted on all-terrain vehicles and quickly survey the shoreline (Morton et al., 1993). Although this method can produce shoreline profiles, there are errors associated with vehicle mounted GPS surveys and specifically depend on the accuracy of the GPS unit, the proximity of survey lines to the exact location and the beach slope (Stockdon et al, 2002). GPS methods are more accurate than aerial photography in identifying specific shoreline features of interest (Pajak and Leatherman, 2002). The greatest error made with the GPS method is caused by the operator (Boak and Turner, 2005).

In the past ten to fifteen years a range of airborne, satellite and landbased remote sensing techniques have become more generally available (Boak and Turner, 2005). One of the remote sensing techniques that has been developed is LiDAR (light detection and ranging technology). LiDAR allows for researchers to conduct surveys to obtain large amounts of data, including position and elevation, within a relatively short amount of time (Nagihara, Mulligan and Xiong, 2003). Another important benefit of using LiDAR is that the subjectivity in determining the location of vertical datum for the shoreline is removed and these features can be easily and accurately found (Stockdon et al., 2002). Scanning airborne LiDAR offers great potential in providing dense data sets over local to regional scales (Sallenger et. al. 2003). Airborne LiDAR has been used in in numerous topographic and land use change detection studies (Huising and Gomes Pereira, 1998l Irish and Lillycrop, 1999; Krabil et al., 1999 Murakami et al., 1999, Sallanger et al., 1999, for studying gully erosion (Jackson et al., 1988; Richie et al., 1994), and for mapping riverbank elevations for flood management (Pereira and Wicherson, 1999). More recently airborne LiDAR is being used for the quantification of beach change (Sallenger et al, 2003) and to estimate biomass and bioenergy (Boudreau et al, 2008; ; Stockdon et al, 2002; Popescu, 2007).

Airborne LiDAR allows for estimates of elevation over tens to hundreds of square kilometers of coast, which allows for unprecedented analysis of the spatial variability of beach and sea-cliff changes (Sallenger et al., 2002). One of the more common errors associated with airborne LiDAR is due to its angular resolutions of approximately

0.01 (Fowler, 2000), which induces error of up to 2.5 cm vertical and 7.4 cm horizontal at 20 degree scan angle and 375 m flight altitude (Thoma et al, 2005). This type of common airborne LiDAR error is not easy to remove and the resultant data resolution depends on aircraft elevation and speed as well as other factors such as laser pulse rate, scan width, scan rate and vegetation cover (Thoma et al., 2005). Many studies using LiDAR surveys have only few survey sets, two in the case of the study of El Nino related coastal change (Sallenger et al., 2002). If only one or two surveys exist of an area it is difficult to establish causation for change and small-scale fluctuations of a shoreline. In certain situations airborne LiDAR is preferable to ground-based methods. For example, studying a vast area and surveying areas where direct measurements are not possible due to unsafe terrain (Thoma et al., 2005).

Ground-based LiDAR is beneficial in developing low-cost time-series data sets to monitor changes (Perroy et al., 2010). A ground based LIDAR system is set up on a tripod and sweeps the surrounding area with optical rays. After the analysis, the reflected rays are then interpolated into a 3D topographical surface and through a series of scans fully three-dimensional model of the surface is created (Nagihara, Mulligan and Xiang, 2003). Contour maps generated from three dimensional scans can appear similar to those generated from traditional surveying techniques, however the level of accuracy and detail is far superior (Nagihara, Mulligan and Xiang, 2003).

While we are facing climate change and related effects to our coastline, it is becoming increasingly important to implement a sustainable resource management

scheme for environmental protection and conservation (Magoon, 1989; Foster, 1991). In order for coastal managers make optimal decisions and policies managers need access to reliable, timely and accurate information (Ricketts, 1992). In recent times, coastal managers have increasingly relied on science in order to develop solutions to coastal problems (Van Koningsveld et al., 2005). The data needed by coastal managers is not often readily available. Rather, the information needed for coastal managers if often in possession of various individuals in government agencies, universities and research institutions (O'Regan, 1996). It is a challenge to collect data needed for specific projects. Shoreline erosion is important for the understanding of shoreline protection and this line of experimentation are paramount. The understanding of erosion trend is important in order to perform successful shoreline protection and to justify the protective efforts and determine the most appropriate mean for protection in the form or hard or soft stabilization (Finkl, 2002).

The efficient management of resources and activities within coastal zone is dependent on the ability to identify, measure and analyze a number of processes that operate and react together in the highly dynamic coastal environment (Cracknell and Hayes, 1989). Since the 1930's, the advent of high resolution and large-scale photography, coastal scientists have made use of data captured using remote sensing devices (Smith and Zarillo, 1990). Aerial photography is the most widely used form of remote sensing and is a well-established source of information for coastal studies. Photography has been used in many applications including morphological and

vegetative studies (El Ashry and Wanless, 1967; Lyon and Greener, 1990; Britsch and Dunbar 1993; Ferguson et al., 1993), prediction of storm surge penetration (Dolan et al., 1978), for the monitoring of coastal land use change and environmental quality (Niedzweidz and Ganske, 1991) and for the determination of shoreline change rates (Anders and Byrnes, 1991; Dolan et al., 1991). Information derived from the analysis of aerial photography is necessary for the planning of shore protection programs and provides a basis for delineating coastal hazard zones (Gibb, 1981; Leatherman, 1983).

A more recently established method of data capture, compared to aerial photography, is satellite imagery. The use of satellites for the observation of the coast for management purposes is advantageous to aerial photographs in that it has a superior scale, regularity of coverage and digital data collection, making them more amenable for computer processing (O'Regan, 1996). Satellites are also very important for coastal management for their ability to record wavelengths beyond that of a photographic film using various onboard sensors (O'Regan, 1996). Another form of remote sensing that has been increasingly deployed to measure and investigate morphology and hydrodynamics in the littoral zone is a low cost video monitoring t technique which is used to monitor and measure a broad range of coastal phenomena. The advantages of digital imagery is that it enables near-continuous analysis of the coastal area in question and quantitative data can be extracted from these images (Turner et al., 2006) In addition to these methos, there are many benefits to an airborne LiDAR system from a managerial standpoint. There are situations where a flexible over flight of an area may be useful for

management including wetland and salinity mapping, bathymetry, tracking coastal plumes and tidal fronts (Klemas, 2013). A combination of airborne techniques with GPS makes it possible to obtain accurate topographic and bathymetric maps (Klemas, 2013).

Beach surveys are used to periodically survey beaches and provides a crucial source of information that helps in determining beach stability and predict future shoreline positions (O'Regan. 1996). It is possible to monitor beach dynamics using land based surveying techniques, however, it is not practical to collect a sufficient amount of data at specific resolutions to construct a three dimensional beach change model (Welch and Remillard, 1992). This is where Ground-Based LiDAR comes in handy. Numerical modeling has been used to predict beach behavior (Pilkey et al., 1990, 1993; Young et al., 1995, 1997; Thieler et al., 2000). However, there are many critics of these types of m models, particularly with the assumptions that go into these models that approximate natural conditions (Finkl, 2002). It has been argued that some of the assumptions that go into models are not realistic and in certain cases do not agree with natural conditions in the field (Young et al., 1995). Reviews of these numerical models in applied coastal studies (Young et al., 1995; Thieler et al., 2000) encouraged useful examination and a discussion of the terminology calibration, validation and verification for these coastal engineering models.

In order to develop a plan for sustainable coastal development and implement effective beach control, flood zone delineation, and ecosystem protection, scientist and

coastal managers alike need short and long term change information taking place along the coast (Bryant and Gilvear, 1999; Gesch, 2009; Pasqualini et al., 1997; West, Lillycrop, and Pope, 2001). Long-term changes have been analyzed using various methods including aerial photographs and satellite data. Our method of analysis, Canopy Biomass LiDAR, would provide coastal managers an effective and relatively inexpensive tool for analyzing short term changes occurring on and along the coastline to help in developing and implementing policy.

Information compiled from a collection of devices can be useful to coastal managers. For example, for wetland mapping, a combination of LIDAR, hyperspectral and radar imagery and narrow band vegetation indices made it possible for researchers to discriminate wetland species but to also estimate biochemical and biophysical parameters of wetland vegetation including water content, biomass and leaf area index (Adam, Mutanga, and Rugege, 2010; Gilmore et al., 2010; Ozesmi and Bauer, 2002; Pengra, Johnston, and Loveland, 2007; Simard, Fatoyinbo, and Pinto, 2010; Wang, 2010).

Certain environmental processes require a higher resolution and temporal scale for proper monitoring. Airborne coastal monitoring can provide accurate topographic and bathymetric maps and shoreline position. However, there are some problems related to airborne monitoring including high cost, the limited spatial and spectral resolution resulting in too many mixed coastal pixels becoming an issue during image analysis and the complexity of the imaging processing procedures resulting in the need for specific software package, large data storage and extended processing time (Klemas, 2013).

While there are many methods that are useful to and are used for coastal monitoring for managerial purposes, Ground Based LiDAR can perform a high resolution and high temporal monitoring of coastal features, specifically, inexpensively and rapidly. In terms of analyzing high angle features, such as eroding bluffs, no other method is more suited than Ground-Based LiDAR. Ground surveys and beach profiles are the main comparison to the data collected for this type of monitoring, however, those methods are time consuming and the data collected is not of great detail. Ground Based LiDAR can rapidly capture details of these features and help Managers make informed decisions. Although extremely useful in specific situations, Ground-Based LiDAR cannot gather as much information over large scales as Airborne LiDAR. As such it is suggested that these methods be used together when needed.

In an environment such as Boston harbor, a system such as the CBL can be deployed almost anywhere and whenever necessary. For example, it there is storm event that directly hit Boston Harbor, the CBL could be deployed in and around the harbor to perform a rapid assessment of damage incurred which can help the coastal managers in their clean up and mitigation work. To understand the seasonal impact of tides and anthropogenic activity on specific high use areas of the harbor, the CBL can be deployed to assess this type of effect. There are many areas where the CBL is the optimal tool for observation and analysis. Ground Based LiDAR system can be used in tandem with other methods such as aerial photography, satellite imagery and airborne LiDAR to give coastal managers a detailed view of their coastline in order to make informed decisions

and develop sustainable policies.

Observing and quantifying changes on the coastline can provide practical, usable information to those who live and work on and around the shore. Short term, accurate and repeatable observations are one of the best tools used to analyze shoreline changes. The purpose of this study is, therefor, to develop baseline imagery of diverse coastal morphologies observed on Lovells Island, Boston Harbor, MA, to establish a protocol for repeat analysis of Ground Based LiDAR, to conduct repeat analysis over short-term temporal scales, and to conduct rate of change analysis. The readily available accessibility of GB-LiDAR, its relative affordability and ease of use makes it the most appropriate choice for this study, and the preferred method amongst the many available at present.

CHAPTER II

THE BLUFF ON LOVELLS ISLAND

Observation and analysis of changes in shoreline position is an important field of study. The quantification, with high resolution information, of coastal elevation is necessary for resource management and planning (Bailey and Nowell, 1996; Klein et al., 2001 ; Bowen and Riley, 2003), the establishment of political and jurisdictional boundaries (Adger, 1999), navigation (Day et al., 2001; Brock and Purkis, 2009), and scientific research (Brock and Purkis, 2009). Accurate and up-to-date topographical maps are needed to establish building setbacks, inventory wetland and agricultural resources and to identify flood and hurricane hazard zones (Liu, Sherman, and Gu, 2007). Management and engineering design rely on the location of the shoreline at the present, in the past and the future (Boak and Turner 2005). Approximately 53% of the population of the US resides on the vulnerable coastal margin (Coastal, 2000) and thus shoreline information is necessary in order to analyze designs of coastal protection (Coastal Engineering Research Center, 1984).

Shoreline position is important in order to monitor and assess sea-level rise (Leatherman, 2001), which is a focus of many studies as global climate change is considered. As we deal with global climate change, variations in weather patterns and sea level, it is important to develop hazard zones (Bellomo, Pajak, and Sparks, 1999; Douglas, Crowell, and Leatherman, 1999) to formulate policies and regulate development on the coast (National Research Council, 1990). Additionally, shoreline location is necessary to calibrate and to verify numerical models such as GENESIS (GENErelized model for SImulating Shoreline change)(Hanson, Gravens, and Kraus, 1988).

Many methods used have been to investigate, observe and measure of coastal change. Methods for observation vary depending on the features and scale and include sequential aerial photography, historic maps, and ground surveys (Jones and Williams, 1991; Kirk, 1975; Lajoie and Mathieson, 1985; Carter and Guy, 1988; Sunamura and Horikawa, 1972; and Hampton and Dingler, 1988; Maio et al., 2012; Maio et al., 2013; Gontz et al., 2011). Similarly, the most common source for long-term, large-scale measures of shoreline position have been topographic maps, rectified aerial photographs, and traditional beach profiles (Dolan et al. 1980).

Though there are many ways of observing coastal change most methods are time consuming, expensive, limited in scope, tedious and labor intensive (Moore, 2000;Perroy et. al. 2010; Sallenger et. al. 2003; Shrestha et. al. 2005). As new technologies have emerged, creating data sets that are spatially dense over specific scales have become

instrumental in identifying patterns and magnitudes of beach and cliff change as well as understanding the large-scale coastal behavior (Sallenger et. al. 2003).

In the past ten to fifteen years a range of airborne, satellite and landbased remote sensing techniques have become more generally available (Boak and Turner, 2005). One of the remote sensing techniques recently developed is LiDAR (light detection and ranging technology). LiDAR allows for surveys to obtain large amounts of data, including position and elevation, within a relatively short amount of time (Nagihara, Mulligan and Xiong, 2003). Another important benefit of using LiDAR is that the subjectivity in determining the location of vertical datum for the shoreline is removed and these features can be easily and accurately found (Stockdon et al., 2002). Scanning airborne LiDAR offers great potential in providing dense data sets over local to regional scales (Sallenger et. al. 2003). Airborne LiDAR has been used in in numerous topographic and land use change detection studies (Huising and Gomes Pereira, 1998l Irish and Lillycrop, 1999; Krabill et al., 1999 Murakami et al., 1999, Sallanger et al., 1999), for studying gully erosion (Jackson et al., 1988; Richie et al., 1994), and for mapping riverbank elevations for flood management (Pereira and Wicherson, 1999). More recently airborne LiDAR is being used for the quantification of beach change (Sallenger et al, 2003) and to estimate biomass and bioenergy (Boudreau et al, 2008; Stockdon et al, 2002; Popescu, 2007).

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efforts and determine the most appropriate mean for protection in the form or hard or soft stabilization (Finkl, 2002). The efficient management of resources and activities within coastal zone is dependent on the ability to identify, measure and analyze a number of processes that operate and react together in the highly dynamic coastal environment (Cracknell and Hayes, 1989)

In order to develop a plan for sustainable coastal development and implement effective beach control, flood zone delineation, and ecosystem protection, scientist and coastal managers alike need short and long term change information taking place along the coast (Bryant and Gilvear, 1999; Gesch, 2009; Pasqualini et al., 1997; West, Lillycrop, and Pope, 2001). Long-term changes have been analyzed using various methods including aerial photographs and satellite data. In addition to these methos, there are many benefits to an airborne LiDAR system from a managerial standpoint. There are situations where a flexible over flight of an area may be useful for management including wetland and salinity mapping, bathymetry, tracking coastal plumes and tidal fronts (Klemas, 2013). Our method of analysis, CBL, would provide coastal managers an effective and relatively inexpensive tool for analyzing short term changes occurring on and along the coastline to help in the development and implementation of policy.

Observing and quantifying changes on the coastline can provide practical, usable information to those who live and work on and around the shore. Short term, accurate and repeatable observations are one of the best tools used to analyze shoreline changes.

The purpose of this study is to develop baseline imagery of diverse coastal morphologies, to establish a protocol for repeat analysis of GB-LiDAR, to conduct repeat analysis over short-term temporal scales, and to conduct rate of change analysis. The readily available accessibility of GB-LiDAR, its relative affordability and ease of use makes it the most appropriate choice for this study, and the preferred method amongst the many available at present.

II.I Study Area

The study site chosen for this project is Lovells Island in Massachusetts Bay (Figure. 1). Lovells Island is owned and managed by the City of Boston and is included in the Boston Harbor Island National Recreation Area (National Park Service, 2009). Of the islands in Boston Harbor, Lovells Island is a good model for the range of processes occurring throughout the Harbor system (Rosen and FitzGerald , 2004), which makes in an appropriate location for this study. Lovells Island is composed of wet meadow, three connected drumlins, a dune that extends for 0.8 km on the south shore and a short dune along the North shore. The Island is surrounded by a rocky shoreline except for the NE side where there is a long section of gravel, sand and shell beach. The Island has 0.25 km^2 of upland area and the highest elevation is 24 m (National Park Services, 2009). In this paper we focus on two of the coastal morphologies observed on Lovells Island, including: 1) High eroding glacial bluff and 2) Beach Cusps on NE-facing beach (Figure 2.2). We sought to acquire baseline imagery and calculate rates and volumes of change for these features.

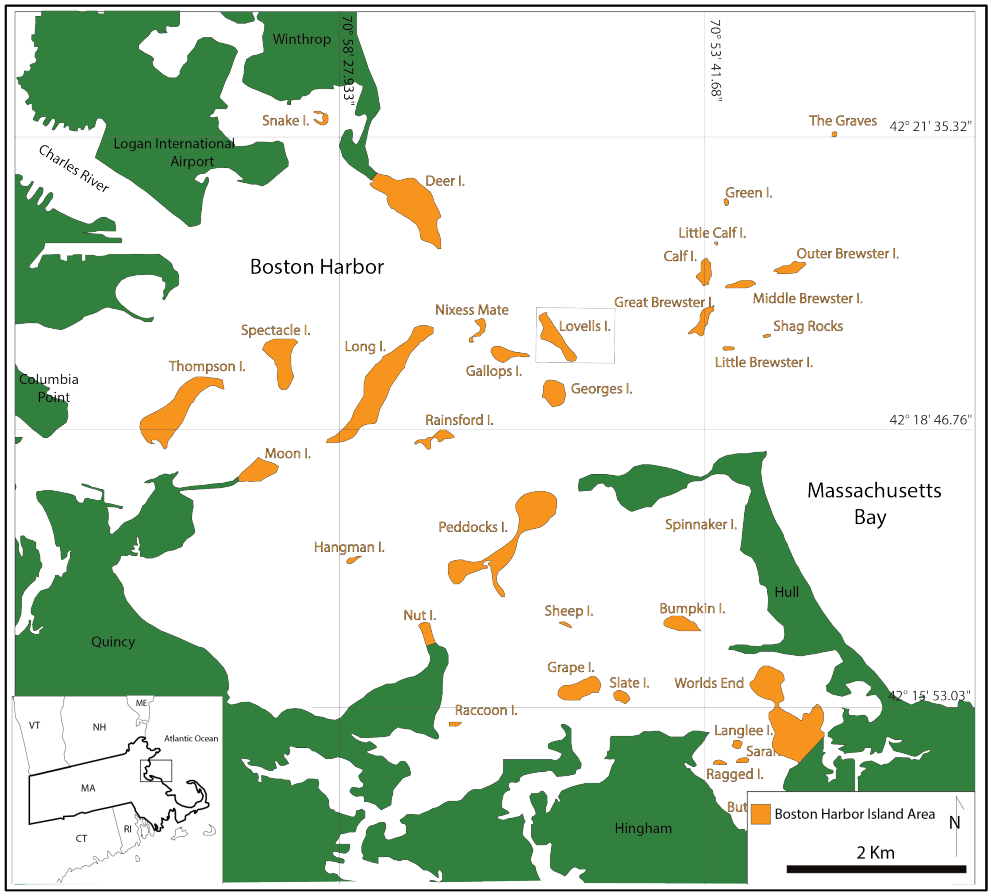

Figure 2.1. Map of Boston Harbor Islands. Lovells Island is located at the entrance of Boston Harbor. Lovells Island is owned and managed by the city of Boston and is 1 of 34 islands included in the Boston Harbor Island National Recreation Area. Because of its location, Lovells Island is exposed to higher wave energy from Massachusetts Bay.

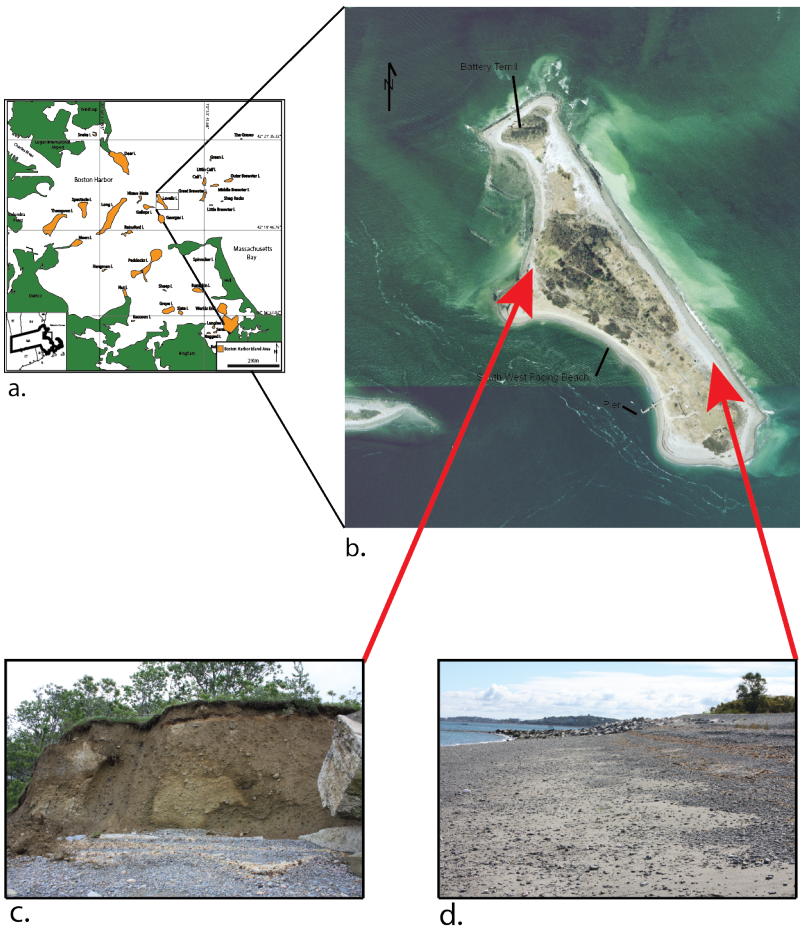

Figure 2.2. Study Locations on Lovells Island. a. Map of the harbor. b. Aerial photograph of Lovells Island. c. Bluff on NW Beach of Lovells Island. d. Beach cusps on NE Beach of Lovells Island.

Theiler and others (2013) examined the coastal systems of Massachusetts to develop a Shoreline Change Atlas. The horizontal rates of shoreline change were calculated based on historic maps and aerial photographs that span the time frame of 1840 to the present. On Lovells Island, Theiler and others (2013) calculated that erosion was occuring at a rate of -1.5 ± 0.09 m/yr at Lovells Island,. This rate represents the

highest rate of erosion in Boston Harbor and was found downdrift of a groin field and breakwater, which runs parallel to the shoreline of the Island.

II.II The Bluff

Many of the islands in Boston Harbor are composed of drumlins, eroding drumlins and depositional features related to the erosion of the drumlins (Rosen and FitzGerald , 2004). The drumlins were deposited during the Wisconsinan Glaciation (Kaye, 1976; LaForge, 1932). The drumlins in Boston Harbor are made up of unstratified gravel, sand, silt and clay scoured by the ice from the region (Knebel et al., 1993; Newman and Mickelson, 1994; Rosen and Brenninkmeyer, 1989). Sediments delivered to the littoral zone through bluff erosion have been reworked and deposited in the form of bars that extend down drift from the drumlin headlands, and in many cases link multiple drumlins together and as these drumlin anchors erode the bluffs retreat (Hammelstoss, et al., 2006).

Lovells Island hosts three drumlins linked by low lying sedimentary plains. The central drumlin on the NE beach is presently eroding and a 10 m high bluff has formed. The bluff will serve as the focus area for conducting change analysis with GB-LiDAR.

II.III Methods

In order to obtain a short term and high accuracy change information of Lovells Island, a portable Ground-Based (GB) LiDAR system, developed by UMB with assistance from the Rochester Institute of Technology, called CBL (Canopy Biomass LiDAR), was used (Figure 2.3). GB LiDAR is beneficial in developing low-cost time-series data sets in order to monitor changes (Perroy et al., 2010). A GB-LiDAR system is set up on a tripod and sweeps a defined area with optical rays (Nagihara, Mulligan and Xiang, 2003). These rays produce reflections when they hit solid objects and the instrument records the coordinate of each reflection point relative to the location of the scanner location by measuring the angle and travel time of each ray (Nagihara, Mulligan and Xiang, 2003). These reflected rays are then interpolated into a 3D topographical surface and, through a series of scans around the target, can produce a fully three-dimensional model of the surface being observed (Nagihara, Mulligan and Xiang, 2003). Though contour maps generated from three dimensional scans can appear similar to those generated from traditional surveying techniques the level of accuracy and detail is far superior ((Nagihara, Mulligan and Xiang, 2003).

Figure 2.3. The Canopy Biomass LiDAR set up for scanning.

II.IV Canopy Biomass LiDAR (CBL)

The CBL was built using off the shelf components and custom design parts by University of Massachusetts Boston staff and students. The original concept for the CBL came from colleagues at RIT. Although the original idea emanated from RIT and the software used is the same, the CBL built at the UMB is considerably different. The basic components that make up the CBL system include a LiDAR scanner, the SICK LMS151, a rotary stage (a stepper motor from MOOG Animatics, geared 90:1 with a Valmex work gear) and an Ethernet bridge from WizNet. Additionally, a 3D inertial

navigation system and GPS receiver was used to determine the location of scans and attitude (level, vibration, tilt, etc.).

In the field, the LiDAR scanner performs a 270-degree scan on the vertical plane, which is centered on the zenith. The scanner is mounted on a rotary stage that performs a horizontal swath of 180 degrees from an azimuth. The motions of the vertical and horizontal scan are synchronized in order for the stage to advance one quarter of a degree each time the LiDAR performs a vertical scan. In total, the scans made by the CBL produces a point cloud of roughly 800,000 points that is almost spherical, barring a 45 degree blind cone at the Nadir, directly behind the CBL scan. The laser is at a wavelength of 905 nm making it eye safe.

The software used with the CBL, called the CBL controller, is written in the QT framework and a dialect of the C++ programming language. The software runs on a Macintosh computer that is running the OS X 11 operating system. When the program is started, a 3-socket communication port is opened with the Ethernet Bridge. The Ethernet Bridge includes the LiDAR port, motor/stage port and GPS/attitude port. When all of these connections are made successfully the software proceeds to acquire the GPS location, heading with respect to magnetic north, and attitude of the scanner. All of this information is saved to a file that has the time stamp embedded in its title. The scan is then initiated and the LiDAR scanner and rotary stage collects vertical scans. Each of these vertical scans is an array of points augmented with the position of the stage for the

particular vertical scan. Once the 180-degree rotation is completed, the software saves the scans on a separate file, which also has a time stamp embedded in its name, and commands the motor to return to the original starting position. Once the scans are performed in the field they are analyzed and rendered using Meshlab.

II.V Experimental Setup

Short time scale series of GB-LiDAR scans of a bluff were collected on Lovells Island, Boston Harbour between June and December of 2013. At the bluff site a transect line, perpendicular to the feature being scanned, was set up. Based on the size of the feature, scanning points were set up roughly 5 meters from each other (Figure 2.4). Each scan point along the transect lines were referenced using hand held compasses to permanent features in sight. Once the scanning points were chosen, low profile flags were set up along the transect line at each scanning point the instrument was set up and leveled using the on board sight level. The tripod was extended to its maximum height and oriented with the transect line. Each scan was initiated from a terminal on a MacBook Air, which was connected to the GB-LiDAR by a Cat5E Ethernet cable and a network bridge mounted on the LiDAR. 1.5 miliradian scans were taken with duplicates at each scanning point moving along the transect lines. After several scans along the transect lines were completed a scan was randomly selected and visualized using Meshlab to check the integrity of the data collected. Once the survey was completed the

scans were isolated from the laptop and stored on an external device. At each scanning point duplicate high quality digital photographs were taken for validation.

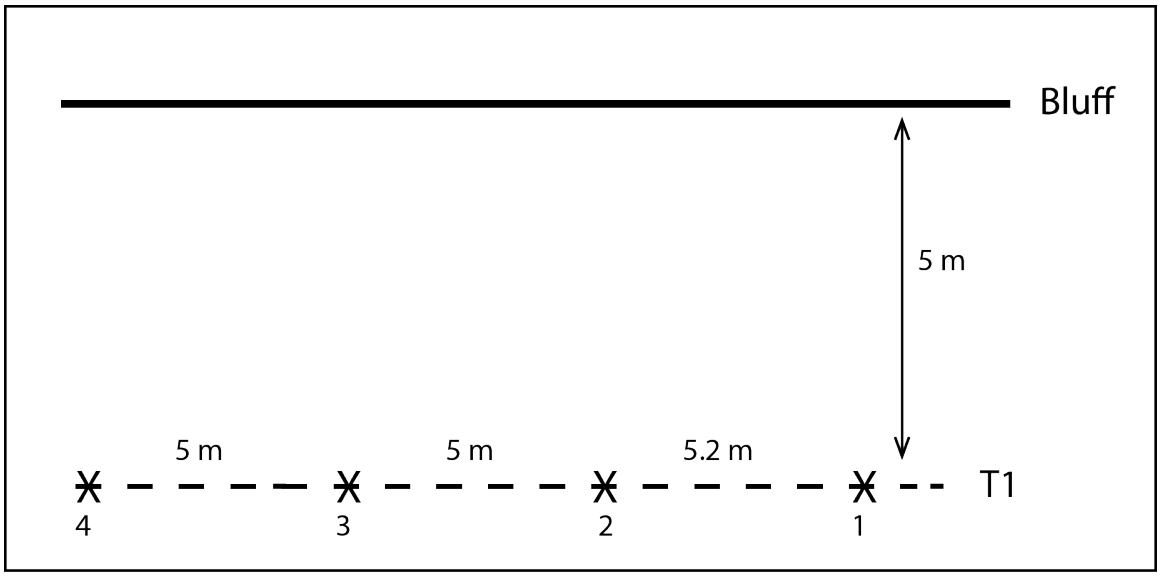

Figure 2.4. Bluff Transect Line. A transect line was setup in order to capture entire bluff with CBL and reoccupy same scanning location during subsequent fieldwork.

II.VI Data Processing

A simple operational methodology was created for the volume change analysis of the bluff (Figure 4). The scans from the surveys were processed using Meshlab, an open source, portable system for processing and editing of 3D triangular meshes which makes it an appropriate system for analyzing point clouds (Cignoni, 2012). The scans were layered on top of each other using the scan manipulator tool. For further analysis the same portion from each scan were excised. The data was excised to remove unwanted data caused by occlusions, vegetation and ice. The conditional vertex selection tool in

Meshlab was utilized to excise the wanted portion of the pointclouds. The freeze current matrix option was applied to the layered scans in order to set the same coordinate system for each scan. After the coordinate is fixed it each scan is exported from meshlab as an .xyz file.

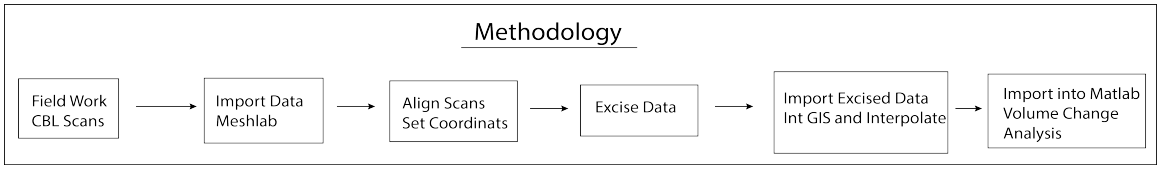

Figure 2.5. Methodology Flow Chart. This chart shows the work flow for the bluff analysis.

The resultant .xyz files could have been analyzed using multiple tools such as a GIS platform or a data analysis tool such as Matlab. For this analysis ArcGIS was used for its interpolation and visualization capabilities (Childs, 2004). Once imported into GIS the pointclouds were interpolated using inverse distance weighted (IDW). IDW was used because we had a data set with points that were dense enough to capture the extent of local surface variation needed for the analysis (Childs, 2004). In order to calculate the volume change the interpolated surfaces of the bluff were subtracted from each other, trip 2 from trip 1 and trip 3 from trip 2. This resultant layer was exported into Matlab, an interactive environment for numerical computation (User's Guide, 2012), for the final

volume calculation. Figure 2.6 shows photos, meshlab pointclouds and GIS interpolation of the bluff at each time point. As we were able to set the cell size of surface in ArcGIS it was possible to easily calculate the volume. Table 2.1 shows the results of this calculation.

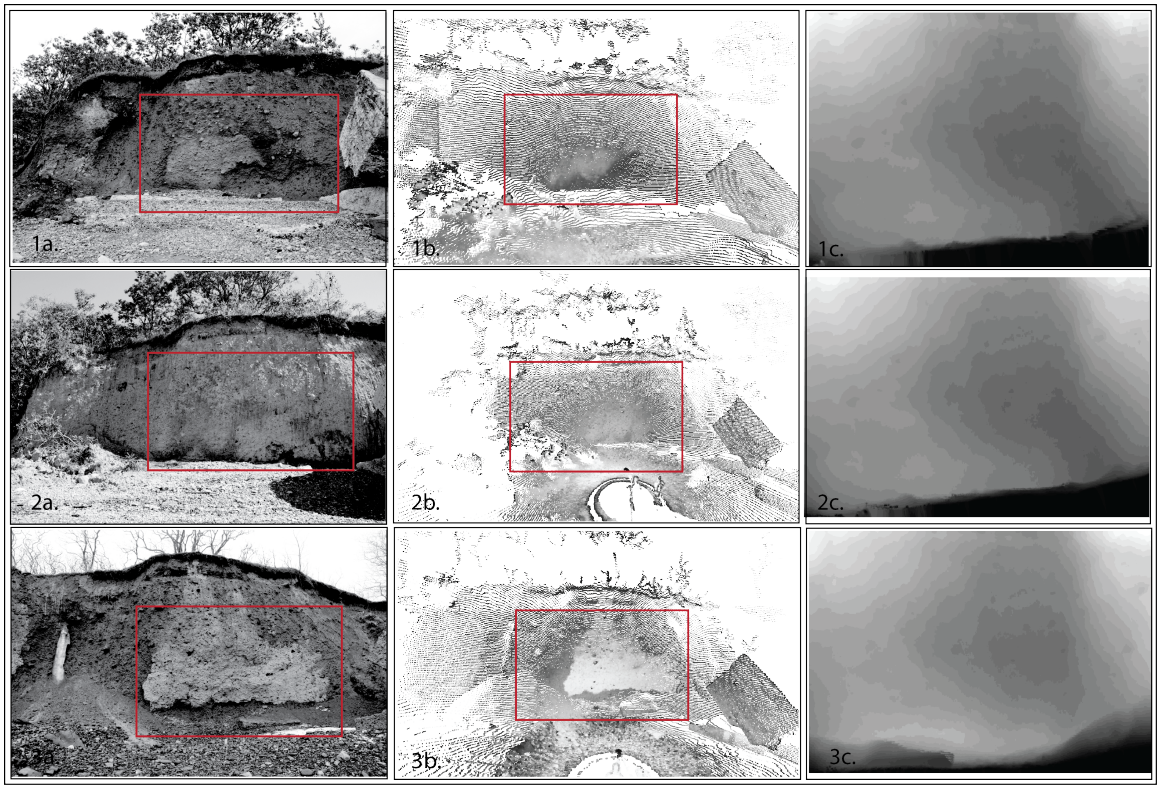

Figure 2.6. Bluff photo, pointcloud and GIS interpolation. 1a. Digital photograph of Northwest Facing Beach Erodig Bluff on June 27th, 2014. 1b.. Raw pointcloud data of Northwest Facing beach from June 27th, 2014. 1c. IDW interpolation of the eroding bluff from June 27th, 2014. 2a. Digital photograph of eroding bluff on September 27th, 2014. 2b. Raw pointgloud data of eroding bluff from September 27th, 2014. 2c. IDW interpolation of the eroding bluff from June 27th ,2014. 3a. Digitap photograph of the eroding bluff from February 21st, 2014. 2b. Raw poingcloud data of eroding bluff from February 21st, 2014. 3c. IDW interpolationof the erodig bluff from Februrary 21st, 2014. ☐ boundary of excised data.

Table 2.1

	Erosion Total (m^3)	Erosion Rate (m^3/day)	Days Between Trips (Days)
Between Trip 1 and 2	**1.358**	**0.015**	**92**
Between Trip 2 and 3	**14.923**	**0.095**	**157**
Totals	**16.281**	**0.065**	**249**

Table 2.1. Erosion totals and erosion rates. Erosion totals and rates between each trip to the bluff on Lovell's Island.

II.VII Results

On the 12th of June, 2013 an preliminary trip was taken to Lovells Island in order to identify features that could be successfully imaged using the CBLs. The bluff on the NE facing beach and beach cups on the NW facing beach were identified as target features. The bluff on the North-West Beach of Lovells Island is an ideal feature for this analysis. Evidence for active erosion was observed, including steep, near vertical and unvegetated bluff face; small talus piles at the base of the bluff; and large slump blocks with vegetation.

On June 27th, 2013 the first scanning campaign took place. On this trip baseline imagery of the bluff on the NE beach were taken. Three scanning points each on two transect lines were set up and duplicate scans were taken at each scanning point. After bearing were taken for future reference for reoccupation of the same scanning location the data were taken back to the University of Massachusetts Boston for initial processing. Major morphological aspects on the bluff could be identified indicating that the scans provide a detailed representation of the bluff surface.

The third outing to Lovells Islsnd occurred on September 27th, 2013. Again, duplicate scans of the bluff were taken as well as digital photographs and bearings in order to reoccupy on the next trip. It was determined after the first trip that only the 5 m transect line was necessary as all of the bluff was identifiable from the scans on that line. The same 5 m transect line was reoccupied and duplicate scans were taken. Between the first and second scanning dates, the bluff did show some change that could be seen visually. There was a large pile of loose sediment sitting directly in front of the bluff with some fallen vegetation on it creating an occlusion. As with the scans from June these scans were processed using Meshlab and the same results from the June campaign were identified.

On February 21st, 2014 a fourth and final field trip out to Lovells Island was made. During this expedition a rescan the bluff on the North-West beach was conducted. As in the previous trips the transect lines delineated during the previous scans was reoccupied using the triangulation points on the island. A visual examination indicated change in the bluff. First, the sediments that had seemingly fallen from the bluff and was sitting in front of the bluff was now gone. Second, on this day, the bluff was eroding as we were standing in front of the bluff.

II.VIII Discussion

II.VII.I Sensitivity Test /Validation experiment

In order to justify out methods for examining small-scale coastal change using the Canopy Biomass LiDAR, a sensitivity test was conducted. A large piece of cardboard was acquired and measured, serving as a substitute for the bluff. Initially, three triangles were cut into the cardboard, running vertically. The triangles were measured and used to calculate a known volume of the cardboard. Once measured, the cardboard bluff was taped on to a wall and the CBL was set up in front (Figure 2.7). The floor where the CBL was set up was marked in order to maintain the same scanning position. Duplicate scans of the "fake" bluff were conducted. In order to simulate erosion of the bluff and to justify the volume change calculation, the same three triangles on the original cardboard bluff were reduced in size for a second scan. The cardboard was once again taped to the wall and scanned from the same location. Figure 2.8 presents the interpolated figure along with the pointclouds.

Figure 2.7. Sensitivity test set up.

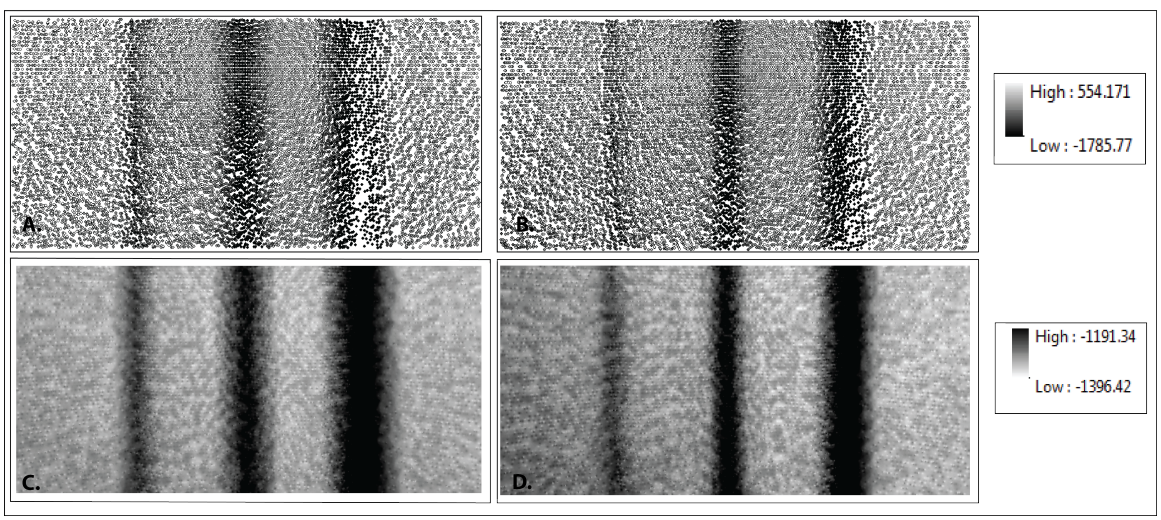

Figure 2.8. Sensitivity test pointcloud and GIS interpolation. A and B are the first and second Fake Bluff raw pointclouds. C and D are the corresponding interpolated surfaces.

The volume change between the two cardboard bluffs were calculated though the established methodology (See Figure 2.5). The volume change was calculated manually for comparison (Table 2.3). The manually calculated volume change and the LiDAR analysis are seemingly far from each other. This was thought to be in part due to noise found in the data, to human errors made during measurement and to the fact that the duck tape holding the cardboard may have not been flush to the wall during the scanning process. Further analysis showed that there is an error associated with the CBL of 50mm. It has not yet been determined whether the 50mm is in one direction only or 25mm in each direction. It has been determined, however, that the error is consistent with range. It has become clear after performing the sensitivity test our fake bluff was too small to demonstrate the viability of our methodology. The error is large enough that some of the change may have been negated, causing the minimal volume change calculated.

Table 2.2

Column1	Manual Calculation (m^3)	Analysis (m^3)
Erosion Totals	0.01292	0.00030676

Table 2.2. Sensitivity test analysis manual calculation and results.

Limitations do exist in our procedures and can be improved upon. Although the CBLs are very easy to transport, in order to perform accurate alignment of the scans a permanent feature must be present in the vicinity of the features being analyzed. It is necessary to select a location that can be reached on foot, which has a control monument,

and at least some erosional activity for change observation. With our study there was obvious erosion and it will be necessary to determine the scale of erosion that can be identified with the CBL in the future.

Other limitations include the GB-LiDAR system's sensitivity to occlusions. Such occlusions in the field of view of LiDAR introduces a source or uncertainty into the range data and some features can be partially or completely hidden from the view of the scanner which results in data loss and uncertainty concerning the position or range (Yapo, Stewart and Redke, 2008). There was vegetation sitting on top of a sediment pile, at the bluff on Lovells island, in front of the far left portion of the view of the scanner resulting in data loss for this analysis.

II. IX Methodology Discussion

In comparison to the GB-LiDAR system, airborne LiDAR allows for estimates of elevation over tens to hundreds of square kilometers of coast, which allows for unprecedented analysis of the spatial variability of beach and sea-cliff changes (Sallenger et al., 2002). One of the more common errors associated with airborne LiDAR is due to its angular resolutions of approximately 0.01 (Fowler, 2000), which induces error of up to 2.5 cm vertical and 7.4 cm horizontal at 20 degree scan angle and 375 m flight altitude (Thoma et al, 2005). This type of common airborne LiDAR error is not easy to remove and the resultant data resolution depends on aircraft elevation and speed as well as other

factors such as laser pulse rate, scan width, scan rate and vegetation cover (Thoma et al., 2005). Many studies using airborne LiDAR surveys have only few survey sets, two in the case of the study of El Nino related coastal change (Sallenger et al., 2002). If only one or two surveys exist of an area it is difficult to establish causation for change and small-scale fluctuations of a shoreline. In certain situations airborne LiDAR is preferable to ground-based methods. For example, studying a vast area and surveying areas where direct measurements are not possible, due to unsafe terrain (Thoma et al., 2005). In terms of analyzing a small-scale system and rapid changes occurring, and in particular high angle coastal features, the CBL are preferable to Airborne LiDAR. The CBL is affordable, has better resolution over a small area and scans can be taken easily and rapidly giving a much better resolution of the changes occurring at a given area.

The results from the volume change analysis are consistant with the visual assessments of the bluff. Between the first trip some change was observed, yet not much. There was also a larger pile of debree sitting in front of the bluff on the second trip rather than the first and third trip, therefore explaining the reason for the values of the first volume analysis. On the third scanning trip the analysis was again consistent with field observations. Figure 2.9. shows the difference figures between the trips. There is generally some change observed throughout the bluff between the three trips. Between the first two trips there is what looks like accretion at the bottom which was a pile of sediment that had eroded off the bluff and collected at the base of the bluff. Between the

second and third trip there is en erosion hotspot visible at the base of the bluff demonstrating the CBL ability to identify such features.

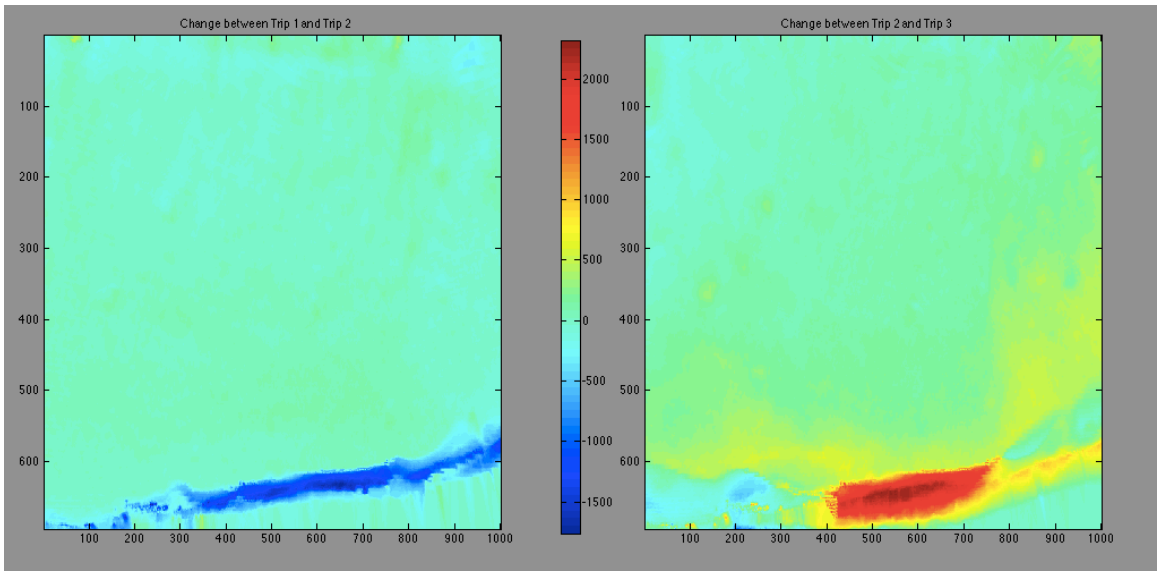

Figure 2.9. Change analysis of the bluff.

While there are many methods that are useful to and are used for coastal monitoring for managerial purposes, Ground Based LiDAR can perform a high resolution and high temporal monitoring of coastal features, specifically, inexpensively and rapidly. In terms of analyzing high angle features, such as eroding bluffs, no other method is more suited than Ground-Based LiDAR. Ground surveys and beach profiles are the main comparison to the data collected for this type of monitoring, however, those

methods are time consuming and the data collected is not of great detail. Ground Based LiDAR can rapidly capture details of these features and help Managers make informed decisions. Although extremely useful in specific situations, Ground0Based LiDAR cannot gather as much information over large scales as Airborne LiDAR. As such it is suggested that these methods be used together when needed.

In an environment such as Boston harbor, a system such as the CBL can be deployed almost anywhere and whenever necessary. For example, it there is storm event that directly hit Boston Harbor, the CBL could be deployed in and around the harbor to perform a rapid assessment of damage incurred which can help the coastal managers in their clean up and mitigation work. To understand the seasonal impact of tides and anthropogenic activity on specific high use areas of the harbor, the CBL can be deployed to assess this type of effect. There are many areas where the CBL is the optimal tool for observation and analysis. Ground Based LiDAR system can be used in tandem with other methods such as aerial photography, satellite imagery and airborne LiDAR to give coastal managers a detailed view of their coastline in order to make informed decisions and develop sustainable policies.

II. X Conclusion

This study demonstrates the useful nature of the CBL and revealed it to be relatively inexpensive tool for studying coastal geologic features and coastal change. GB-LiDAR is an effective tool for identifying and characterizing high angle coastal features and erosion hotspots. In particular, the CBL was successfully employed to identify coastal features and to calculate volume change and erosion rates on an eroding bluff on Lovells Island, Boston Harbor. The GB-LiDAR system is highly portable and can be deployed in many environments without much difficulty. Compared to other methods, this method is simple and easy to execute. In certain studies GB-LiDAR has been shown to outperform airborne systems (Perroy et. al., 2010).

There is almost infinite possibility for the future application of the CBL. Due it its inexpensiveness it can be produced and used in numerous studies. The GB-LiDAR system could be used in rapid assessment of shoreline change, to study immediate storm impacts and also to calculate sediment budgets. Further research should be conducted on the eroding bluff on Lovells Island, looking at post storm response and short-term response to tides. A detailed sensitivity analysis should be conducted on the CBL in order to better understand the errors and limitations associated with these methods. Using tools such as the CBL for coastal studies is increasingly important due to the changing climate and impending storm intensification and sea level rise. The availability of these tools will help in addressing effects of these changes and may help us adjust accordingly.

CHAPTER III

BEACH CUSPS

III.I. Background Information

Beach cusps are undulations found along a beach face that is characterized by distinct alongshore periodicity. A beach cusp is often defined as a sequence of horn-bay-born where the horns of the cusps extent seaward and coupled with steeper slopes and bays landward and coupled with milder slopes. The sequences of beach cusps can be relatively regular on the alongshore direction, and the spacing is defined by the distance between consecutive horns, ranging from centimeters (Komar, 1983) to tens of meters (Coco et al., 1999) The horns are located at right angles to the shoreline and are spaced at relatively regular intervals along the shore (Gary et al., 1974). Beach cusps can occur in a variety of sediment sizes ranging from fine sand to boulders (Mii, 1958; Russell and McIntire, 1965) and generally show sorting of the material between the horns and bays where the horns are made up of the coarser sediment and the bays are made up of the finer material (Longuet-Higgins and Parkin, 1962; Komar, 1983). Beach cusps have

been proven to be difficult to explain for they are fairly uniform features which have no obvious formation mechanisms to account for their symmetrical appearance (Nolan, Kirk and Shulmeister, 1998) Many scientists have attempted to correlate measured beach cusps spacing to wave conditions (Aoki and Sunamura, 2000; Pais-Barbosa, 2007) or to values of spacing given by theoretical expressions (Holland and Holman, 1996; Holland, 1998, Masselink, 1999). Coco et al. (1999) pointed out that there is a desperate need for three-dimensional observations of the evolution of beach cusps.

On the Northwest facing beach on Lovells island there is a system of swash cusps, as supposed to giant cusps, which have a much larger spacing, over 75m wavelength, ,(Inman & Guza, 1982). There have been two different views on the mechanisms for the development of swash cusps (Coco et al. 1999). The two theories are the standing endge wave model (Guza and Inman, 1975) and the self-organization model (Wener and Fink 1993; Coco, Huntley and O'Hare, 2000). There are beach cusps located along the shoreline of the Northwest facing beach on Lovells Island, Boston Harbor. Each beach cusp is roughly 4 to 5 m horn to horn and have an elevation at the embayment in the 10-20 cm range.

III.II. Experimental Set Up

The Ground Based LiDAR, CBL, was used to scan the beach cusps on Lovells Island, Boston Harbour on September of 2013. A transect line perpendicular to the beach

cusps was established (Figure 3.1). Four scanning points were set up roughly 5 meters from each other. Each scan point along the transect lines were referenced using handheld compasses to permanent features in sight. Once the scanning points were chosen, low profile flags were set up along the transect line at each scanning point the instrument was set up and leveled using the on board sight level. The tripod was extended to its maximum height and oriented with the transect line. Each scan was initiated from a terminal on a MacBook Air, which was connected to the GB-LiDAR by a Cat5E Ethernet cable and a network bridge mounted on the LiDAR. 1.5 miliradian scans were taken with duplicates at each scanning point moving along the transect lines. After several scans along the transect lines were completed a scan was randomly selected and visualized using Meshlab to check the integrity of the data collected. Once the survey was completed the scans were isolated from the laptop and stored on an external device. At each scanning point duplicate high quality digital photographs were taken for validation. Once the survey was completed the GB-LiDAR, computer and data were carefully packed up and taken back to the lab for analysis.

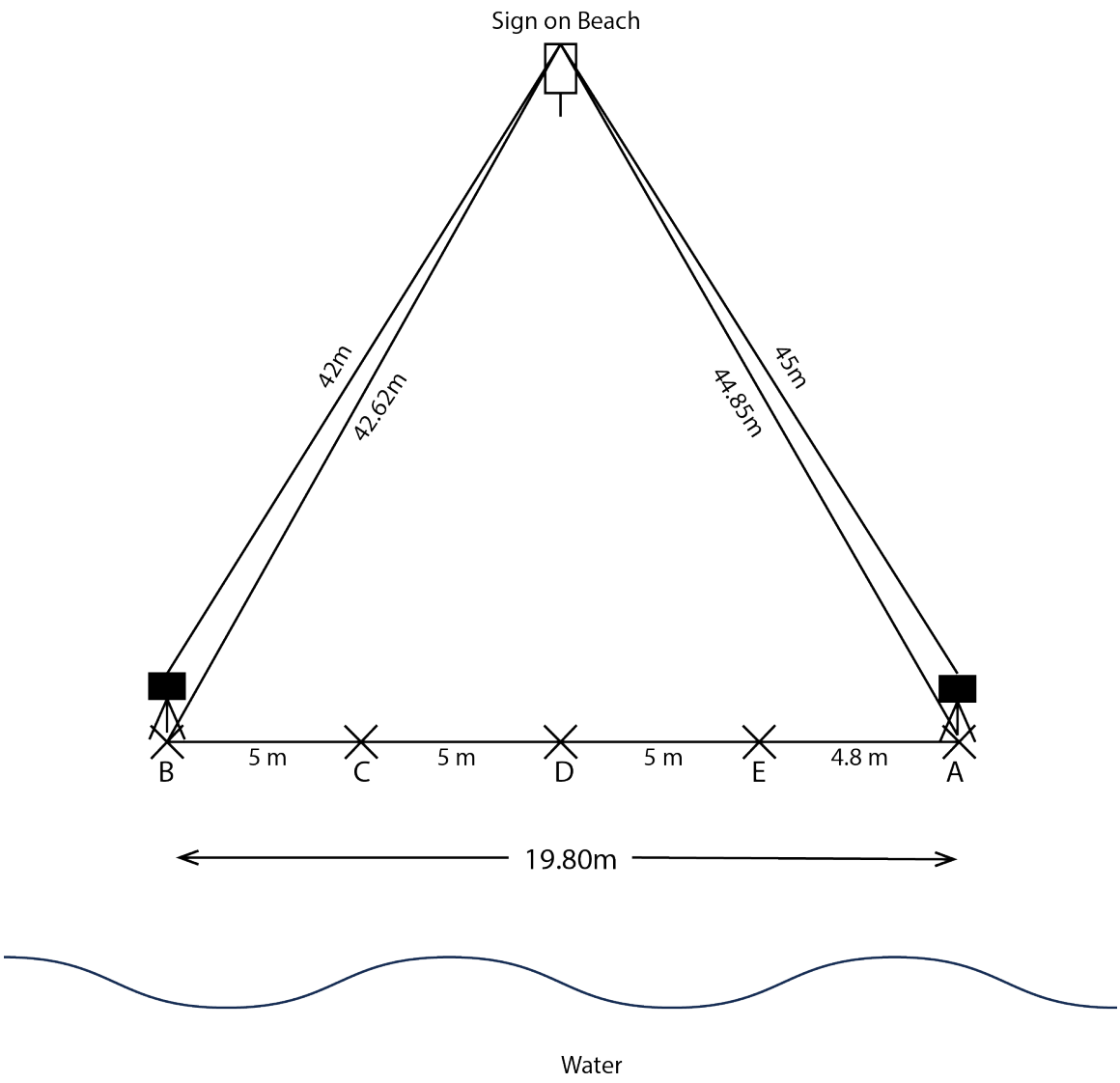

Figure 3.1. Beach cusp transect line. A transect line was set up in order to be able to capture multiple beach cusps and reoccupy the same scanning location in the future.

III.III. Discussion

The standing edge wave model proposes that an alongshore-standing subharmonic edge wave is superimposed on a normally incident reflected wave and this action produces a systematic alongshore variation in the swash height that eventually results in a regular erosional perturbations which leads to the cups formation (Guza and Inman 1975). The standing wave amplitude is reduced by the formation of the cusps (Guza and Inman, 1975; Guza and Bowen 1981), which leads to the process being self-limiting and a fully reflective wave condition is required for this model to be applied. Some believe that this methods may explain the initiation of the cusp formation but another explanation, a positive feedback is needed to maintain the cusp formation (Dodd et al, 2008).

The self organization model of the flow is represented as discrete volumes with associated velocity and sediment carrying capacity and water particle motion is described by using the ballistic theory on a slope where the sediment transport flux is a cubic relationship with the local particle theory where particles of water deposit sediment while it is decelerating (Werner and Fink 1993; Coco et al., 2000; Coco et al., 2003). The individual changes in local cellular beach level are smoothed eventually and are distributed without water and the smoothing principle comes into effect, minimizing the local variation to a plane (Co co et al., 2000).

Up until this point the field evidence is not consistent, where Masselink et al (2004) found that there is no evidence for the existence of edge waves in a cusp field and

Ciriano et al. (2005) recorded edge wave activity. Neither of these methods has been proven without a doubt (Dodd et al., 2008). Many of the previously published studies on beach cusp formation has focused on modeling. With the use of the CBL it may be possible to add high resolution and short temporal data set to aforementioned theories.

After analyzing the CBL data, using the same methods as the Bluff on Lovells Island, it is clear this method requires additional work. Some undulations can be identified in the ArcGIS image (Figure 3.2) yet usable information has not been extracted from the data. The scans of the bluff were taken perpendicular to the coastline looking up beach. Scans of these features may need to be taken looking down on the features.

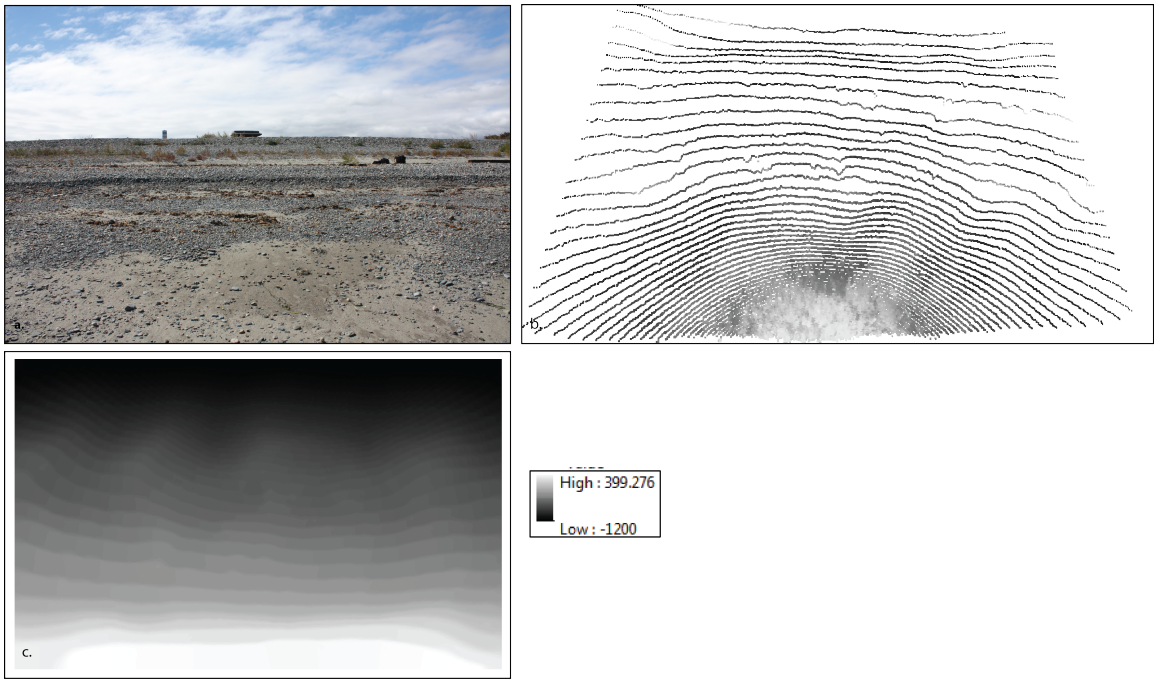

Figure 3.2. Beach cusp analysis. This figure shows the digital photograph (a.), raw pointcloud data (b.) and GIS interpolation analysis (c.) of the beach cusps on Lovells Island.

III.IV. Future Work

Although initial results are encouraging, in order to analyze the motion of the Beach Cusps in response to tidal events and storm events further scans must be collected. Multiple trips out to Lovells Island should be conducted to collect scans and a method for the analysis of the beach cusps using the CBL data needs to be developed. The thinking at present is to identify the high points going up the beach to identify the trough of the cusps. If this is possible the new scan can be analyzed in the same way and whether the trough moved or not can be determined. The limitation related to this method is that if the cusps moved by a wavelength or two then change will most likely not be observed. It may also be valuable to take images of the scans facing down on the beach.

CHAPTER IV

CONCLUSION

A feasibility study for the analysis of coastal geographic features was conducted using the Canopy Biomass LiDAR, a Ground-Based LiDAR system created at the University of Massachusetts Boston, in cooperation with the Rochester Institute of Technology. A bluff on Lovells Island in Boston Harbor was examined using the CBL on three separate occasions and beach cusps on the opposite side of the island were also examined. Through the use of pointcloud and spatial data analysis tools, meshlab, matlab and ArcGIS, a volume change analysis was successfully performed on the bluff data. The CBL was determined to be an extremely useful tool for the analysis, visualization and rapid assessment of coastal erosion on high angle coastal features.

A sensitivity test was conducted in order to justify the methods used for the bluff analysis. Interesting results came out of the sensitivity test. The sensitivity test involved creation and analysis of a fake bluff, with triangular cylinders, and subsequent reduction of the triangular cylinders. Once the data was extracted and analyzed it was found that

there is an error associated with the CBL. The calculated value of the volume change was not close to the manually calculated value. This is most likely due to the fact that our fake bluff was too small for this type of analysis, given the error of 50mm. The error may either be 50mm in one direction or 25mm in either direction, still to be determined. In either case the error was found to be consistent with range, meaning that the distance of the CBL from the feature of interest does not change the amount of error. Although the test did not exactly work as expected it did reveal important information regarding the error and the data analysis. It is important, with this new knowledge, to perform a detailed sensitivity test over using various sizes and shapes to fully describe the error and incorporate it into the analysis. A sensitivity test with multiple changes is suggested in order to determine the scale of change that can be analyzed. In this manner the minimum size of the features being analyzed can be determined to avoid future issues.

A second feature was analyzed on Lovells Island, the beach cusps on the NW facing beach. Beach cusps are undulations found along a beach that is characterized by a repeating pattern. These beach cusps are lower angle features, in comparison to the bluff, and it was not initially clear whether usable data of the cusps could be captured using the CBL. After a preliminary visual assessment of the raw pointcloud data and subsequent interpolation the beach cusps seem to have been captured. Further analysis must be cucondted on this data. In order to determine the evolution of the beach cusps along the beach it is necessary to take repeat scans and to determine an appropriate analysis methodology.

Through the different analysis conducted for this research it has been determined that GB-LiDAR, in particular the Canopy Biomass LiDAR, is a useful tool for the analysis of coastal geologic features. An erosion study was successfully conducted on the eroding bluff on Lovells island and beach cusps were successfully scanned and captured. Though there are limitations associated with this method, including the necessity for high angle features for appropriate resolution and the need for a control monument, it is a useful tool for conducting rapid assessment of the coast and for the identification of hotspots.

With global climate change, in addition to studying variation in weather patterns and sea level, it is important to develop hazard zones (Bellomo, Pajak, and Sparks, 1999; SDouglas, Crowell, and Leatherman, 1999) to formulate policies and regulate the development at the coast (National Research Council, 1990). The use of a ground based LiDAR system such as the CBL and the methodology we employed it is possible to monitor the coast and the effects of sea level rise through erosion and land form analysis. The use of a CBL like system can aid scientists and policy makers in understanding the effects of climate change on the coast and make informed decisions.

In order for coastal managers to make informed decisions and implement sustainable management scheme for environmental protection and conservation, accurate and timely information is required (Ricketts, 1992). Coastal managers must rely on science in order to plan and develop solutions to coastal problems (Van Koninsgveld et al., 2005). Erosion trend analysis is important in order to perform successful shoreline

protection (Finkl, 2002). Using technology such as the CBL, coastal managers can conduct surveys on an area fairly rapidly, identify erosion hotspots and calculate erosion rates. With this information managers can plan an appropriate response which will benefit the local environment and community. Other methods, including photography, digital video capture and satellite imagery have also been used by coastal managers to monitor shoreline dynamics and change and make informed management decisions. The CBL will provide managers with an effective and relatively inexpensive tool for analyzing short term changes occurring on and along the coastline to help in the development and implementation of policy.

The Canopy Biomass LiDAR is currently being used on a variety of projects at the University of Massachusetts, Boston. In addition to this study of coastal features and erosion, the CBL is being utilized in forestry, biomass and bioenergy calculation, satellite imagery validation, mangrove biomass studies and in salt marshes boundary identification and classification. Because the CBL can be deployed almost anywhere, for it is easy to transport, and the time between scans using the CBL is fast there are diverse potential scientific applications. In Boston Harbor specifically, the CBL can be deployed to conduct an assessment of damage incurred to the islands and the coastline due to various seasonal anthropogenic recreational activities and environmental changes, namely boating, camping on the islands, seasonal tides and storm effects during the fall and winter. Ideally the CBL could be deployed directly before and after a predicted tropical storm or winter nor'easter in order to perform a rapid assessment of damaged

incurred and help scientists and coastal managers understand storm effects on the coast determine the appropriate clean up tactics and mitigation work. There is a thought that the CBL could be mounted on a commercially available drone to conduct low altitude scans of geologic features. This type of data will provide us with data density which is between a ground based survey and airborne survey. This data will give a highly accurate view of an area, larger than that which could captured on the ground at a much lower cost than an airborne survey. There may also be some use of the CBL that is nether science or management based. The CBL was built based on a ground-based LiDAR used for customs purposes where a crate would be scanned before and after delivery to ensure the contents of the crate had not changed. The CBL can be used to identify structural damage to buildings by scanning specific areas of a building over a certain time period and assessing damage and rate of change. Terrestrial laser scanning, or ground-based LiDAR, has been used by archaeologists in order to obtain three dimensional models for survey sites for the digital documentation of both sites and artifacts (Lerma et. al., 2009). The CBL should be able to be used in this archaeological capacity as well, producing high resolution images of sites and artifacts.

There are certain cases where information is required on a much larger scale, for example a study of the coastline which extends to tens to hundreds of Kilometers. In those cases, technology such as the airborne LiDAR will allow for estimations of elevation over those tens to hundreds of kilometers and provide the data necessary that a ground-based LiDAR system cannot provide. However, ground-based LiDAR can

provide specific detail on a small scale which can be coupled with the airborne data. The resolution of the CBL is higher than that of an airborne LiDAR, even with the error associated with the CBL, which is lower than the error normally associated with airborne data.

The CBL is preferable to many other methods of coastal analysis employed to study coastal erosion and change for its ease of use, ability to collect a large amount of data, in a short amount of time, and relative low cost (Perroy et al., 2010). A system such as the CBL has many applications both in science and management. As discussed the CBL is currently being used in many scientific projects and has applications which can specifically be utilized for coastal management. With predicted sea level rise and an ever-changing climate, it is important to be able to conduct relatively inexpensive rapid assessment of our coastline. As more than half of the population of the US lives along the coast the potential uses of this technology for storm mitigation, coastline protection and other coastline analyses are innumerable.

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