MONITORING CHANGE: APPLICATION OF A TERRESTRIAL LASER SCANNER IN A CALIFORNIA ESTUARY

A thesis submitted to the faculty of
San Francisco State University
In partial fulfillment of
The Requirements for
The degree

Master of Science
In
Marine Science

by

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August 2009

MONITORING CHANGE: APPLICATION OF A TERRESTRIAL LASER SCANNER IN A CALIFORNIA ESTUARY

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2009

I present a novel investigation on geomorphologic variability in response to changing hydrologic conditions over various temporal scales in the wetlands of Elkhorn Slough, California. For the first time, serial, high-resolution (<5 cm) surveys of the marsh and mudbank environments of this rapidly degrading estuary have been obtained using a state-of-the-art terrestrial laser scanner (TLS). New techniques were developed to collect, post-process, and analyze the geospatial data. Factors that can lead to errors in TLS data measurements and to potential misinterpretations of surface variability were identified. Long-term monitoring, spanning 15 months at four key sites, revealed a 30% increase in the widths of mudflat creeks and localized episodes of failure and slope retreat at the pickleweed edges. Additionally, small-scale erosive events were identified along the edges of tidal creeks during a major spring tidal cycle and as a consequence of increased tidal flow caused by the opening of a culvert.

ACKNOWLEDGMENTS

I wish to thank several people and organizations who contributed to this study. Financial support was provided by the David and Lucile Packard Foundation and the Elkhorn Slough Foundation. I am especially grateful to my advisor, Ivano Aiello, for his breadth of knowledge and his ability to incorporate many different concepts of geomorphology and laser scanning into a rewarding and meaningful project. I am also indebted to the assistance and valuable comments I received from my other committee members, Ellen Hines and John Oliver.

I would like to express my sincere gratitude to Dr. H. Gary Greene who has employed me at the Center for Habitat Studies since first arriving at Moss Landing Marine Labs several years ago. His encouragement and support during all my endeavors has provided me with a rich background of experience and skills.

At Elkhorn Slough Foundation, Bryan Largay deserves special thanks for his assistance in providing me access to the railway culvert at North Azavedo Pond while Eric Van Dyke was extremely helpful in establishing finely tuned benchmarks that were useful in determining survey locations.

I am also grateful to the numerous faculty, staff, and fellow students at Moss Landing Marine Labs that contributed to the success of this project.

And finally, I wish to thank my family and wife, Ann, for their patience, love, and support throughout this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

Appendix Page

Table of Contents

INTRODUCTION

Remote Sensing:

Since their development several decades ago, remote sensing techniques have become an essential way to detect and monitor environmental change. Remote sensing is particularly ideal for monitoring wetland environments due to the non-invasive techniques and the collection of high resolution data in areas that may be inaccessible or sensitive to disturbance (Shuman and Ambrose, 2003; Tuxen et al., 2008). LiDAR (light detection and ranging) has proven to be one effective method that combines highly accurate data acquisition over broad spatial scales. Developed in the 1960's, LiDAR instruments, which use infrared laser light as opposed to sound or radio waves used by sonar or radar instruments, are used to measure distance with extreme precision. The instrument sends a pulse of light that travels to a target, which then bounces off the target and returns to the instrument's detector. The two-way travel time of the light pulse is then divided in half and multiplied by the speed of light to calculate a "Z" distance from the instrument. "X" and "Y" positions of the target are calculated relative to the position of the instrument which, in turn, is determined using known benchmarks in the field and/or highly precise portable GPS units. Oftentimes, the scanner location may be further rectified using post-processing information of GPS satellite data. The precision of LiDAR instruments has increased from several meters to a few centimeters since their initial application in the early 1960's (Bellian et al., 2005).

Although airborne LiDAR has proven to be an effective method for rapid, high resolution (0.5 – 1 m) data collection over broad spatial scales, it suffers from limited accuracy, resolution, and data collection feasibility (high cost). On the other hand, terrestrial LiDAR, also known as terrestrial laser scanning (TLS), offers much higher data resolution (<0.01 m), accuracy, and repeated survey feasibility, but over much smaller spatial scales (Heritage and Hetherington, 2007)(Figure 1). Moreover, the primary advantage of TLS, in lieu of tape measures, theodolites, and walkie-talkies once required for accurate field measurements, is its ability to collect thousands, or even millions, of high resolution topographic data points (also known as a "point cloud") in a matter of hours. Thus, attempting to measure micro-topographic variability in an estuarine environment, through repeated measurements of the same surface, is best achieved using a TLS instrument such as the Trimble VX Spatial Station, the instrument used in this study (Figure 2).

Previous studies incorporating Terrestrial Laser Scanning (TLS):

Initial studies that incorporated terrestrial LiDAR measurements primarily focused on the urban environment where highly detailed three-dimensional representations of building facades could be captured (Yamada et al., 2003). More recently, terrestrial LiDAR equipment has been applied to the natural environment. Bitelli et al. (2004) conducted repeated slope surveys on a small landslide body located on the Northern Appennines in Italy, and reported on landslide dynamics. Nagihara et al. (2004) used three-dimensional laser scanning technology to obtain high resolution topographic surveys of barchan dunes in the White Sands National Monument, New Mexico. They succeeded in mapping the dune morphology with a spatial resolution that could enable mathematical models of dune evolution. Additionally, Hetherington et al. (2005) quantified barform change across a glacial outwash plain. Bellian et al. (2005) showed how the centimeter resolution of LiDAR scanning, together with directly sampled data, may be used to construct 3D Digital Outcrop Models (DOM's), thereby aiding geologic interpretations of stratigraphic correlations and fault planes. Heritage and Hetherington (2007) report on the detailed accuracy and precision of a laser scan survey of a rugose riverbed, while also assessing the limitations of the instrument due to terrain character. Milan et al. (2007) used a 3-D laser scanner to obtain repeated scans of a proglacial river plain in Switzerland. By comparing digital elevation models (DEM's) over a ten-day period, they identified short depositional and erosional episodes and changes in channel morphology.

Study Objectives

Clearly, TLS has proven to be an effective method for assessing geomorphologic characteristics in various natural environments, yet no studies have discussed its use in an estuarine environment where local tidal cycles can produce micro-topographical variability on a daily basis. The goals of this study, then, are three-fold: to establish a methodology (i.e. field operation, post-processing, and data analysis techniques) for a high resolution TLS survey in a tidal wetland; to investigate potential sources of measurement error with respect to infrared laser beam divergence, angle of incidence, surface properties, and reflectivity; and to investigate the TLS results of case studies that attempt to calculate fine-scale geomorphologic variability in different wetland environments over short and long time-spans (e.g. relative to tidal cycles, seasonal conditions, and immediate anthropogenic modifications). I will discuss these objectives in greater detail following an introduction of the study site in Elkhorn Slough, CA as well as a brief summary of past attempts to monitor variability in Elkhorn Slough over large temporal and spatial scales.

Estuaries and Study Site

Estuaries, unlike other coastal environments, are geologically ephemeral shallow-water systems extremely sensitive to climate and sea level change and to anthropogenic modifications. They act as sinks for sediments from both marine and fluvial sources, and contain sedimentary facies influenced by tide, wave and fluvial processes. Estuaries are rare, and thus extremely important, along the geologically active west coast of the US, making up only a fraction of the coastline. Historically, wetlands along California's coast were once much more abundant than they are today; 91% have been lost due to residential, commercial, and agricultural development (Larson, 2001; Van Dyke and Wasson, 2005). Today, the wetlands that do remain are often threatened by increased degradation and erosion by other anthropogenic modifications and/or marsh plain subsidence (Patrick and DeLaune, 1990; Lowe, 1999; Van Dyke and Wasson, 2005).

Elkhorn Slough is a shallow tidal embayment that winds 11.4 kilometers inland from its mouth on the eastern-most point of Monterey Bay on the central coast of

California (Figure 3). A tide-dominated estuarine embayment flanked by intertidal mudbanks, tidal flats and salt marshes, Elkhorn Slough (ES) contains a rich variety of intertidal and subtidal ecosystems and ecological niches. The existence of these ecosystems is extremely sensitive to the interactions between hydrodynamics and physical processes. During the last century, ES has been strongly affected by increased agricultural activity and by modifications of the coastline. Anthropogenic modifications, both direct and indirect, have significantly altered the hydrodynamics and the geology of the estuary, contributed to the ongoing erosion problem, and, ultimately, affected the ecosystems. Preventing future, and possibly irreversible, modifications, and restoring key ecologic areas is now a priority for ES as well as for other endangered estuarine systems in California and elsewhere (ESTWP, 2007). Within this context, researchers have recently begun collecting a variety of historical datasets documenting geomorphologic changes within ES over the past one hundred years. Unfortunately their findings, although notable, are incapable of detecting small-scale, rapid changes to specific environments within ES.

Elkhorn Slough Geologic and Historical Setting

Following the Last Glacial Maximum (LGM) approximately 18,000 yrs ago, rising sea levels inundated the coastal river valleys in the Monterey Bay, converting Elkhorn Valley into a tidal embayment by 10,000 years B.P. (Van Dyke and Wasson, 2005; Masters and Aiello, 2007) (Figure 4). Elkhorn Slough continued to evolve, via marine transgression, from a system with a high energy tidal inlet around 8000 years B.P.

to a considerably larger than present-day estuary 4500 years B.P., and finally to a quiet water, depositional estuary since 2000 yr B.P (Schwartz et al., 1986; Masters and Aiello, 2007). Core samples indicate that *Salicornia* salt marshes in ES were approximately half their present day size approximately 4500 years B.P., with broad intertidal mudbanks lining the margins of the Slough's main channel. Since then, salt marsh habitat has extended more than 50 m toward the axis of ES burying older mudbanks (Schwartz et al., 1986). Beginning in the mid-1800's, however, major anthropogenic modifications to the estuary resulted in large losses of salt marsh habitat that continue to this day. The first major development to have a significant impact on the ES landscape was a substantial diking project in 1872 for the creation of an embankment to carry the Southern Pacific Railroad directly through the eastern portion of the Slough wetlands. All marshes to the south and east of the railway embankment were separated from the main channel, thereby severely decreasing tidal flow to these areas which were subsequently used as pastureland (Wassen et al., 2001). Later in 1909, the Salinas River mouth was relocated from its historical location, 1.5 km north of Moss Landing, to its present position, approximately 8 km south of Moss Landing (Gordon, 1996; Schwartz, 1986). Thus, Elkhorn Slough, once a tributary to the Salinas River, was shut off from a major fluvial sediment source that once contributed significant amounts of material with each incoming tide (Gordon, 1996; Van Dyke and Wasson, 2005). The most significant modern alteration to ES occurred in 1946 when the Army Corps of Engineers constructed jetties directly west of the Slough's main channel, breached the shoreline dunes, and dredged a wide, deep channel to permit boat access to the newly created Moss Landing Harbor (Gordon, 1996; Schwartz, 1986; Van Dyke and Wasson, 2005). At once, tidal volumes entered Elkhorn Slough's main channel at unprecedented levels, resulting in tidal erosion of the main channel, undercutting of tidal creek banks, and loss of salt marsh that has continued to the present day.

Recent Changes in Elkhorn Slough

One of the more alarming and readily apparent changes to ES since the 1946 jetty construction is the sharp decline in the percent cover of *Salicornia virginica* (pickleweed), a salt-tolerant plant species that makes up the majority of the Slough's intertidal salt marsh habitat (Lowe, 1999; Van Dyke and Wasson, 2005). By comparing several sets of historical aerial photographs from 1931 to 1997, Lowe (1999) documents the largest declines in pickleweed habitat to have occurred in the decade following the opening of the harbor mouth when tidal range and volume suddenly increased, and another decline in the late 1980's and early 90's following the Loma Prieta earthquake. The more recent decline appears to be due to subsidence of the marsh plain, potentially a result of the Loma Prieta earthquake in 1989 (Lowe, 1999). Van Dyke and Wasson (2005), however, argue that marsh loss in this area began decades before the earthquake, resulting in a 43% decrease in salt marsh vegetation within five regions of Elkhorn Slough's undiked marshlands in the period 1931-2003. The authors recognize greater tidal velocities and amplitude, and extended periods of marsh inundation resulting from the 1947 harbor opening as the principal causes of marsh degradation. Additionally, they found that mean tidal creek width increased nearly 500% over the same time period, likely creating a positive feedback loop by further enlarging the tidal prism and by extending the reach of tidal flow to more areas of the marsh. Other factors have also likely contributed to a 12 cm average decrease in marsh plain elevation since the opening of Moss Landing Harbor, as measured by Crampton in 1994. Tidal scour of surface sediments, groundwater overdraft in the surrounding region, and lack of sediment accumulation due to restricted tidal flow (i.e. areas south and east of the railway levee) have likely contributed to marsh degradation over the past several decades (Lowe, 1999; Van Dyke and Wasson, 2005).

By closely examining historic maps and photographs, Van Dyke and Wasson (2005) note that thinning of salt marsh vegetation appears to progress from the interior of the marsh, initiating the formation of mud pannes (also known as salt pannes) and eventually extensive mud flats. Immature mud pannes are identified as small mud-flat areas devoid of vegetation and slightly depressed in elevation relative to the surrounding *Salicornia* habitat. Over time, the edges of the mud panne may expand as pickleweed plants located along the fringes of the panne die back and mud, now lacking the support of pickleweed roots, collapses towards the center. This progression leads to larger mature mud pannes, which may eventually coalesce into mud-flat regions. Although the mechanisms by which mud panne initiation begins are poorly understood, several studies attribute the cause of marsh degradation and mud panne development to a relative lowering of the marsh plain and an accompanying increase in the frequency and duration of inundation (Phillips, 1986; DeLaune et al., 1994; Hartig et al., 2002, Van Dyke and Wasson, 2005). Lowe (1999) conducted pickleweed transplant experiments in ES and discovered that most plants transplanted into areas 11 cm below mean high water (MHW) died within 9 months after harvest, while those in higher elevations survived. Her elevation surveys also suggest that pickleweed may have difficulty growing as little as 6 cm below MHW, suggesting that even moderate marsh plain subsidence can have significant impacts on the growth and survival of *Salicornia virginica*.

Previous methods of detecting change in ES and other estuaries

Beginning in the 1980's, researchers have used a combination of direct measurements in the field, as well as remote sensing to detect modern geomorphologic and hydrographic change to Elkhorn Slough wetlands. The following paragraphs summarize these attempts according to the targeted environment within the ES watershed.

Channel Banks: Malzone (1999) established 57 stations of PVC pipe adjacent to channel banks in ES in order to detect erosion rates between April 1994 to April 1996. The markers used by Malzone were abandoned in the late 1990's but were re-established in 2000 through a cooperative effort between the Monterey Bay National Marine Sanctuary (MBNMS), the Elkhorn Slough National Estuarine Research Reserve (ESNERR), and a SJSU graduate researcher. From the first year of data, erosion rates were averaging 40 cm/yr, with a maximum of 2 m/yr at some sites. As of 2001, monitoring erosion at these markers was expected to continue on an annual basis (Wasson et al., 2001).

Tidal Creeks: Aerial photographs of ES, taken in 1980, 1988, and 1992 were calibrated using known reference points and analyzed at 19 locations by Malzone (1999) to determine relative changes in the widths of the main channel and adjacent tidal creeks. In the 1980's, Oliver et al. (1988) estimated a 70% average increase in tidal creek width 40 years after the opening of the harbor mouth. Recently, Van Dyke and Wasson (2005) digitized, georectified, and interpreted 26 historic maps and charts dating from 1853 to 1925, and 13 aerial photograph flights (comprised of more than 300 individual photos) taken between 1931 and 2003. Analysis of historic photographs using an ArcView GIS script was used to quantify changes to tidal creek widths. Their results support Oliver et al.'s findings of tidal creek widening, whereby mean cross section width of tidal creeks in undiked areas increased from 2.5 m to 12.4 m (Figure 5a).

Salt Marsh: Oliver et al. (1988) examined the change in percent cover of marsh vegetation in ten areas of the ES using aerial photos from 1931, 1980, and 1987. Eight of these areas consistently decreased in vegetation coverage, averaging 23% between 1931 and 1980, and 8% between 1980 and 1987. P. Lowe (1999) conducted a similar study using aerial photos and found a significant decline in pickleweed cover between 1949 and 1956, following the opening of Moss Landing Harbor, and another significant decline between 1989 and 1993, the period just after the Loma Prieta earthquake. Many researchers agree that subsidence of the marsh plain is the leading cause for interior marsh thinning and pickleweed dieback (Wasson et al., 2001; Crampton, 1994; Lowe, 1999). Crampton's (1994) work shows marsh plain elevation having decreased by an average of 12 cm since the opening of the harbor. Additionally, Lowe (1999) conducted pickleweed transplant experiments and discovered that most plants transplanted into areas 11 cm below MHW died within 9 months after harvest, while those in higher elevations survived. Her elevation surveys also suggest that pickleweed may have difficulty growing as little as 6 cm below MHW, suggesting that even moderate marsh plain subsidence can have significant impacts on the growth and survival of *Salicornia virginica*.

Van Dyke and Wasson (2005) quantified changes in vegetated marsh cover using a custom ArcView Spatial Analyst application that performs semi-automated image interpretation. Their results show mean percentage of salt marsh vegetation in five regions distributed throughout ES decreased from 89.6% in 1931 to 46.4% in 2003 (Figure 5b).

Aerial LiDAR has recently been used to measure elevations within the Elkhorn Slough watershed. A high resolution (1 m) DEM (digital elevation model) was acquired by the Seafloor Mapping Lab at CSUMB in 2005 and serves as an excellent baseline dataset with which to compare future changes to ES's terrestrial morphology. Moreover the current dataset can be used to assess marsh plain elevations throughout Elkhorn Slough.

RESEARCH OBJECTIVES

Objective #1: Establishing a methodology for a high resolution TLS survey in a tidal wetland: field operation, post-processing, and data analysis techniques.

To the author's knowledge, the use of a TLS to monitor erosional and depositional processes in a coastal wetland has not yet been attempted. As such, this will be the first study to address the need for highly efficient, economical, and detailed analyses of geomorphologic change occurring over very short time spans (days to months) to even longer time-series (years). Since the Trimble VX Spatial Station is a relatively new tool in the realm of remote sensing for the purpose of geomorphologic investigations, I set out to develop a consistent and efficient field methodology for its use in a wetland environment. General set-up and field operation techniques are employed and modified to address specific environmental conditions and research objectives. Moreover, data post-processing and analysis techniques are developed and tested to ensure an effective means by which to identify and interpret geomorphologic change in a highly dynamic wetland setting. Containing a suite of environments that includes mudflats, intertidal salt-marsh, tidal creeks, and mud pannes, Elkhorn Slough serves as an excellent location for developing a TLS methodology that can be applied to measuring geomorphologic variability in other estuaries in the future.

Objective #2: Investigate potential sources of measurement error with respect to beam divergence, angle of incidence, surface properties, and reflectivity.

The ability of TLS to measure fine-scale features in the natural environment inherently requires a thorough investigation into the potential sources of error associated with the instrument. The use of TLS has become increasingly widespread in the past several years due to technological improvements in hardware and major advances in software applications that can handle large 3D datasets. Yet, as Buckley et al. (2008) states in their recent paper, "the techniques are far from 'standardized'" despite all the advances that have been made. The authors focus on describing the workflow involved in a typical TLS survey and provide specific details on the processes required for a successful survey for solving geologic problems. Especially valuable is their discussion of the quality and accuracy of collected data and the potential for errors to propagate through the workflow. Below I attempt to summarize some of their findings with respect to TLS accuracy while also introducing the relationship between beam divergence, angle of incidence, reflectivity, and surface properties, and their effects on spatial resolution and data accuracy.

The Trimble VX Spatial Station is considered a hybrid instrument; a cross between a spatial station and a terrestrial laser scanner. Spatial stations are primarily used for collecting site specific single point x, y, and z information. Terrestrial laser scanners, on the other hand, are capable of collecting several million point measurements (known as a "point cloud") over a non-specific area within a very short time frame. Both utilize the time-of-flight principle, described above, whereby the return time of an emitted laser pulse is measured and converted into a range value (Buckley et al., 2008; Bellian et al., 2005). Horizontal and vertical angles are simultaneously recorded, and, together with the range measurement, provide a calculation of 3D coordinates (x, y, and z). The frequency at which laser scanners emit a laser pulse will determine their range and beam width; longer range instruments use a higher frequency but have greater beam divergence, while lower powered lasers have a limited range, but a less divergent beam (the Trimble VX laser uses a near-infrared beam frequency of 870 nm, placing it in the class of a long-range TLS) (Buckley et al., 2008). Laser beam divergence is constant over distance and essentially determines the beam footprint size. A smaller beam footprint provides higher point accuracy and spatial resolution since more points can be collected closer together without overlapping one another (Buckley et al., 2008; Lichti and Jamtsho, 2006). Footprint size, then, can be used to determine the spatial resolution of a survey at a particular distance and incidence angle (the relative angle between the laser pulse and the target surface). Tables 1 and 2 show the calculated areas and diameters of beam footprint size on a target surface at different distances and incidence angles for the Trimble VX Spatial Station. The values were calculated based on factory technical specifications of a beam divergence of 8 cm vertical and 4 cm horizontal at 100 m. Note that angles of incidence greater than 60^o can result in large increases in vertical beam diameter, an important consideration when surveying broad flat areas such as tidal mudflats. Increases in beam diameter result in lower accuracy not only due to the increased area over which measurements are averaged, but also due to lower reflectivity, as discussed below.

Another consideration when assessing the accuracy of TLS data is the reflectivity acquisition. Reflectivity refers to the intensity of the beam's backscattered signal power. Backscattering decreases when the angle between the laser beam and the normal to the observed surface increases. With higher angles, backscattering is low, fewer points are acquired, and the accuracy decreases (Pesci and Teza, 2008). The backscattered signal power is a function of the physical properties of the reflected material, incidence angle, and distance to the target (Pesci and Teza, 2008; Buckley et al., 2008). Physical property conditions that include high moisture content, low surface complexity, and dark (absorbent) coloration result in lower backscattered signal power. Other sources of backscattered signal attenuation can be a result of atmospheric conditions, such as humidity which disperses the laser light and reduces the maximum range (Buckley et., 2008). Similarly, evapotranspiration over wetland areas or water bodies can further reduce reflectivity levels. And, on numerous occasions over the course of this study, I observed considerable reductions in the speed of data acquisition during periods of low sun-angle, such as shortly before dusk. I attribute this to an increase in background infrared radiation that may interfere with the range of reflectivity returned to the instrument detector. This phenomenon has been neither documented nor verified by the manufacturer, but it could potentially introduce a further source of error during data collection.

During the course of this study, the majority of my surveys targeted environments that can be considered as having low reflectivity. Thus, a key goal of this project was to evaluate the surface conditions of the target area (angle of incidence, physical properties, distance) in an attempt to understand the potential range of error and accuracy in our measurements. Other potential sources of error that arise during TLS survey data acquisition and processing are outlined in Table 3 (Buckley et al., 2008). The authors simply estimate the error budget for each of the items since many of them cannot be directly quantified. Nonetheless, they note that even with very high accuracy input (for example, the Trimble VX factory specifications state a maximum of 3 mm at less than 150 m) there is still potential for large discrepancies and accumulated inaccuracies during workflow to affect the final data interpretations. Many of the items listed in the table are included in the workflow of my own study. As such, however, the errors associated with most of them are generally incalculable but must not be dismissed as insignificant. Those that are calculable, such as errors associated with angle of incidence ("obliquity of laser") and surface properties ("target material"), are quantified and included in the Results Section 2.2.

Objective #3: Investigate the TLS results of case studies that attempt to calculate fine-scale geomorphologic variability in different Slough environments over short and long time-spans.

The Elkhorn Slough Tidal Wetland Project Team (2007) reports bank erosion rates along the main channel of ES to be averaging 0.4 to 0.6 m yr^{-1} in the upper slough and 0.3 m yr^{-1} in the lower slough, with some areas approaching 2.1 m yr^{-1}. Similarly, Van Dyke and Wasson (2005) report uniformly moderate (<0.1 m yr^{-1}) to very high (>0.25 m yr^{-1}) rates of tidal creek widening across the lower and mid slough and predominantly very high in the upper slough. Thus, one of our key goals was to compare the previously determined average rates of widening and bank erosion with directly measured and quantified rates from our study period. Results of my analyses, then, would help to inform our understanding of mudflat evolution, as well as mudbank and pickleweed bank recession in relation to hydrologic processes (i.e. tidal action and rain events).

Although numerous sites were initially chosen throughout ES, in this paper I report on four selected sites (Figure 6). Case studies of these sites include analyses of short-term geomorphologic changes during a major tidal cycle (Sites 2 and 3), anthropogenic effects on tidal creek morphology (Site 4), and long-term monitoring of a mature mud panne (Site 1, heretofore referred to as a “mudflat”) and intertidal mudflat (Site 2). The figures that introduce each site below show examples of wetland environments specifically targeted during data post-processing, which include exposed intertidal mudflats, mudflat creeks, mudbanks, and pickleweed edge that forms the interface between exposed mudflats and the *Salicornia virginica* (pickleweed) marsh plain.

Two easily accessible sites within the Old Salinas River (OSR), west of Moss Landing Marine Labs, were chosen for case study investigations based on the numerous high resolution surveys that I completed here over a time period of more than a year. Site 1 was located at the southern end of the OSR, just north and west of the Potrero Rd. bridge, where an exposed mudflat is surrounded on three sides by a pickleweed edge (Figure 7). The road adjacent to this site offered a good vantage point and unobstructed view of the mudflat. Site 2 was located at the northern end of the channel, just south of Sandholdt Bridge, where an exposed mudflat is situated at the confluence of a bifurcated channel (Figure 8). The bridge also offered a high vantage point and unobstructed view from which to establish a station.

Numerous historic georeferenced aerial images provided evidence of significant change in the OSR. For example, Figures 9a-c show a portion of the OSR having experienced episodes of variability between 1937 and 2008. Clearly apparent from these images is the increase in small tidal creeks that line the western bank of the channel. Meanwhile, marsh accretion occurs in the southern portion of the marsh plain where a major channel nearly disappears. One can also see how the main channel of the OSR becomes less sinuous along its length. Variations in marsh cover in the southern portion of the OSR are also apparent between 1993 and 2008 (Figure 10). A simple GIS analysis and calculation of the exposed mudflat area just north of Potrero Rd. reveals a mudflat increase of 1160 m^2 over a 15 year time period. Although it appears that much of that change occurred between 1993 and 2004, the rate of change (marsh habitat loss) at this site alone is equivalent to 77 m^2 yr^{-1} (20.6 cm edge recession). These rates are comparable with the rates determined by Van Dyke and Wasson (2005). In light of these observations, then, my study areas adjacent to Potrero Rd. and Sandholdt Rd. are well situated to test the ability of TLS to measure geomorphologic change on a much shorter time scale.

A third site established for testing pickleweed mudbank change included a portion of the north bank of the main channel, east of Hwy 1 near the bird observation platform (Figure 11). This site provided a good vantage point from which to monitor potential changes to a mudbank that marked the junction between a tidal creek and the main channel. Considering maximum tidal current velocities having increased from 0.61 to 1.5 m/s since the 1970's in the main channel (ESTWP, 2007) and tidal creek widening is estimated at 14 cm/yrVan Dyke and Wasson, 2005), I chose this location to conduct a high resolution survey completed within 48 hrs during an extreme tidal cycle (Dec. 9-11, 2008). A third survey was also performed approximately 1 month later to test for additional geomorphologic change.

A final site used to test for mudbank and mudflat change included a tidal creek located west of a railroad culvert that connects North Azavedo Pond with a northern section of Elkhorn Slough (Figure 12). This site was selected for two reasons: its location situated near to and high above the tidal creek provided an unobstructed view immediately above the target area; and its location was adjacent to a recent construction project, supported by the Elkhorn Slough Foundation, to restore tidal flow (for water quality purposes) through the culvert that had been blocked by a collapsed levee on the east side. My objective, then, was to survey the tidal creek mudflat and banks on the western end of the culvert before and after construction in an effort to detect geomorphologic change associated with increased tidal velocities. Unlike the other sites, results of comparative surveys at this site would be directly associated with anthropogenic effects.

METHODS

Equipment and Materials

The Trimble VX Spatial Station is a transportable, remotely-operated (via the Trimble TSCII controller) instrument that delivers high precision (0.003 m factory-stated accuracy) surface data measurements. Near-infrared laser reflection intensity (also known as reflectivity), which varies according to target distance, surface angle, moisture content, and sediment properties, is also recorded with each data point measurement. Single data points may be collected up to a distance of 2.5 km (Figure 2) using a reflective prism. Alternatively, direct reflex (DR) scanning of a surface is possible up to 150 m in distance, depending on surface conditions. During data collection, The Trimble VX Spatial Station uses an electromagnetic server robotic mechanism to rotate on a level horizontal axis. See Appendix 1 for more information regarding the technical specifications and limitations of the Trimble VX Spatial Station.

Station setup, field operation, and data collection

Station setup:

The establishment of a base station (foresight) is the first step required for any TLS survey. Since one of my goals was to perform multiple surveys of the same geologic surface and compare it over time, the location of the base station was chosen based on the following characteristics: relatively easy access; a stable site with firm ground that would not change (e.g. subsidence) throughout the course of the study; and a site that would provide an unobstructed and elevated view over the target area to minimize the angle of incidence of the laser pulse. Once a suitable station location was established, the point over which the instrument was positioned was marked with either a steel rod and flag (if over soft ground) or with an indelible marker or paint (if over concrete or other man-made feature). Using a Trimble DGPS Pathfinder and Pro XRH Receiver (with Trimble Pathfinder post-processing software) or a known benchmark, the x and y coordinates of the location were recorded (accurate to less than 0.1 m) and the elevation of the site (z coordinate) was estimated (Table 4). Elevation estimates provided a vertical reference relative to only that particular survey location and no other. Thus, repeatable surveys were possible as long as the original elevation value remained the same. The disadvantage of simply estimating the elevation of a survey site is that it is not possible to directly compare z data values from one survey location to another.

Although a station setup is a well-established procedure based on the techniques detailed in Compton's Manual of Field Geology (1962), minor complications can arise due to the changing environmental conditions of a wetland area. With the exception of the site at the Elkhorn Slough bird observatory, all survey sites were established above the higher high water tidal level. This not only ensures that the tripod will be set on firm ground, but it also minimizes the risk of slight variations in the elevation of the ground surface that may occur in the marsh habitats (a result of repeated wetting and drying). I was unable to establish a station setup in the supratidal zone at the bird observatory site.

The next step in completing a station setup involved surveying a single known reference point, known as a "backsight". The backsight provides the TLS with a horizontal reference framework since an azimuth can now be calculated between the two known points. Similar to the station location, the measured backsight location was always the same point used during multiple surveys (Table 4). Theoretically, then, the measured distance and azimuth between the station foresight and backsight should be the exact same for each survey. Any departure from this distance is due to errors. The backsight point would consist of a permanent feature, such as a steel pole, or would more typically be a highly reflective target or prism that would be erected over the known point. Next, additional control points would be measured which provide extra point locations for registration purposes during post-processing. Once the station setup is complete, data collection would commence.

One complication that may lead to potential errors when performing multiple surveys is the ability to accurately measure the location of the backsight. Of the surveys used for this study, Potrero Rd. was the only survey site where a special reflective prism or target was not used. Accurately identifying and measuring a non-prism target, especially at great distances such as Potrero Rd., can be difficult. I chose a telescope stand (located on the west side of Moss Landing Marine Labs; 447 m from the station) for the backsight. The distance not only made it difficult to repeatably measure a precise location on the stand, but it also twice resulted in no distance measurement at all. Instead, an "angles only" calculation was necessary to complete the station setup. The disadvantage of using this method is that no measured point can be calculated and figured into the error calculations (see Post-processing methods)

Field operation and data collection:

The Trimble VX Spatial Station is equipped with a 2 megapixel camera that produces moderate resolution, georeferenced, landscape images. Still images of the survey area were captured prior to each survey. Each survey differed according to individual survey objectives that took into account the size and scope of each survey, the time allotted due to tidal cycles and/or weather conditions, and the resolution of the desired point cloud. All data points were collected using direct reflex scanning or individual topo points. Direct reflex scanning refers to the process of defining a survey area using the Trimble TSCII Controller, and surveying that area directly with the IR laser pulse. Since each target area is geomorphologically different, each survey would require specific horizontal and vertical sample spacing parameters (i.e. density of data points, also known as resolution). Sample spacing was usually determined in the field according to a number of factors including: obtaining the highest resolution model of the geologic surface; the time available before submergence of the incoming tide; matching a new scan with a previously collected one. The collection of individual control points, on the other hand, was performed using a reflective prism attached to a rod of known length. By using the "autolock" function, the TLS would "lock" onto the prism, thus allowing the surveyor to walk with the rod and take measurements of surface points that would not be directly "seen" by the laser alone, often due to vegetation. For example, the TLS is unable to penetrate the dense stands of pickleweed (*Salicornia virginica*) in order to measure the elevation of the mud surface. We can overcome this obstacle, however, by using the prism rod and autolock function. For the purposes of this study, the autolock function was used only for establishing some of the backsights (Table 4).

Based on my results, direct reflex scanning provides the most efficient method of data collection for most target areas that are generally less than 100 m in distance. With increasing distance, the target's reflective properties must be very high and/or the angle of incidence (relative to normal) must be smaller. I found that data collection speed (an indicator of reflectivity) also varied according to the angle of the sun above the horizon. At or near dusk, during clear evenings, data collection slowed considerably, regardless of the physical properties of the target area or the distance and angle from the station. As the sky began to darken after dusk, data collection speed would resume to normal. This happened on several occasions and could only be attributed to infrared interference with the sun. To date, no Trimble representative has responded to our inquiry in this matter.

The duration of each survey would primarily depend upon the size of the target area chosen and the desired resolution of the point cloud (together which determine the number of points to be collected). Since I was working in a tidal environment and wanted to maximize data collection while mudflats were subaerially exposed, every effort was made to begin data collection at least one half hour prior to low tide. Occasionally, due to poor laser reflectivity, I would need to adjust the target area according to either standing water or incoming tidal water. Data collection slows down considerably in saturated or water-covered areas and can also lead to erroneous (or even an absence of) point measurements (see post-processing: cleaning the data). Otherwise, during normal operation with good reflectivity, the rate of data collection is approximately 5-15 points per second (Appendix 1). Thus, collecting 40,000 points from a target area would take about an hour.

The initial process of defining a target area, prior to data collection, evolved over the course of the study. During early surveys, I would typically define a large target area, a somewhat coarse resolution, and survey as much area as possible before the incoming tide. Eventually, I focused data collection on specific areas of interest (see Objective #3) that would be beneficial for future comparisons.

RESULTS

Objective #1: Post-processing

Cleaning data

Trimble RealWorks Survey Advanced v.6.3.1 was used to manage, organize, edit, and interpret the hundreds of thousands of data points that were collected from each scan location. “Cleaning the data” is one of the first and most important tasks involved in the processing of any geospatial dataset, whereby the user physically removes unwanted data points that affect the quality of the resulting point cloud. Unwanted points may include points that are clearly erroneous measurements and/or points that may represent vegetation. The process of cleaning a point cloud often requires the use of georeferenced photographs taken prior to each survey. Then, from a 2-D station-based perspective, it is possible to use the photograph, with a point cloud overlayed upon it, as a reference for identifying unwanted points, such as those that “hit” vegetation. Occasionally, due to infrared refraction from water surfaces, points may be recorded in locations that appear valid using a 2-D perspective, but can actually be identified as invalid when using a 3-D perspective. Using the “examiner” mode in RealWorks Advanced v6.3 allows the user to tilt and adjust the point cloud in three dimensions, facilitating identification of erroneous points.

A major source of concern, when establishing and conducting a survey, is the presence of standing water and/or incoming tidal water. We have observed, on numerous occasions, how the TLS will record points from such areas. It is very difficult to ascertain whether measurements from submerged regions represent the water surface, or the mud surface beneath the water. Oftentimes, the water depth is less than a few centimeters, but nonetheless significant when attempting to make volume comparisons of a mudflat surface over repeat surveys. At times when water surface measurements are a potential pitfall, surveys were either aborted or strict note-taking was necessary for helping to identify "bad" points during post-processing. To illustrate, Figure 13 is an example of data points collected during an incoming tide where water was washing over the mudflat surface. The arcuate lines are a result of slightly higher elevation values measured while a thin layer of water was covering the mudflat surface. The curvature of the lines traces the track of laser points collected as the station rotates on a level, horizontal axis. As the higher water surface intercepts the laser beam, data gaps are left on the mudflat surface ahead of the laser beam path. Learning to identify such measurements as erroneous data, and subsequently removing them, is paramount to producing a clean dataset for accurate interpretation.

Another method I employed, when post-processing, to help identify such points was the use of a reflective intensity filter. Using the sampling tool in RealWorks v6.3, along with the station-based perspective high resolution photograph, points may be filtered according to their reflective intensity (aka reflectivity). As described earlier, reflectivity is a function of the physical properties of the target surface, the planar orientation of the target surface relative to the path of the laser, and the target distance from the TLS station location. Since there is an inverse relationship between reflectivity and moisture content of the target (i.e. more saturated sediment has less reflectivity) points that appear near water that show low reflectivity values relative to the surrounding points (of equal distance and angle of incidence) were filtered and discarded. This is not to say that all of the filtered points are inaccurate; they simply have a higher probability of containing inaccurate measurements that, using a conservative approach, should not be used in comparison calculations of repeat surveys.

Data analysis

Numerous types of geospatial software exist today that can be used to organize, edit, and analyze complex 3-dimensional datasets. Comparisons can be accomplished using geospatial software, such as RealWorks or ArcGIS. RealWorks provides 3-dimensional viewing, making it a useful program for comparing point clouds of complex surfaces. ArcMap, on the other hand, provides only 2-dimensional viewing, but is very useful in creating gridded "raster" surfaces from point cloud datasets. For mudflat comparisons, I utilized both sets of software. Figure 14 highlights the various functions that are unique, and similar, among the two different software packages. Using RealWorks to make comparisons of datasets, the user defines the plane of reference and spatial resolution. These, in turn, define a spatial grid with each cell of the grid representing the distance from the plane to a surface; a surface can be either a reference or comparison surface represented by a point cloud or Triangular Irregular Network (TIN, also known as "mesh"). In each cell, the result is an average over the zone that falls into the cell (i.e. an average on all the points of the 3D point clouds or an average on the mesh within the defined spatial zone). Using the “twin surface inspection” method in RealWorks, this process is applied twice, once for reference and once for comparison; then the difference of these two values is computed and displayed as a color value in the final inspection map (Trimble representative, pers. communication).

Mudflat comparisons

As previously discussed, point clouds of mudflat surfaces need to be carefully cleaned so as to remove points that may represent the surface of standing water or tidal flood waters. Once this is accomplished for each survey, point clouds can be compared over time to identify geomorphologic changes in relief and area of the mudflat surface. Depending on the size of the mudflat, distance from the TLS station, and/or features of particular interest (i.e. sandbars, mudflat creeks, mudflat surface) a point cloud may be partitioned into different zones of comparison. The point cloud is then compared at the finest resolution possible which is determined by the coarsest resolution of the two comparison point clouds. Since all mudflat areas are generally flat with little relief, I performed point cloud comparisons relative to a horizontal plane (normal to the z-axis) which gives results as elevation differences within an “inspection surface”. The inspection surface was then used to calculate both the volume (m^3) and area (m^2) lost or gained. I also calculated the average thickness (m) of material lost or gained by simply dividing the volume by the comparison area. Calculations were also normalized with respect to the area of comparison since no two scan comparisons cover the exact area. Another way to make comparisons and detect change involved using the RealWorks "sections and shifts" tool. The "sections and shifts" tool displays differences in elevation along evenly spaced profile lines that represent the reference and comparison surfaces. The user defines the orientation of the profile line as either vertical or horizontal to the reference surface. By calculating the total area (difference) between the polylines, we can identify areas that could potentially represent significant change. Additionally, inspection lines, which represent the elevation difference between the reference and comparison surfaces, can be exported as 3d lines and their distance calculated using ESRI® ArcMap™ 9.2. In some circumstances, it was possible to perform a twin surface inspection, represented by volume/area calculations as well as sections and shifts over a broad mudflat area, and then sub-sample the area according to features of particular interest.

Pickleweed edge comparisons, Experiment

During post-processing and analyses of comparative surveys using RealWorks Survey Advanced v.6.3.1, it became apparent that methods used to detect change on the mudflat surface could not be used to detect change along a vertical surface, such as the bank that separates the pickleweed edge from the horizontal mudflat (heretofore referred to as "pickleweed edge" or "edge"). Oftentimes, the pickleweed edge included a significant undercut and overhang that further complicated the data processing. Thus, using the data collected at the Site 1, I experimented with making survey comparisons of the edge using different reference planes, as described below, and compared the results of the respective comparisons. As previously discussed, all point clouds used for comparison were initially inspected for errant points and cleaned.

When choosing a reference plane of comparison, the idea is to choose a plane that not only best fits the cloud of points being compared, but one that also facilitates calculation of surface change along a plane that best represents the most probable direction of change within the targeted natural landscape. For example, we can expect accretion or erosion along a pickleweed edge to mostly occur along a vertical plane parallel to that edge. With the exception of material eroding or depositing at the base of the edge, we are less likely to detect change along a horizontal plane. Of course, a pickleweed edge can be a very complex surface, making it difficult to choose one single plane for all comparisons. Generally, a pickleweed edge is vertical, so one approach involved choosing an imaginary comparison plane parallel to the z-axis (vertical), with an azimuth oriented normal to the station (Figure 15). In this way, points are compared perpendicular to the plane (horizontally), providing a reasonable approach to detecting undercutting of the edge and/or slumping/failure of overhanging mud and vegetation. A second approach involved choosing a vertical plane, but along an orientation that best fit the mean azimuth of the edge (Figure 16). Like the first approach, it compares the distance between points horizontally, but now the distance is oriented normal to the edge. Using this approach, the point clouds need to be first partitioned according to the planar orientation of the edge. A third approach allows the user to define a plane based on a "best-fit" scenario that is determined by the RealWorks software (Figure 17). A fourth comparison approach simply uses a default horizontal plane, similar to that used when making mudflat comparisons (Figure 18). The latter two approaches were initially attempted, but overall resulted in poor results (for vertical edges) and not worthy of further testing. The first two approaches gave the most promising results and were then compared using the methods described below.

To test methods concerning pickleweed edge comparisons, I chose four point clouds for comparison (Port2, Port8, Port9, and Port10; see Table 5 for details of each survey), selecting only those points that covered the area of interest on the western edge of the mudflat (Figure 19). The resolution of each of the point clouds used in the comparison was similar, ranging between 5 and 10 cm. For this exercise it was assumed that the most significant geomorphologic change would have likely occurred between surveys Port2 and Port8 since it represented the longest time series of comparison (nearly 14 months); surveys Port8 through Port10 would likely show the least change since they were completed within 1 month of each other. Thus, I decided to compare Port2 with Port8, Port9 and Port10 for 2 reasons: 1) to confirm that any significant differences observed in the Port2 v Port8 comparison were also identified in the other two comparisons (see Case Study methods); 2) to have multiple sample sites of significant change to test for differences in the two reference plane approaches (i.e. perpendicular to the station, and parallel to the azimuth of the bank edge).

All point cloud partitions were compared using a 5 cm resolution. Prior to each comparison calculation, I would choose the appropriate reference plane that I was testing, either normal to the station's line of sight or parallel to the azimuth of the edge. For each comparison, I used the RealWorks Twin Surface Inspection tool which generates an inspection surface colored by surface change in distance (m). The second tool I used was the Sections and shifts tool in tandem with ESRI® ArcMap™ 9.2 for calculating distances, as described earlier. From the initial results of the survey comparisons, I focused on collecting surface change data from two particular zones within the study area (Figure 20). I chose these areas based on the similar results returned from each survey comparison, and because each area displayed change that was either all positive or all negative, which allowed for easier calculations using ArcMap (ArcMap will only calculate distances as absolute values). In all, six survey comparisons were completed (3 normal to station, 3 parallel to bank) and from those, five subsets of vertical profiles (results from Sections and shifts tool) were sampled from both plane comparisons. For each reference plane, between 15 to 31 samples were averaged, per subset, and compared.

Results of the reference plane experiment reveal a significant difference between the two approaches. Figure 21 shows the mean differences of each comparison subset. All subsets show greater difference measurements (m) when using a reference plane oriented normal to the station as opposed to parallel to the bank. A reference plane oriented 'Normal to station' resulted in 32% to 100% greater offset than a reference plane oriented 'Parallel to bank'. This is not surprising considering that the mean angle between the station and pickleweed edge is approximately 45^{o}, meaning that any difference observed normal to the edge should be 41% lower than differences observed 45^{o} to the edge. Although there are infinite possibilities for how change may occur along any pickleweed edge, we can assume that it will occur along a plane that is oriented perpendicular to the slope of the mudbank immediately in front of the edge. Afterall, this is typically how the leading edge of a mudbank is naturally situated. For instance, as the slope of the mudbank steepens, the leading edge of the bank will begin to recede as material erodes down the face of the slope. Therefore, we must attempt to detect change along this planar orientation so as to avoid an overestimation of potential change.

Objective #2: Angle of Incidence and Beam Divergence

Experimental Approach

I conducted an experiment in an effort to understand the effects of beam divergence on distance measurements recorded by the spatial station. Beam divergence refers to the increase in laser beam width as it travels from a source. The Trimble VX Spatial Station uses an infrared (IR) laser DR 300+ (Pulsed laser diode 870 nm) with an estimated horizontal beam divergence of 4 cm per 100m and a vertical divergence of 8 cm per 100 m, thus defining an ellipse (Appendix 1). The effects of beam divergence are significant when considering the spatial resolution of a point cloud. At greater distances, the “footprint” of the laser beam striking the surface is larger, thereby reducing the cloud resolution by yielding an average value of a larger geological surface. The footprint of a laser beam striking a surface is also proportional to the beam’s angle of incidence. For example, a large angle of incidence will result in a divergent beam striking the surface at different times, while also elongating across the surface in the direction of beam travel, creating an elongated ellipse (different than the ellipse created by the laser itself) (Figure 22). Since time of beam flight equals distance, it is unclear what distance measurement is actually being recorded across the surface ellipse. Although laser beam divergence and angle of incidence are well-represented in the literature, it is also unclear how surface properties (grain size, moisture content, etc.) affect the intensity of the beam returning to the detector. My objective, then, was to understand how the measured distance between the station and a target relates to the location and size of the divergent beam ellipse on the surface of the target sample. By comparing distance measurements with variations in set target distance (25, 50, 75, and 100 m), angles of incidence (0^o, 45^o, 70^o, and 80^o to normal), and target grain size (mud and sand), I may begin to shed some light on the limits and potential error associated with surface measurements.

Field methods:

The following tests were performed on a level field with no obstructions. Target locations at 25, 50, 75, and 100 m from the station were determined using the Trimble real-time kinematics (RTK) display of distance and a surveying rod with a reflective prism (Figure 23a). The following procedures were then performed altogether at each target distance, starting with 25 m. A tripod and survey target prism that enables leveling, rotation, and angular rotation was established at the pre-determined distance location. Effort was made to match target height with station height. The target prism was removed for the purpose of the experiment, leaving only a black metal face with a hole in the center. The center of the hole represented the center point of the fulcrum, about which the entire metal face could pivot. Upon this face was placed a shallow cap filled with sediment, either sand or mud, covering the hole. The surface of the cap, when packed with sediment, perfectly aligned with the horizontal fulcrum (Figure 23b). Thus, a distance measurement from the station to the very center of the target (with sediment cap) would theoretically yield the same measurement regardless of the orientation of the face (angle of incidence). Using a clinometer, four face angles (0^o, 45^o, 70^o, 80^o) were measured and marked. Sediment samples consisted of mud collected from the Moss Landing Harbor North, and the sand was a mixture of medium to coarse-grained sand (water added to allow for packing and retaining shape). Using the Trimble's 30x magnification scope (2.6 m field of view at 100 m), I focused the crosshairs on the center of the hole prior to placing the sediment cap in place. Ten distance measurements ("topo point" measurements) were performed for each face angle and sediment type, totaling 80 measurements altogether for each target distance.

Post-processing:

Using RealWorks v.6.3, all points were carefully examined prior to export as numeric text files. Means, standard deviation, and standard error were calculated for each treatment type and control. Mean distance measurements for face angle (angle of incidence) 0^o at each target distance and grain size were used as the control, or reference measurement (i.e. the measurement taken at the known center of the target). The control means were then subtracted from each of the treatment means (angle of incidence, distance, and grain size) to obtain a Δ Measured Distance (mm).

Experiment Results

Overall results show an increase in Δ Measured Distance (Δ MD) with respect to target distance, sediment type, and angle of incidence. For both sand and mud samples within each target distance, Figure 24 shows significantly greater Δ MD as the angle of incidence increases (i.e. a shorter measured distance than predicted). For both sand and mud among target distances, there is also a strong trend toward greater Δ MD (i.e. the further the target from the station, the more the angle of incidence "effect" becomes relevant, up to 48 mm for mud and 40 mm for sand). With the exception of 45^o and 70^o results at 25 m target distance, Δ MD results for all mud samples are greater than those for sand samples.

To understand the results of this experiment, it may be useful to place them in the context of previous experiments that investigate reflectivity with respect to physical properties and angles of incidence. Kukko et al. (2008) used a terrestrial laser scanner (TLS) to measure reflectance values as a function of angle of incidence and target brightness. Their results show a significant drop in reflectance values with an increase in angle of incidence for all targets except the least brightest. Their results also show a significant decrease in reflectance with decreasing target brightness. Since reflectance is a good indicator of measured distance accuracy, it is important to understand how reflectance plays a role in determining the distance of an angled target. However, our inability to precisely measure reflectance values with the TLS requires the use of the relationship between distance measurements and angles of incidence as a proxy to understanding the accuracy. Using coarse values of measured reflectance from my observations with the Trimble VX spatial station, it became apparent that target distance, physical properties of the substrate (i.e. moisture content and grain size), and beam incidence angle are all significant factors in determining reflectivity. For example, Figure 25 shows a top-down view of measured reflectivity values across a surveyed mudflat at Sandholdt Bridge (Site 2) in Moss Landing. In this example, the station is located approximately 17 m from the points in the upper right of the image. Backscattered reflectivity is highest near the station and decreases with increasing distance and angle of incidence. Lower reflectivity values are also apparent in the drained mudflat creeks where moisture content is higher relative to the surrounding mudflat. By keeping distance and moisture content constant, then, my results reveal how measured distance values change with variations in the incidence angle and grain size of the target. Moreover, we can begin to interpret the role that backscattered reflectivity plays on the accuracy of TLS measurements. The difference in observed distance between the control distance (angle of incidence 0^{o}) and the treatment distance (when measuring the same point with an inclined angle) is likely to be the result of the variation in reflectivity levels recorded across the surface of the target. My interpretation of the measured distance, relative to reflectivity, will be discussed in detail below as it contains important implications for understanding the physical interactions between the laser beam pulse and the surface being measured, and ultimately, the resolution and accuracy of the recorded measurement.

When a divergent beam strikes an inclined target surface it creates an elongated ellipse, one that is even greater than the ellipse produced by the emitting laser diode itself (Appendix 1). We can assume that reflectivity is greatest at the leading edge of the ellipse since it marks the point nearest to the station (laser beam source). Since the Trimble VX laser records the average of a series of measurements from millisecond pulses, it is likely that the recorded average distance of a divergent beam is a function of those pulses that return the highest reflectivity values (i.e. those at the “leading” edge of the ellipse). The difference in results obtained using mud vs. sand at various angles of incidence appear to confirm these assumptions whereby the brighter, more rugose surface of sand contains more grain facets oriented normal to the laser pulse to produce higher reflectivity values. This presumably skews the range of maximum recorded reflectivity values, and hence the distance measurement, across the elongated ellipse and closer to the reference point (Figure 26). The opposite is true of the mud surface which contains fine grained particles with less brightness (more absorbent to light); the maximum reflectivity values are more a function of distance, concentrated closer to the leading edge of the ellipse, and resulting in a distance measurement further away from the reference point (Figure 27).

Similar experiments were performed in a recently published report by Pesci and Teza (2008). They compared distance and angle of incidence measurements on four targets: a white frame, a white plate, a dark flat unit, and a dark irregular unit (comprised of several types of pasta of different sizes and shapes) (Figure 28). Not surprisingly, their results reveal an inverse relationship between incidence angle and reflected backscatter intensity for the white plate and dark flat unit (a white frame was fixed and used as a reference with a well-defined shape and reflectance). Reflected intensity values for the dark irregular unit, however, do not significantly change with an increase in incidence angle (Figure 29). They attribute this to the likelihood of the laser pulse being diffused over an irregular surface that lacks any preferential direction; therefore an equal amount of macroscopic elements are always normal to the incident laser beam. Pesci and Teza's results, then, help to confirm my interpretation of a rugose, multi-faceted surface as containing a broader area over which a laser pulse may be averaged.

Calculating beam divergence:

Δ MD results for target distance and sample type were used to plot best-fit lines and calculated slope for each of the three angles of incidence (Figure 30a-b). For simplicity of calculations, I used the Δ MD slope to calculate one of the legs of an acute triangle whose origin is the target reference. Using Pythagorean's Theorem, the other leg and hypotenuse of the triangle were calculated to obtain the beam radius (b) and the beam footprint radius (c) for each sample, distance, and angle of incidence (Tables 6 - 7). According to the technical specifications for the Trimble VX, our results are far lower than the calculated beam radius and footprint radius at each distance (Table 8). However, as discussed above, our results may more accurately represent the range of surface intensity values that most contribute to the averaged measurements. Then again, it's possible that the targets I used were too small to capture the effects of a very large divergent beam. Although I can't be certain without repeating the experiment with a much larger target, I would argue that it is unlikely for a divergent beam on a mud surface to capture enough reflectivity at locations further away from the leading edge to significantly influence the recorded measurement values. Over a more rugose surface, however, a broader range of reflectivity values may contribute to a more intense backscatter return (especially at higher incidence angles) across the surface of the target, thereby recording an average distance value closer to the center.

Nonetheless, I present the results of this experiment as the minimum value of a range over which the recorded measurement is being averaged; the maximum value is represented by that calculated from the factory technical specifications (Tables 1 - 2).

Summary of results and previous investigations

To summarize my findings and those of previous investigations, Figure 31 illustrates the relationship between the physical parameters of the target area and the accuracy of TLS measurements. This can be a useful guide when assessing the accuracy of TLS data collected at all of the survey locations reported in this study. For example, Table 9 shows the calculated ranges of distance and angles of incidence as well as estimates of maximum beam footprint sizes for different environments at each of the survey locations. Additionally, substrate type (i.e. grain size), moisture content, and backscatter reflectivity levels are recorded. These measures provide a relative quality assessment of accuracy by which we can judge the confidence of geomorphologic interpretations. Most importantly, however, is a quantitative assessment of the offsets measured at backsights and/or other control points when performing repeatable station setups. Offsets were calculated for each survey site and will be discussed in further detail in the Case Study results below.

Objective #3: Case Studies

Sampling strategy: All sites

As previously discussed, I set out to investigate high resolution geomorphologic variability at four different sites in ES that included effects from short-term (e.g. tidal cycles), long-term (e.g. seasonal), and anthropogenic-related events. Dates of data collection varied considerably among each survey site. During the early stages of the project in late 2007 and early 2008, I attempted to collect data from a number of sites in Elkhorn Slough. Due to various factors such as limited accessibility, failure of the site to meet overall research objectives, and poor survey results, I chose to abandon several of the initial sites (Figure 32). Nonetheless, it was necessary to utilize as many low tides as possible for creating a baseline data inventory to which we could compare future surveys. For these reasons, data collection dates at various survey sites in early 2008 did not adhere to any strict schedule. During summer 2008, very few surveys were performed due to the majority of lower low tide events occurring during the late evening or early morning hours (which both restricted accessibility to certain sites or posed a safety-risk at sites that required station setups on or near the road). Beginning in October 2008, data collection became more regular with one or more sites being surveyed during each spring tide cycle. Preliminary analyses of survey results along with extreme tide or weather events also contributed to more frequent surveys, such as at Potrero Rd. in the early part of 2009.

Site #1: Potrero Rd.

Methods

The exposed mudflat north of Potrero Rd. and east of the Old Salinas River Channel was surveyed on ten different occasions (Table 5), totaling 453,000 points. Depending on tidal conditions or specific areas of interest, between 6,000 to 80,000 points were collected per survey. Point cloud comparisons were performed on areas containing the highest density of points, such as the southern mudflat and the western and northern pickleweed edge. All ten surveys included a large portion of the southern mudflat which allowed for a long-term series comparison that spanned nearly 15 months. Point cloud resolution of the first scan performed here (12/10/2007), however, proved too coarse for relative comparisons. Volume and area calculations were performed for the entire mudflat, shallow tidal creeks within the mudflat, and a sandbank region on the eastern portion of the mudflat.

Comparison results, using RealWorks, would often show a high amount of variability within the small mudflat creeks. Some of the variability can be attributed to morphology "shadowing" the edges of the creek that face away from the TLS location. Also known as "blind spots", areas that cannot be directly surveyed can potentially result in an overestimate (or underestimate) of the true elevation. This is especially true when comparative surveys do not have the same resolution (i.e. point spacing), leading to inconsistencies in data interpolation. Other data interpolation techniques, as discussed below, help to fill in data gaps.

Additionally, using ESRI® ArcMap™ 9.2, I performed mudflat creek morphology comparisons between two surveys that spanned the duration of the study period, from December 2007 to March 2009. Point cloud data was first converted to a gridded raster dataset using an inverse distance weighted (IDW) interpolation technique available with the ArcEditor™ Spatial Analyst Toolset. IDW interpolation determines cell values using a set of sample points that are linearly weighted. The weight is a function of inverse distance, whereby points that are further away have less influence on determining the interpolated cell value, and vice versa. With IDW, the user can control the "power," or significance, of known points on the interpolated values based on their distance from the output point. A higher power setting will place more emphasis on the nearest points, while a lower power will provide more influence to surrounding points that are farther away. Additionally, the user can limit the number of input points used for calculating each interpolated point, further altering the characteristics of the interpolated surface. Since IDW is a weighted distance average, a resulting value cannot be greater than the highest or less than the lowest input value. This means that the IDW technique will not create ridges or valleys if such extreme values have not already been sampled (Watson and Philip, 1985). For the IDW interpolation I performed on both datasets, I specified a power of 2 with 12 input points. These were the ESRI-defined default settings for the IDW technique and appeared to produce adequate results with respect to the surface observed in the photographs. The resulting raster datasets were then clipped to equal extents and used to create sun-illuminated ("hillshaded") digital elevation models (DEM's) for visual display and reference. Also, I used Neighborhood Statistics (3 x 3 cell neighborhood) to calculate rasters of standard deviation (SD) values (Figure 33). A grid of SD values can be helpful in determining elevation variability over a surface, and especially useful in identifying patterns, such as along the edges of mudflat creek banks (Figures 34 - 35). For example, SD values decrease at the top edge of the mudflat creek banks where there is less surface variability across the neighboring raster cells (i.e. less slope). Thus, I used the SD raster as a quantitative guide in defining the mudflat creek edges during vectorization (Figure 36). Using ArcEditor™, I created a polygon shapefile, overlaying the mudflat, and manually subdivided the mudflat into polygons of creeks and banks/terraces. I then bisected the creeks (perpendicular to their axis) with manually drawn polylines set approximately 25-40 cm apart to create creek cross-sections (Figures 37 - 38). Polylines were drawn only at locations that included well-defined banks on either edge of the creek (i.e. where there were distinct boundaries between SD values). The same polyline file was used for bisecting the mudflat creeks of both polygon shapefiles drawn from the two different rasters. Lastly, I used a Clip function to erase the portion of each polyline that overlapped the outer edge of the creek bank. The resulting files were two polyline shapefiles, each containing 118 lines that spanned the mudflat creeks at the exact same locations (Figure 39). Distance calculations were then performed on each line segment and individually compared. Methods similar to those above, using the SD raster, were also used to identify thalweg widths (i.e. the width of the creek at the deepest point). Additionally, single thalweg elevation (z) values were extracted from each line segment at locations that intersected a manually drawn thalweg profile (polyline that ran the length of each creek). Contour lines (5 mm intervals), created with Spatial Analyst, were used to draw the thalweg profile. All cross-section and thalweg data were categorized and compared by creek, beginning with Creek A nearest to the pickleweed edge, and ending with Creek E, furthest from the pickleweed vegetation and nearest to the central drainage zone of the mudflat.

The site at Potrero Rd. also provided a good opportunity to measure the rate of change along the interface between healthy pickleweed marsh and degraded mudflat. High resolution surveys were focused on the western and northern edges of the mudflat which were clearly visible from the TLS station (Figure 40). The northern pickleweed edge, shaped as a convex arc seen from above, is located approximately 65-75 m from the TLS station. The study area stretches for approximately 30 m. A deep undercut with a vegetated mud overhang is clearly visible along much of the study area. Horizontal distances of this overhang can be as high as 40 cm. Three high resolution surveys from October 2008 to February 2009 were performed in an attempt to detect small-scale changes along the edge or undercut of the bank. Post-processing and comparison methods included using vertical planes of reference oriented parallel to the edge (see *Pickleweed edge comparisons, Experiment*). Since the pickleweed edge is arc-shaped, this required segmenting the edge into seven different partitions (referred to here as "boxes"), each approximately 4 meters in length (Figure 41). Twin surface inspections (RealWorks), at 4 cm resolution, and volume and area calculations were performed for each of the seven boxes and compared.

Pickleweed edge comparisons were also made at the southwestern edge of the mudflat (refer to Figure 19). The comparison area was approximately 7 m in length by 0.8 m in width and included over 1000 points per comparison (reference + comparison points). Point spacing generally ranged between 5 and 10 cm for all comparative surveys. I compared one of the earliest surveys performed at this location, 12/19/2007, with three surveys recently completed in early 2009. Similar to the methods stated above for the northern bank, all comparisons were made relative to a vertical reference plane oriented parallel to the edge. Since the azimuth of the edge was fairly consistent over its entire length, it was not necessary to partition the edge according to azimuth. Instead, after performing a twin surface inspections (5 cm resolution), I focused on partitioning areas that showed consistent change between the reference survey and each of the three comparative surveys. For example, Figure 42 shows the inspection profile line results from the three comparative surveys as well as the three zones used to partition the results for volume and area calculations. The zones were chosen based on a visual inspection of profile lines that showed fairly consistent results from each of the comparative surveys.

Volume and area calculations for each of the three zones were standardized to correct for minor differences in area coverage. The results were then averaged over all 3 comparative surveys.

Results

Potential errors associated with survey results, excluding those previously mentioned in Section 2 relating to angle of incidence, beam divergence, and surface properties, can be calculated by analyzing the residuals of control points (offset from the mean) used to set up each survey. With the exception of the surveys performed at Potrero Rd, backsight residuals are most commonly used. However, since the distance to the backsight at Potrero Rd. far exceeded the distance of the target area, I chose to analyze the residuals of a local control point ("Potrero rail") to assess potential errors. Figure 43 shows that most of the residuals are within 6 mm (easting and northing) of the mean and two (Port3 and Port5) are within 14 mm. Thus, the higher residuals from surveys Port3 and Port5 prevent me from confidently interpreting very small differences (<14 mm) when comparing these surveys with any of the others at this site. Appendix 2 contains a table of all control point locations and residuals used during this study.

Successive survey comparisons at the Potrero mudflat show a gradual volumetric increase from December 2007 to June 2008, with approximately 1.88 cubic meters of accretion (normalized over an area of 520 m^2) (Figure 44). Accretion continued at an even faster pace between June and October 2008 with an additional 5.91 m^3, followed by another 0.19 m^3 by mid-November. Volume calculations then decline 1.82 m^3 by Jan 07

2009, followed by an increase of 2.32 m^3 over the next month. From Feb 10 to Feb 21, there is a second episode of volume reduction (1.55 m^3), immediately followed by an increase of 0.56 m^3 by March 6. Six of the eight successive survey comparisons of the mudflat reveal an increase in sedimentary volume, equal to roughly one half meter of accretion per month. In all, nearly 14 m^3 of material (non-normalized) were either added or lost during the course of the study, with nearly 40% of that occurring between June and October 2008. Elevation differences are more pronounced within the tidal creeks and along the sandbank edge, as discussed below.

Isolated volume calculations of the sandbank on the eastern side of the mudflat show patterns of variability similar to the entire mudflat area (Figure 45a). One exception is the comparative survey between December 19, 2007 and March 28, 2008 where the sandbank volume increases. The western sandbank edge, approximately 12 meters long and slightly arcuate, accumulated nearly 0.45 m^3 of material with an average surface elevation gain of 4 cm and a maximum gain of 8 cm. Surface profiles show how the sandbank has migrated several centimeters to the west (Figure 46). The sandbank edge appears to have changed little between March 2008 and March 2009.

I also focused volume comparisons on a single tidal creek, just north of the station, that was free of any blind spots in order to avoid potentially erroneous measurements. Volume change here followed similar patterns as the entire mudflat area, but on a much smaller scale (Figure 45b). More notable, however, are the results of the GIS mudflat creek comparisons of morphologic variables between December 2007, October 2008, and March 2009. Among five mudflat creeks, mean creek cross-section widths increased significantly over the duration of the study (Figure 47). By October 2008, mean creek width increased by 23.5 cm (19.6 %), and increased another 11.3 cm by March 2009 (29% total increase). Widths of all creek thalwegs also increased; 20 cm (73%) by October 2008 and another 13 cm by March 2009 (121% total increase). Calculated ratios of total cross section width to thalweg width, an indicator of the cross section shape of a creek (low values close to 1 represent more of a 'U' shape, whereas higher values represent more of a 'V' shape) drop from 4.9 in December 2007 to 2.7 in March 2009 (44% decrease) (Figure 48a). Thalweg depths increase approximately 2.8 cm over the course of the study, while bank to thalweg distance (an indication of creek shoaling or deepening relative to the bank and mudflat) remain fairly constant. Calculated ratios of width-to-depth (an indicator of bank stability; high values are associated with instability) averaged over all creeks, increased slightly (14%) during the study period (Figure 48b). Individual creek comparisons, meanwhile, suggest the most change occurred within Creek A where differences in creek width-to-thalweg width ratios decreased nearly twice as much as any of the other creeks (becoming more 'U'-shaped) and width-to-depth ratio increased substantially (a result of the creek widening and shoaling, indicating bank instability) (Figure 49). Results from the other creeks are more uniform.

Discussion of Results

Volume calculations from nine surveys, mean mudflat creek comparisons from three surveys, and individual creek comparisons between the first and last surveys of the study period all help to establish an interpretation of the evolution of the Portrero mudflat and its implications for geomorphologic variability in the future. Especially interesting is the overall trend of increasing volume within the mudflat between the early and later surveys of the study period. Although the volume gains are equivalent to less than 2 cm in elevation between the first and final surveys (averaged over the entire mudflat), the fact that two other early surveys produced similar results helps to confirm that additional material was deposited in the mudflat by the end of October 2008. Over the same timeframe, however, one can see substantial increases in the widths of mudflat creeks which suggests instability and erosive processes. For example, Figure 50 illustrates an evolutionary model of a typical stream or creek profile within a degrading environment. Due to bank instability, creek banks will recede away from the axis of the creek, potentially depositing material within the creek thalweg, and gradually developing a more ‘U’- shaped profile. Over time, a single large storm event or tidal surge may contain enough energy to resuspend the softer, wetter sediments in the creek channel and deliver them to the main channel; an erosive process that cuts deeper into the existing mudflat creek bottom. What’s left is a network of wider and deeper creeks that may continue to expand and eventually coalesce. Meanwhile, the expansion of mudflat creeks nearest to the pickleweed edge will effectively steepen the embankment and undermine the pickleweed edge, leading to failure and erosion.

The discussion above, however, is fairly simplistic in that it assumes erosive processes to be the dominant mechanism by which the mudflat evolves. Of course, this would be a safe assumption in the case of Elkhorn Slough where tidal creeks have widened significantly and salt marsh vegetation has decreased by more than 40% since 1930 (Van Dyke and Wassen, 2005). However, by the final survey of the study period, I do not see evidence of accumulated surface sediments being flushed away or a return of the mean surface elevation to previous heights. A probable explanation, then, is that even within a mudflat that has shown substantial expansion since 1993, we are witnessing short term variability of accretion and erosion that may or may not be contributing to the long term trends. Nonetheless, the results are especially useful when attempting to determine a causal relationship with potential forcing mechanisms. One mechanism, for example, that may play a significant role in the geomorphologic variability of the surface mudflat is rainfall during the winter months.

The Elkhorn Slough watershed has a reputation for high erosion rates due to the soil impacts from agriculture and other human activities in the area. In upland areas of ES, disturbed soil is extremely susceptible to heavy rainfall events that can lead to sheet erosion and concentrated gully erosion (Los Huertos and Shennan, 2002). With continued rainfall and runoff, the eroded material is transported into the channels of the slough creating a dark body of sediment-laden water. A recent storm that occurred on Dec. 14, 2008, for example, produced a dark plume of water clearly visible at the mouth of Moss Landing Harbor following a strong ebb tide (personal observation). It is not clear, however, just how much of the suspended sediment may actually be derived from exposed mudflats within the ES watershed. Although low tide rainfall events have been implicated as a significant contributing mechanism to mudflat erosion and nutrient recycling in other estuaries, it has not been investigated in Elkhorn Slough.

Using a portable sprinkler system, Mwamba and Torres (2002) demonstrated how a single thunderstorm can entrain 67-120 tons of marsh sediment per km^2. Torres et al. (2004) investigated the fate of low tide rainfall-entrained intertidal sediment and found that it contributes to the cycling of intertidal material enriched in organic nitrogen, C3 and C4 carbon, and algal matter. During low tide, kinetic energy from raindrop impacts will eject sediment away from the impact zone and break apart a low tide sedimentary surface comprised of typically cohesive sediment (Mwamba and Torres, 2002; Torres et al., 2004). Sediment stabilization can occur through the binding of sediment particles by exopolymers produced by highly mobile benthic diatoms (Paterson, 1989; Tolhurst et al., 2006; Torres et al., 2004). Exopolymer distribution leads to greater sediment cohesion and higher critical shear stress. Sediment dehydration during low tides can even enhance biogenic cohesion by thickening the matrix and further stabilizing the sediment (Paterson et al., 1990; Torres et al., 2004). Raindrops, however, will create lateral shearing forces immediately after impact with the potential to detach highly cohesive intertidal sediment. These shear stresses can typically be orders of magnitude greater than shear stresses exhibited by tidal currents flowing over a marsh surface (Christiansen et al., 2000). Timing and intensity is critical, however, since rainfall events of lower intensity and/or occurring during high tidal stage or flood stage will have a negligible impact on sediment entrainment, or may only lead to redeposition within the marsh (Torres et al., 2004).

By examining the results of the mudflat variability at Potrero Rd., I investigated a potential correlation between decreases in mudflat volume and rainfall events that occurred simultaneously with low tides (< 0.8 m MLLW). Local rainfall records show that the ES region received approximately 33.5 cm of rain from October 2008 to early March 2009 (rain data collected using a tipping bucket rain gauge at the Caspian Weather Station ("elkcwmet"), located at the Elkhorn Slough Foundation. The data were compiled by the National Estuarine Research Reserve System-wide Monitoring Program (NERR SWMP) and accessed through their web portal (NOAA, 2004)). Of that, no single daily total exceeded 25 mm, suggesting less intense storms compared with the previous 5 winter seasons (Figure 51a-b). Nonetheless, our compilation of data indicates that tidal levels were less than 0.8 m MLLW for 38% of the time when rain was falling. I investigated the timing and intensity of rainfall events with tidal cycles (hourly data) over five study periods that coincided with the TLS data collection dates at Potrero Rd. Although rainfall intensity levels never reached those observed by Torres et al. (2004) in their study of low tide rainfall events in the North Inlet Estuary in South Carolina, there were a few storms of moderate intensity that occurred during low tide in ES. One in particular occurred on Dec. 14, 2008 where 2.4 cm of rain fell during 5 hours of one of the lowest tidal cycles of the entire year (Figure 52). Mudflat volume during this study period decreased 1.8 m^3 (over a 520 m^2 study area). One other study period (February

11-21) also experienced a decrease in mudflat volume, during which three rainfall events with intensity greater than 4 mm/hr occurred during ebb or low tide. The other three study periods contained few or no moderate rainfall events that occurred during low tide. Mudflat volume increased slightly during two of these study periods, while the study period of Jan. 7 – Feb. 10, 2009 experienced a substantial volume increase (see Appendices 3-6). Figure 53 and Table 10 illustrate the variability in mudflat volume coupled with low tide rainfall events during six study periods.

Although further work is needed to specifically address the potential for rainfall-induced erosion in ES, my results appear to suggest a possible correlation between mudflat erosion and higher intensity rainfall events that occur during low tide. A reclassification of LiDAR elevation values using ArcGIS, allows us to calculate the intertidal mud area in ES that might be exposed during low tide. Figure 54 shows the results which appear to nicely match the morphology of mudflats and tidal creeks where exposed intertidal mud would expect to be found. Using an estimate of nearly 4 km^2 exposed during low tide and an extrapolation of my results from the Potrero mudflat (1.5 m^3 volume loss over 500 m^2) indicates a potential volume loss of over 11,800 cubic meters of sediment during one rainfall event. Between 2003 and 2008, annual rainfall in Elkhorn Slough averaged 43.9 cm, well below the 119-year average of 55 cm cited by Caffrey (2002). Winter seasons that include more intense storm events could have the potential to severely erode exposed mudflat areas. It may be worthwhile to investigate historic records of the timing and intensity of significant rainfall events (i.e. during the 1997-98 El Nino season) and compare them with observed tidal cycles.

Results of survey comparisons of three high resolution surveys along the northern pickleweed edge of the Potrero mudflat, from October 2008 to February 2009, reveal an interesting pattern of change, but remain fairly inconclusive. Figure 55 shows the results of cumulative volume change that occurred within each box between October 2008, January 2009, and February 2009. For comparison, cumulative results are relative to the October 2008 dataset. Boxes 1-4 reveal small losses in volume along the pickleweed edge from October to January, and then little to no change from January to February. Boxes 5-7 also show a small amount of volume loss from October to January, but then reveal substantial increases in volume from January to February. Since it's unlikely that edge accretion is realistically occurring within the short time-frame, the increase in volume may be attributed to edge failure that results in positive measurements at the base of the edge. For this to happen, however, one would expect to see a corresponding decrease, or removal of material, just above the base of the edge where the mud had failed and left a gap. To illustrate, Figure 56 depicts the evolution of a receding bank as a result of undercutting and failure along with examples of representative inspection profiles. Thus, accretion would be balanced by erosion with net change equal to null. Figure 57 shows a few vertical profiles within Box 6 where this could have occurred. The question remains, then, why the results show a net positive change when cumulated over the entire box. An alternative explanation suggests that small variations in vegetation, due to natural factors such as growth, dieback, wind, etc., among point cloud measurements from one survey to the next can potentially obfuscate the results and lead to large errors. When cumulated, these errors may be recorded as net change. Therefore, it is best to err on the side of caution when assessing results that include vegetation and it's potential for ephemeral change. High resolution digital photographs, taken during each survey, help to confirm the observed results of survey comparisons. Unfortunately, Figure 57 shows how photographs taken from far away (i.e. greater than 60 m) during this survey are inadequate for these purposes.

Survey comparisons calculated for a portion of the pickleweed edge on the western-most boundary of the mudflat reveal more promising results with respect to our ability to confidently detect pickleweed edge change. Here, the use of multiple comparisons relative to an initial survey provided a better assessment of true change detection, albeit over a much longer time-scale, than the north bank comparison. Results show strong consistency of either positive or negative volume change over the three comparative surveys with Zone 2 having the lowest standard deviation of change (Figure 58). The consistency of the results, then, confirms that change detected here cannot be due to random artifacts of ephemeral change in vegetation, as suggested from the results of the north pickleweed edge. Rather, it's likely that the negative volume results from Zone 1 and Zone 3 represent portions of the edge that had collapsed prior to the initial survey (Dec 2007), and then subsequently eroded by the time the first comparative survey was performed (Feb. 7, 2009). If erosion was ongoing, we would expect to see a further increase in negative volume by March 6, 2009, which is indeed confirmed by the overall results from Zone 3. In contrast, Zone 2 results suggest accretion of the pickleweed edge over the course of the study, likely due to recent failure and collapse. Again, high resolution photographs and groundtruthing would be extremely helpful in confirming these interpretations. Nonetheless, the repeatability of results increases the likelihood that true surface change can be detected using TLS data collection and processing. Moreover, the results show strong evidence of the dynamic nature of a pickleweed edge, one that recedes and advances over time.

Site #2: Sandholdt Bridge

Methods

Sandholdt Bridge offered an excellent vantage point from which to monitor long-term geomorphologic variability of an exposed mudflat. Located just south of Sandholdt Bridge, the mudflat was surveyed on seven different occasions (Table 5), totaling 221,000 points. Depending on tidal conditions or specific areas of interest, anywhere between 7,000 to 70,000 points were collected per survey. Due to the negative mean elevation of the target area, the mudflat was exposed for only a short duration of time during low slack tide. This required "opportunistic" surveying of specific areas of interest. In other words, it was not always possible to scan the entire area prior to inundation from the incoming tide; individual areas had to be chosen and prioritized. For this reason, a relatively small area of exposed mudflat (90 m^2 normalized) was selected for comparison which happened to include a portion of the point cloud from each scan date. Other features within the mudflat, including small tidal creeks, were also used for comparison, but contained fewer repeatable surveys. Additionally, I performed two very high resolution (2 cm) surveys of a small area of the mudflat surface on Dec. 10th and Dec. 12th, 2008. The purpose of these surveys was to understand how much change occurred on the mudflat over 48 hours during the most extreme tidal range of the year.

RealWorks Advanced v.6.3 was used to post-process point cloud data and perform twin surface inspections. Volume comparisons were performed at 10 cm resolution for each successive survey. Point clouds covering the mudflat surface for "sandholdt" surveys 3, 4, 6, and 7 (Table 5) were also converted to rasters using an IDW interpolation in ArcGIS v.9.2, and subsequently clipped to the specific area of interest. Raster resolutions were set to 5 cm for jobs 3 and 4, and 2 cm for jobs 6 and 7. "Raster calculator" was used to subtract elevation (z) values between comparative surveys to assess differences.

Results and Discussion

Results of long-term successive survey comparisons at the Sandholdt Bridge mudflat, from 4-Feb to 12-Dec, 2008 reveal little appreciable change, with the exception of 6-June to 29-Oct when 0.56 m^3 of material eroded from the 90 m^2 mudflat area (Figure 59). Backsight residuals reveal that the vertical and horizontal precision was very good between these two surveys thereby helping to confirm the validity of the results (Figure 60). Results of a comparison between the interpolated rasters reveal an overall elevation decrease, concentrated in small pockets on the mudflat (Figure 61). The final survey comparison (10-Dec – 12-Dec, 2008) showed the least amount of change among any comparison (Figure 62). This is not surprising given that the surveys were completed only 48 hours apart. Results of the high resolution survey completed during the same time period, adjacent to the mudflat area compared above, also reveal little to no change.

With the exception of some minor erosion during the summer months and other surface variability throughout the study period, the results at Sandholdt Bridge are not robust enough to develop any significant pattern of geomorphologic change. The small pits and depressions are possibly a result of scouring from water turbulence or bioturbation from burrowing clams, harbor seals, or sea otters (Oliver, personal communication). The results from the extreme tidal cycle comparison are also useful in understanding the limits of detecting fine-scale variability using a TLS.

Site #3: Bird Observatory, ES Main Channel

Methods

Similar to the high resolution surveys performed at Sandholdt Bridge, I performed two high resolution (2 cm) surveys of the mudflat surface and the pickleweed edge and mudbank at the junction of a tidal creek and the main channel near the ES Bird Observatory. The two surveys were performed within 48 hours of one another on Dec. 9th and 11th, 2008 during the extreme tidal cycle. These short-term surveys were designed to address the cause-and-effect relationship, frequently cited in the literature, between extreme tidal velocities and tidal creek widening (Byrd, 2009; ESTWP, 2007; Van Dyke and Wasson, 2005; Caffrey and Broenkow, 2002). A third survey was also performed here approximately one month later on Jan. 9, 2009 to test for any further change. Of the three surveys, approximately 128,000 points were collected and post-processed for comparison (Table 9).

RealWorks Advanced v.6.3 was used to post-process point cloud data and perform twin surface inspections. Point clouds were partitioned into 3 separate zones based on morphology (i.e. mudbank, mudflat, and pickleweed edge) and compared using unique planes of reference: pickleweed edge comparisons used a vertical plane of reference oriented parallel to the tidal creek; mudbank comparisons used a tilted plane of reference that best fit the slope of the bank; and mudflat comparisons used a horizontal plane of reference (Figure 63). All twin surface inspections were performed using the highest resolution possible (between 2 and 4 cm) depending on the spacing of the points. Additionally, the mudflat and mudbank areas from the first two surveys were converted to rasters (3 cm resolution), using the same interpolation techniques used for the Sandholdt and Potrero scans, and compared (raster subtraction) to assess differences.

Results and Discussion

Backsight residuals at the Bird Observatory are extremely low (less than 2 mm easting and northing), helping to confirm the validity of all results (Figure 64). Similar to the results of the 48-hr experiment conducted at Sandholdt Bridge, comparison results at the Bird Observatory show little change over the mudflat surface. Results of the pickleweed edge are more difficult to decipher due to the rugose surface of the vertical edge with many pockets, indentations, and protrusions. In other words, there is a greater chance for misinterpreting a non-uniform surface that is essentially “smoothed” through the process of interpolation between points (when using RealWorks Survey Advanced, the software uses a Triangulated Irregular Network {TIN}to perform the twin surface inspection). Higher resolution surveys and/or multiple surveys may help to remedy this problem and could add more confidence to small observed differences. As such, the results of the pickleweed edge do not reveal differences large enough to overcome the uncertainty. Results of the third area of comparison, the moderately sloping mudbank adjacent to the tidal creek, show an overall decrease in elevation by as much as 2 cm (equivalent to approximately 0.005 m^3 per m^2, or 5 kg/ m^2). Seen in Figure 65b, this zone of change appears to strongly correlate with location and slope angle. For example, the slope of the mudbank is approximately 18-21^o compared with the slope of the mudflat at 2-3^o. Location is another factor that may contribute to the observed differences; the mudbank is situated parallel to the axis of the tidal creek which makes it more susceptible to strong tidal currents. On Dec. 11th, the tidal range was approximately 2.5 m, compared with the ES mean diurnal tide height of 1.7 m (Caffrey and Broenkow, 2002), which would have resulted in an extremely high tide that could dislodge sediment and other detritus from the marsh surface. The entrained material would then be carried away with a fast-moving ebb tide, potentially abrading the mudbanks that line the tidal creeks. Rapid, abrasive ebb currents may also help to explain the removal of material from the upstream edge of the small mudpile on the mudbank and deposition on the downstream edge (Figure 65c).

Results of the comparisons between the second and third surveys, completed nearly one month apart, reveal more conspicuous results of change occurring along the pickleweed edge. Figure 66a-b shows the results of two separate twin surface inspections performed on the mudbank and pickleweed edge nearest to the station. One can immediately recognize evidence of a small section of the pickleweed edge having failed and collapsed onto the mudbank slope below. This is also evident in the photographs taken prior to each survey (Figure 66c-d). The size of the hole left in the mudbank is approximately equal to the volume of the mudpile on the bank (0.004 m^3 equivalent to about 4 kg of mud). Evidence of a portion of the pickleweed edge having failed is also apparent at the northern end of the survey area. Unfortunately due to time constraints, only a small portion of this area was surveyed, yet we can clearly identify, in both the photographs and twin surface inspection, a large mudpile that has fallen onto the mudbank slope (Figure 67). Calculations show approximately 0.02 m^3 of mud were deposited here, equivalent to roughly 20 kg. Due to shadows in the photograph and a lack of data points along the pickleweed edge directly above the mudpile, I cannot confirm the location on the pickleweed edge from which the mudpile originated. Collectively, the results of the Bird Observatory surveys strongly suggest an actively eroding tidal creek bank and pickleweed edge identifiable over the course of one month from an analysis of both photographs and data collected with a TLS. Additionally, high resolution TLS data, unlike photographs, can provide a precise and quantifiable assessment of change along the tidal creek mudbank and adjacent mudflat over the course of just two days.

Site #4: North Azavedo Pond

Methods

To test the anthropogenic effects of hydraulic alterations to a tidal creek channel, I collected approximately 169,000 data points over four surveys from Oct. 14, 2008 to March 31, 2009 (Table 9). The first three surveys were all completed in October 2008, prior to the start of construction work on the eastern side of the culvert. Two of the surveys were performed at or after dusk which limited our ability to take station-based photographs. With the exception of the first survey (NAzavedo4), all surveys were referenced to an existing benchmark. Due to unresolved complications with the first survey, and a lack of identifiable control points, I chose not to include this data for point cloud comparisons. Surveys "NAzavedo5" and "NAazavedo7" were compared at 2 cm resolution using a horizontal plane of reference for the mud-gravel-cobble area just west of the culvert opening. Vertical reference planes of 3 cm resolution were used to test for change along the pickleweed edges on the northern portion of the survey area. In addition to twin surface inspections performed with RealWorks Survey Advanced, I also created 2 cm resolution interpolated (IDW) rasters using ArcGIS and performed comparisons using Raster calculator.

Results and Discussion

Similar to the other sites, backsight residuals for North Azavedo Pond are very low; less than 3.5 mm northing and easting between the two comparative surveys, "NAzavedo5" and "NAzavedo7" (Figure 68). Comparisons of these two surveys (Oct. 17, 2008 vs March 31, 2009) from the area west of the railway culvert reveal mixed results. Undoubtedly, significant change took place here over the course of 5.5 months, yet there is no strong pattern of consistent geomorphologic change. For example, Figure 69 shows the results of a raster subtraction between the two interpolated datasets. Although there appear to be several areas where change exceeded 5 cm, they are relatively scattered within the survey area. The southern edge of the survey area, however, predominantly shows erosion along the bottom edge of the north-sloping mudbank, as well as a steepening slope (Figure 70). A significant amount of deposition also appears to have occurred within the central portion of the channel (west of the culvert opening). Large cobbles and boulders, some greater than 12 cm diameter, lie scattered about the central channel. Photographs show that many of the boulders did not move from their position in October, whereas others appear in areas where they didn't exist before. Twin surface inspections performed on the pickleweed edge on the north side of the culvert opening also reveal signs of bank recession, as much as 10 cm in places (Figure 71).

It's unclear how large boulders could have been deposited along the channel floor since tidal current velocities would not be swift enough to transport them, even after construction was completed on the east side and currents began to flow through the culvert. A more likely scenario is that they tumbled down from the railway embankment where they had been placed during railway construction during the mid-1800's. Extreme tides during December may have loosened or dislodged the material from higher sections of the bank. Additionally, presumably faster currents flowing through the culvert, following construction, were the likely cause of bank-undercutting and removal of material on the south side. A steepened bank, then, would not only expose buried levee material but would also weaken the stability of the bank, causing other material to fall from above. It's also not clear whether erosion along the pickleweed edge could be attributed to increased tidal velocities through the culvert or to general trends of creek widening identified by Van Dyke and Wasson (2005). Nonetheless, the TLS results again provide a useful means for identifying and quantifying fine-scale geomorphologic variability in a wetland environment.

CONCLUSIONS

The use of terrestrial laser scanners to monitor geomorphologic variability is in its infancy stage, having only recently been applied to high resolution data collection in various environments. To date, no published reports have discussed its use in a coastal wetland environment where surface changes can occur over very short time spans (tidal cycles). The objectives of this study, then, were designed to address the need for data collection and post-processing techniques that are specific to the dynamic and geomorphologic elements of a wetland setting. Moreover, I investigated factors that can lead to potential errors in TLS data measurements that can, if overlooked, lead to a misinterpretation of surface variability. And lastly, I analyzed high resolution datasets of different wetland environments in Elkhorn Slough with the goal towards identifying change and understanding fine-scale geomorphologic processes. Below, I have listed the results according to each objective set forth in this study. I have also included "Follow-up Suggestions" for future studies to address issues that were uncovered during this study, yet were beyond the scope of the project goals.

Objective #1

- The ubiquitous presence of incoming tidal water and/or standing water in a wetland requires strict attention to cleaning point clouds during post-processing. Clean datasets are less likely to introduce error and misinterpretation of geomorphologic processes.
- Software packages, such as Trimble RealWorks Survey Advanced (v.6.3.1) and ESRI ArcInfo (v.9.3) were used extensively during data post-processing to facilitate data cleaning, surface modeling, analysis, quantification, and interpretation. Numerous data-processing techniques were developed and employed during this study.
- *Follow-up Suggestions:* Numerous data interpolation techniques exist that can produce slight variations in the rendering of a raster surface. Further work must address the applicability, effectiveness, and accuracy of some of the other techniques when making geomorphologic interpretations of TLS datasets.

Objective #2

- TLS data accuracy is a function of backscatter intensity and is controlled by the following factors: distance, angle of incidence, and the physical properties of the target surface (i.e. moisture content, brightness, grain size).
- Experimental results suggest that angle of incidence and distance to a target can strongly affect the accuracy of data measurements. At high angles and distance, fine-grained (mud) surfaces consistently produce less accurate results than coarse-grained (sand) surfaces. Depending on the surface material, angle of incidence, and distance, data offset can be as high as 5 cm *less* than predicted. Thus, skewed or distorted datasets are a potential pitfall when making interpretations.
- All target parameters (distance, angle of incidence, physical properties, etc.) can be calculated and combined to create a qualitative assessment of TLS accuracy. Quality assessments play an important role in the confidence of geomorphologic interpretations.
- *Follow-up Suggestions:* Future studies should investigate methods that may incorporate all quantitative target parameters, weighted according to the degree of influence each parameter has on the reflectivity and resolution of point measurements, to create a quantifiable accuracy assessment of a TLS dataset. Such an assessment would provide researchers with an even stronger tool to make

high resolution geomorphologic interpretations based on confidence and quality assurance.

Objective #3

- Data collected from high resolution terrestrial laser surveys, never before attempted in a wetland environment, were used to create digital elevation models (DEM's) and make surface comparisons of fine-scale geomorphologic features. Sub-centimeter analyses of sedimentary and erosional processes were performed at specific wetland environments at four different sites in Elkhorn Slough (ES).
- *Site #1: Potrero Rd.*
  - Widths of mudflat creeks increased by nearly 30% over the course of 14.5 months, with cross-section profiles evolving from V-shaped to U-shaped, likely due to bank instability.
  - Mudflat volume calculations, relative to Dec. 2007, increased substantially, suggesting sedimentation playing a dominant role over the course of the study.
  - Short-term variability in mudflat volume calculations between winter 2008-2009 surveys (Port5 through Port10) correlate fairly well with the frequency and intensity of low-tide rainfall events; high intensity low-tide rainfall events coincide with decreases in mudflat volume while low intensity- or zero-low tide rainfall events coincide with minimal change or increases in mudflat volume.

  - Pickleweed edge comparisons prove difficult to interpret due to complex surfaces and vegetation that can interfere with accurate analyses. Nonetheless, the use of multiple comparisons relative to an initial survey provided a good assessment of true change detection.
- *Site #2: Sandholdt Bridge*
  - Results suggest an overall decrease in mudflat volume over the course of the study as well an overall decrease in elevation, concentrated in small pockets on the mudflat. No significant pattern of geomorphologic change was identified at this site.
  - Results of a 48-hr surface comparison reveal no significant change (+/- 5 mm), yet are useful in understanding the highly accurate detection limits of the Trimble VX Spatial Station over repeat surveys.
- *Site #3: Bird Observatory*
  - Results of the 48-hr experiment show the following: little to no change over the mudflat surface; indecipherable change across the pickleweed edge due to its rugose vertical surface with many pockets, indentations, and protrusions; and an overall decrease in elevation by as much as 2 cm along the moderately sloping mudbank adjacent to the tidal creek.
  - Extreme high tides over the 48-hr period may have included higher concentrations of suspended sediment that could have abraded the mudbank surface during ebb flow.

  - Results from both photographs and comparative survey data reveal two sections of pickleweed edge having failed over the course of one month.
- *Site #4: North Azavedo Pond*
  - Repair of a collapsed channel opening on the east side of the railway culvert may have played a role in increasing tidal velocities through the culvert and eroding channel edges on the west side.
  - Comparative surveys, before and after anthropogenic modification to the tidal regime, reveal bank-undercutting and significant removal of material. Areas of deposition were also apparent, as well as large boulders and cobbles appearing in locations not previously observed.
- *Follow-up Suggestions:* Results of this study have shown that TLS data can be used to monitor geomorphologic variability of mudflat/mudbank surfaces on a sub-centimeter to centimeter scale. Such efficient, high-resolution analyses enable us to track surface elevation changes on a daily basis following hydrologic or meteorological events, such as tidal fluctuations and low-tide rainfall. Future studies may benefit from the development of a consistent methodology to perform high resolution surveys of a mudflat/mudbank surface immediately before and after such events, and investigate other sources of data (i.e. turbidity or geochemical signatures from data-logging buoys) that may be linked to the erosion of exposed intertidal mudflats.

References

Bellian, J.A., Kerans, C. and Jennette, D.C., 2005. Digital Outcrop Models: Applications of terrestrial scanning LIDAR technology in stratigraphic modeling. Journal of Sedimentary Research, 75(2): 166–176.

Bitelli, G., Dubbini, M. and Zanutta, A., 2004. Terrestrial laser scanning and digital photogrammetry techniques to monitor landslide bodies, Proceedings of the XXth ISPRS Congress, Istanbul.

Buckley, S.J., Howell, J.A., Enge, H.D. and Kurz, T.H., 2008. Terrestrial laser scanning in geology: data acquisition, processing, and accuracy considerations. Journal of the Geological Society, 165: 625-638.

Byrd, K.B., 2009. Remote sensing and spatial analysis of watershed and estuarine processes for conservation planning in Elkhorn Slough, Monterey County, California. In: X. Yang (Editor), Remote Sensing and Geospatial Technologies for Coastal Ecosystem Assessment and Management. Lecture Notes in Geoinformation and Cartography.

Caffrey, J.M., 2002. Climate. In: M.B. J. Caffrey, W.B. Tyler, M. Silberstein (Editor), Changes in a California estuary : a profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, Calif., pp. 25-28, 280 p.

Caffrey, J.M. and Broenkow, W., 2002. Hydrography. In: M.B. J. Caffrey, W.B. Tyler, M. Silberstein (Editor), Changes in a California estuary : a profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, Calif., pp. 29-42, 280 p.

Christiansen, T., P.L. Wiberg, T.G. Milligan, 2000. Flow and sediment transport on a tidal salt marsh surface. Estuarine, Coastal and Shelf Science, 50: 315-331.

Compton, R.R., 1962. Manual of Field Geology. John Wiley and Sons, Inc., New York, New York.

Crampton, T.A., 1994. Long term effects of Moss Landing Harbor on the wetlands of Elkhorn Slough, University of California, Santa Cruz.

DeLaune, R.D., Nyman, J.A. and Patrick, W.H., 1994. Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. Journal of Coastal Research, 10: 1021-1030.

Elkhorn Slough Tidal Wetland Project Team (ESTWP), 2007. Elkhorn Slough tidal wetland strategic plan. A report describing Elkhorn Slough's estuarine habitats, main impacts, and broad conservation and restoration recommendations.

Gordon, B.L., 1996. Monterey Bay Area: Natural History and Cultural Imprints. The Boxwood Press, Pacific Grove, CA.

Hartig, E.K., Gornitz, V., Kolker, A., Mushacke, F. and Fallon, D., 2002. Anthropogenic and climate change impacts on salt marshes of Jamaica Bay, New York City. Wetlands, 22: 71-89.

Heritage, G. and Hetherington, D., 2007. Towards a protocol for laser scanning in fluvial geomorphology. Earth Surface Processes and Landforms, 32: 66-74.

Hetherington, D., Heritage, G.L. and Milan, D.J., 2005. Reach scale sub-bar dynamics elucidated through oblique lidar survey, International Association of Hydrological Scientists Red Book Publication. IAHS Publication, pp. 278-284.

Kukko, A., Kaasalainen, S. and Litkey, P., 2008. Effect of incidence angle on laser scanner intensity and surface data. Applied Optics, 47(7): 986-992.

Larson, E.J., 2001. Coastal wetlands-emergent marshes. In: C.M.D. W.S. Leet, R. Klingbeil, E.J. Larson (Editor), California's Living Marine Resources: A Status Report. California and California Department of Fish and Game, Sacramento, California, pp. 483-486.

Lichti, D.D. and Jamtsho, S., 2006. Angular resolution of terrestrial laser scanners. Photogrammetric Record, 21: 141-160.

Los Huertos, M. and Shennan, C., 2002. Soils. In: M.B. J. Caffrey, W.B. Tyler, M. Silberstein (Editor), Changes in a California estuary; A profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.

Lowe, P.B., 1999. Marsh Loss in Elkhorn Slough, CA: Patterns, mechanisms, and impact on shorebirds, San Jose State University.

Malzone, C.M., 1999. Tidal scour and its relation to erosion and sediment transport in Elkhorn Slough, San Jose State University.

Masters, P.M. and Aiello, I.W., 2007. Chapter 3: Post-Glacial Evolution of Coastal Environments, California Prehistory. Altamira Press, Berkely, CA.

Milan, D.J., Heritage, G. and Hetherington, D., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. Earth Surface Processes and Landforms, 32: 1657-1674.

Mwamba, M.J. and Torres, R., 2002. Rainfall effects on marsh sediment redistribution, North Inlet, South Carolina, USA. Marine Geology, 189: 267-287.

Nagihara, S., Mulligan, K.R. and Xiong, W., 2004. Use of a three-dimensional laser scanner to digitally capture the topography of sand dunes in high spatial resolution. Earth Surface Processes and Landforms, 29: 391-398.

National Oceanic and Atmospheric Administration, Office of Ocean and Coastal Resource Management, 2004. National Estuarine Research Reserve System-wide Monitoring Program. Centralized Data Management Office, Baruch Marine Field Lab, University of South Carolina.

Oliver, J.S., King, J.A., Hornberger, M. and Schwartz, D.L., 1988. Extensive salt marsh erosion caused by human activities in Elkhorn Slough, California, Report prepared for Elkhorn Slough National Estuarine Research Reserve, Watsonville, California.

Paterson, D.M., 1989. Short-term changes in the erodibility of intertidal cohesive sediments related to the migratory behavior of epileptic diatoms. Limnology and Oceanography, 34: 223-234.

Paterson, D.M., Crawford, R.M. and Little, C., 1990. Subaerial exposure and changes in the stability of intertidal estuarine sediments. Estuarine, Coastal and Shelf

Science, 30: 541-556.
Patrick, W.D. and DeLaune, R.D., 1990. Subsidence, accretion, and sea level rise in south San Francisco Bay marshes. Limnology and Oceanography, 35: 1389-1395.
Pesci, A. and Teza, G., 2008. Effects of surface irregularities on intensity data from laser scanning: an experimental approach. Annals of Geophysics, 51(5/6): 839-848.
Phillips, J.D., 1986. Coastal submergence and marsh fringe erosion. Journal of Coastal Research, 2: 427-436.
Schwartz, D.L., Mullins, H.T. and Belknap, D.F., 1986. Holocene geologic history of a transform margin estuary: Elkhorn Slough, central California. Estuarine, Coastal and Shelf Science, 22: 285-302.
Shuman, C.S. and Ambrose, R.F., 2003. A comparison of remote sensing and ground-based methods for monitoring wetland restoration success. Restoration Ecology, 11: 325-333.
Tolhurst, T.J., Friend, P.L., Watts, C., Wakefield, R., Black, K.S. and Paterson, D.M., 2006. The effects of rain on the erosion threshold of intertidal cohesive sediments. Aquatic Ecology, 40: 533-541.
Torres, R., Goni, M.A., Voulgaris, G., Lovell, C.R. and Morris, J.T., 2004. Effects of low tide rainfall on intertidal zone material cycling. In: M.M.S. Fagherazzi, L.K. Blum (Editor), The Ecogeomorphology of Tidal Marshes. American Geophysical Union, Washington, D.C.
Tuxen, K.A., Schile, L.M., Kelly, M. and Siegel, S.W., 2008. Vegetation Colonization in a Restoring Tidal Marsh: A Remote Sensing Approach. Restoration Ecology, 16(2): 313-323.
Van Dyke, E. and Wasson, K., 2005. Historical ecology of a Central California estuary: 150 years of habitat change. Estuaries, 28(2): 173-189.
Wasson, K., Van Dyke, E., Kvitek, R., Brantner, J. and Bane, S., 2001. Tidal erosion at Elkhorn Slough. Elkhorn Slough National Estuarine Research Reserve.
Watson, D.F. and Philip, G.M., 1985. A refinement of inverse distance weighted interpolation. Geo-processing, 2: 315-327.
Yamada, O., Takase, Y., Shimoda, I. and Nakagawa, T., 2003. Significance of digital reconstruction of historic buildings using 3d laser scanner case study: Prasat suor prat n1 tower, Angkor, Cambodia. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Xxxiv(5/w12): 342-346.