Accuracy Assessment of Lidar Saltmarsh Topographic Data Using RTK GPS

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Abstract

An evaluation was completed to compare the accuracy of lidar (Light Detection and Ranging) against a statistically representative array of Real-Time Kinematic (RTK) GPS data in a low gradient, vegetated Southeastern U.S. salt marsh. In order to discern potential bias, analyses were carried out separately on the platform-only data, the creek-only data and then the combined datasets. Lidar data were found to overestimate the RTK GPS topographic data by an overall average of only 7 cm. Additionally, these data showed little effect from the dominant macrophyte vegetation within the lidar footprint. From this evaluation, 7 cm appears to be an appropriate vertical adjustment factor for using lidar data in low gradient salt marshes. However, local ground control will continue to be crucial in studies of intertidal environments incorporating airborne laser data collection.

Introduction

Lidar (Light Detection and Ranging) is becoming widely used for acquiring topographic data from difficult settings such as salt marshes, where mobility and accessibility problems prohibit conventional ground-based surveying. Although dense lidar data can be collected rapidly over large areas, it is uncertain if lidar has the accuracy in salt marshes to justify the costs of obtaining such data.

The purpose of this study is to test the accuracy of a lidar-derived topographic dataset in a low gradient, vegetated salt marsh by navigating to lidar point locations and collecting ground data with Real-Time Kinematic (RTK) GPS having a vertical accuracy of ±1 cm to 4 cm (Trimble Navigation, Ltd., 2002). Other studies have suggested that lidar data can be utilized to reveal natural drainage schemes in salt marshes in order to aid in understanding and modeling processes that create the geometry and elevation patterns found in these systems.

Salt marshes, as a whole, exist over wide latitudinal ranges and in a variety of climate conditions within the intertidal zone where the generally muddy substrate supports varied stands of halophytic plants (Allen and Pye, 1992). Western Atlantic marshes encompass over 20,000 km^2 in total area and constitute a large proportion of global coastal salt marsh resources, despite substantial anthropogenic destruction (Frey and Basan, 1985). The tidal ranges vary from microtidal conditions in the Gulf of Mexico to macrotidal in the Bay of Fundy.

The dominant salt marsh plants, specifically in the lower marsh, are macrophytes. Previous studies have shown positive correlations between marsh elevation and vegetation vigor (Morris, 1982; Cornu and Sadro, 2002; Edwards and Proffitt, 2003). Other investigations suggest that the interaction of physical processes with biogenic processes regulate the distribution and availability of tidal energy in the marsh system (Collins *et al.*, 1987; Friedrichs, 1993; Reed and Hobbie, 2000; Boumans *et al.*, 2002).

Although salt marshes are typically known as depositional environments, the processes involved in their development are not entirely understood (Pethick, 1992). The general perception is that salt marshes are flat open areas with little if any relief other than topographic changes due to the tidal creek networks that incise the marsh platform (Eiser and Kjerfve, 1986). However, slight elevation changes have been shown by Cornu and Sadro (2002) to play a significant role in tidal channel development, influenced by the marsh surface gradient as well as elevation. Subtle platform features can influence such important parameters as inundation period and duration, factors which in turn affect the vegetation and microhabitats (Cahoon and Reed, 1995; Allen, 1997). Platform topography also exerts a strong influence on the spatial and temporal variability of over-marsh currents during ebb and flood tides.

Although interactions between marsh platform topography and tidal creek networks strongly control marsh hydrodynamics, in order to obtain a better understanding of the morphological evolution of salt marshes detailed elevation data are needed (Klimaszewski, 1988; French and Stoddart, 1992; Fagherazzi *et al.*, 1999; French and Clifford, 2000).

Study Site

This study was conducted on a salt marsh Island within the North Inlet-Winyah Bay NOAA National Estuarine Research Reserve (NERR) site located in Georgetown County, South Carolina (Figure 1). North Inlet-Winyah Bay is a relatively pristine mesotidal, ebb dominated lagoonal-estuary that drains 32 km^2 of intricately networked tidal creeks and channels. Tides are semi-diurnal with a mean range of 1.5 m (Eiser and Kjerfve, 1986). The dominant intertidal macrophyte is *Spartina alterniflora* with *Juncus roemerianus* dominating in the upper marsh. Both plant species exhibit temporal and spatial variations in density, height and composition, which are largely controlled by season and the subtle platform topography.

The North Inlet basin was formed mainly by hydraulic adjustments to gradual submergence of the previously terrestrial landscape (Gardner and Bohn, 1980). The estuary is bound to the east by barrier islands and sand spits and to the west by forested Pleistocene beach ridges. River-dominated Winyah Bay forms the southern boundary. Tidal channels

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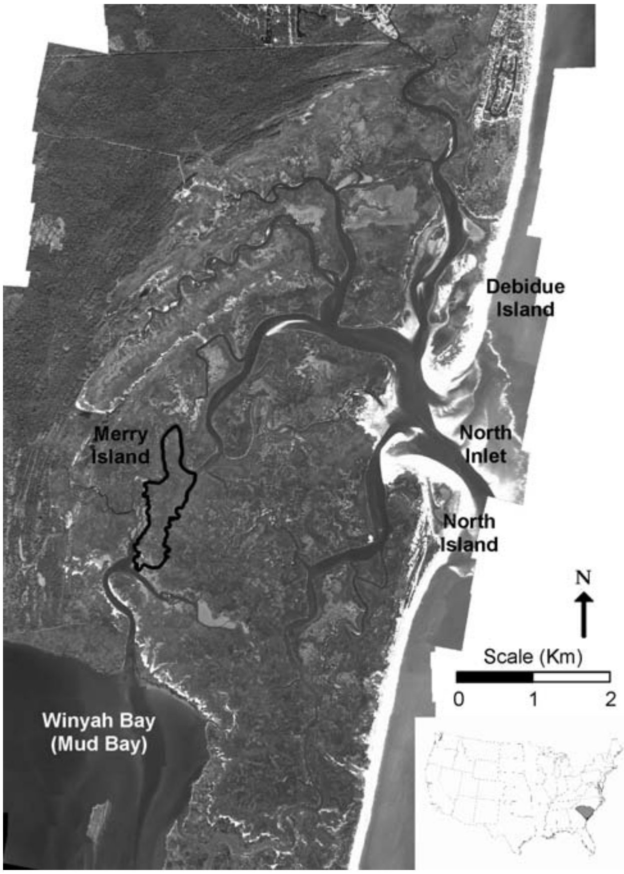

Figure 1. Airborne Data Acquisition and Registration (ADAR) image with 0.7 m resolution of the NOAA National Estuarine Research Reserve (NERR) site in Georgetown County, South Carolina. The study island is outlined in black.

incising the marsh platform vary in spatial arrangement and channel density (Novakowski *et al*., 2004).

The study island is approximately 1.5 km offshore from the forested ridges and is approximately a 1.05 km^2 area of relatively pristine uninhabited marsh dissected by 22 tidal creeks varying in size and cross-sectional geometry. The marsh platform of the island has very little relief, varying between about 10 cm to 70 cm, including levees. In the southern portion and along creek banks of the island, *S. alterniflora* stands as tall as 2 m. Throughout the intermediate marsh and within depressions between the creek levees, the dwarf version stands about 0.5 m tall.

Methods

The inherent density of lidar data cannot be matched in the field with conventional surveying methods. For this reason, a sample size for a desired margin of error was calculated using the reported 95 percent accuracies for the lidar and RTK GPS systems, ±12 cm and ±4 cm, respectively (Trimble Navigation, Ltd., 2002; Airborne1 Corporation, 2003). This computation resulted in a minimum sample size of 265 lidar target points to attain a ±1 cm margin of error and is further constrained with 99 percent confidence intervals (Moore and McCabe, 1993). Sample targets were randomly generated for the marsh platform then biased with targets within the creek networks; this combined sample statistically represents the entire population of lidar data.

Fieldwork to acquire the sample ground data comprised over 120 hours for a two-person team during the months of December 2003, and March, April, and June 2004. The data were obtained on foot using the RTK GPS system to locate each exact lidar target location where the target position and elevation were then measured. The marsh surface, also termed the "platform," and the creek networks are the main geomorphological features on the island. This study uses both datasets separately as well as combined; datasets are termed *platform-only, creek-only*, and *combined*. Daily validation of the RTK GPS operation in the field was accomplished using the NGS Benchmark PID Number AJ5767 located in the northern portion of the island. The overall standard deviation for the field surveys was less than ±1 cm, well within the centimeter-level accuracy of Trimble equipment specifications. RTK GPS ground data for 279 platform and 55 creek lidar targets make up the sample for this study (Figure 2). At each sample location particular care was taken to minimize disturbance of the surrounding sediment and vegetation.

A critical part of the accuracy study was to assess the spatial variability of marsh topography within 37 cm, determined from 0.25 m horizontal laser footprint and ±12 cm lidar system accuracy. These additional data consist of measurements in the four cardinal directions (N, S, E, and W) for 109 targets. The maximum elevation difference for each target was calculated and examined to test if the slightly varying topography in the footprint has an effect on the dataset.

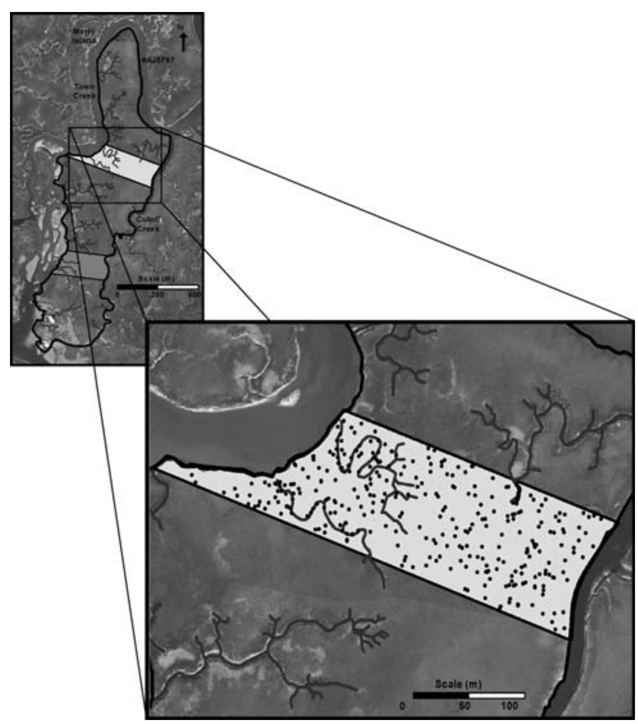

Figure 2. ADAR image of the study Island superimposed with two lidar swaths collected for Georgetown County. The uppermost swath through the center was chosen for this study. The 140 m wide area consisted of over 144,000 lidar data points having a nominal spacing of 0.25 m. The larger inset superimposes the 334 RTK GPS ground data over the lidar data.

The statistical tests used in this study consisted of distribution histograms, normal probability plots (often called a normal quantile plot), and regression analysis using the least-squares method. Residuals were computed, plotted and a surface derived using the kriging interpolation technique with a cell size of 0.2 m. The lidar data are the predicted values and RTK GPS data were assumed to be the observed true ground measurements.

Lidar Data

The density and accuracy of data unique to laser systems offers an alternative solution to the difficulties of ground surveying while providing relatively accurate data at densities > 50,000 points per km^2 not feasible with other survey technologies (Gomes Pereira and Wicherson, 1999; Irish and Lillycrop, 1999; Lohani and Mason, 2001; Bowen and Waltermire, 2002). Due to the rapid laser firing, pulses can penetrate partly into and possibly through the vegetation cover of a landscape. This feature makes lidar technology particularly well suited for measuring topography in marsh environments (Ackermann, 1999). Laser data allows for determination of two-way travel times though, the post-processing necessary for bare earth measurements due to the vegetation can be a drawback.

On 16 January 2003, Airborne1 Corporation carried out a mission to collect lidar data of the North Inlet-Winyah Bay landscape for Georgetown County. From the larger dataset, high-density sections with 0.25 m spacing through the central part of the island were provided for this study. The midsection swath is approximately 0.06 km^2 in area and is comprised of 144,384 lidar data points producing a swath that trends northwest to southeast (Figure 2). This 140 m wide swath was chosen due to its accessibility by boat and foot and the vegetation in this area was low enough to facilitate the collection of ground measurements needed for this experiment.

From an airborne platform 1,150 m above ground level, Optech Inc.'s. ALTM 2025 lidar pulse system traveled at 51 ms^{-1} and delivered laser shots at 25 kHz per second. The lidar mission was flown during low tide, with the creeks mostly dry. Airborne1 Corporation processed the data and delivered bare-earth 3D values. Post-processing software determined the kinematic trajectory from the flight GPS file and the ground GPS (base) file. This trajectory combined with the IMU data yielded the best estimate trajectory. This trajectory was used to compute shot positions on the ground and then converted to client dependent specifications (Personal Communication with B. Bertrand, Director of Data Processing, Airborne1 Corporation).

Post-processing generated a bare earth file compilation from portions of four flight lines with over 220,000 *X, Y*, and *Z* values over the island. The stated accuracy of this data is ±12 cm (Airborne1 Corporation, 2003) which is partially determined by how well features, including vegetation are classified and filtered. The lidar data presented here are referenced to NAD 83/NAVD 88 computed using the Geoid99 model.

RTK GPS Data

The Trimble 5700 RTK GPS System includes a rover setup with a windows based Trimble Survey Controller (TSCe™) and an integrated base station receiver that combines dual-frequency RTK with Trimble GPS technology. With this system, centimeter-level accuracy (horizontal ±1 cm and ±2 cm vertically at 68 percent confidence) in all three dimensions can be expected (Large *et al.*, 2001; Trimble Navigation, Ltd., 2002). The accuracy of RTK GPS is largely due to the local constraints or network used for the study. For this study site 11 NGS published monuments comprise the network, including two benchmarks established on the island. The purpose of network calibration is to remove random errors and provide a single solution, which ensures repeatability of current and future measurements (Trimble Navigation, Ltd., 2002).

The Trimble 5700 base receiver was placed on the tidal benchmark PID Number DD1355 having first order horizontal and vertical accuracy (±0.5 cm) (Federal Geographic Data Committee, 1998). The two control points on the island installed by the South Carolina Geodetic Survey (SCGS) are PID Number AJ5767 on the northern end and PID Number AJ5765 in the southern portion, both of first order accuracy.

Results

Subtracting the RTK GPS data from the lidar elevation within the 37 cm footprint of 109 targets yielded a mean elevation difference of 9.6 cm and does not appear to have any pattern that may correlate spatial variability and elevation error in this low-gradient setting (Figure 3). A linear regression produced a slope of −0.281 and an R^2 of 0.007, these values further show little correlation between the footprint area topography and the elevation differences determined from the lidar and RTK GPS data. Therefore, the effects seem negligible at this site.

The combined platform and creek dataset illustrates a frequency histogram with a single peak and a small gap in the distribution at −0.4 to −0.5 m (Figure 4a). To discern if outliers resulted from the data type (i.e., platform versus creek), these data were evaluated separately. The platform-only histogram shows no gaps or obvious outliers, and both sides are fairly smooth from a single center peak illustrating the distribution of the platform elevation differences are approximately normal (Figure 4b) having a mean of 7.2 cm and standard deviation 8.3 cm. On the other hand, the creek-only histogram is slightly right-skewed and accounts for the gaps and outliers in the data (Figure 4c).

Normal probability plots are used to judge whether data are approximately normally distributed. Figure 5 shows this plot and that a normal distribution fits this entire dataset well. Scatterplots for the lidar datasets (predicted) and RTK GPS (observed) were compiled (Figure 6a, 6b, and 6c). A visual inspection of the combined data plot exhibits an irregular scattering at lower elevations (e.g., creek-only data) and a dense grouping in the top portion (platform-only data) (Figure 6a). Divided into separate creek and platform components, Figure 6b illustrates the creek-only data

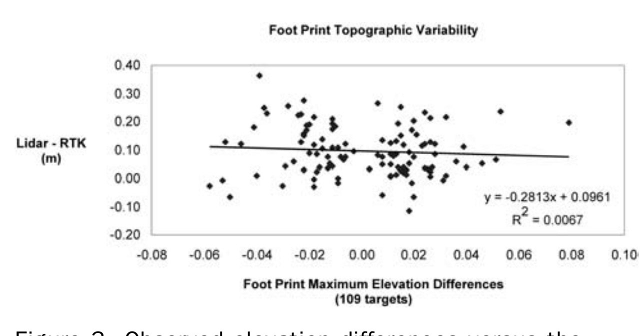

Figure 3. Observed elevation differences versus the slope from within a 37 cm radius about 109 targets. Graph shows little correlation between elevation error and the spatial variability within laser footprint area. Slope of linear regression = −0.28, R^2 = 0.0067.

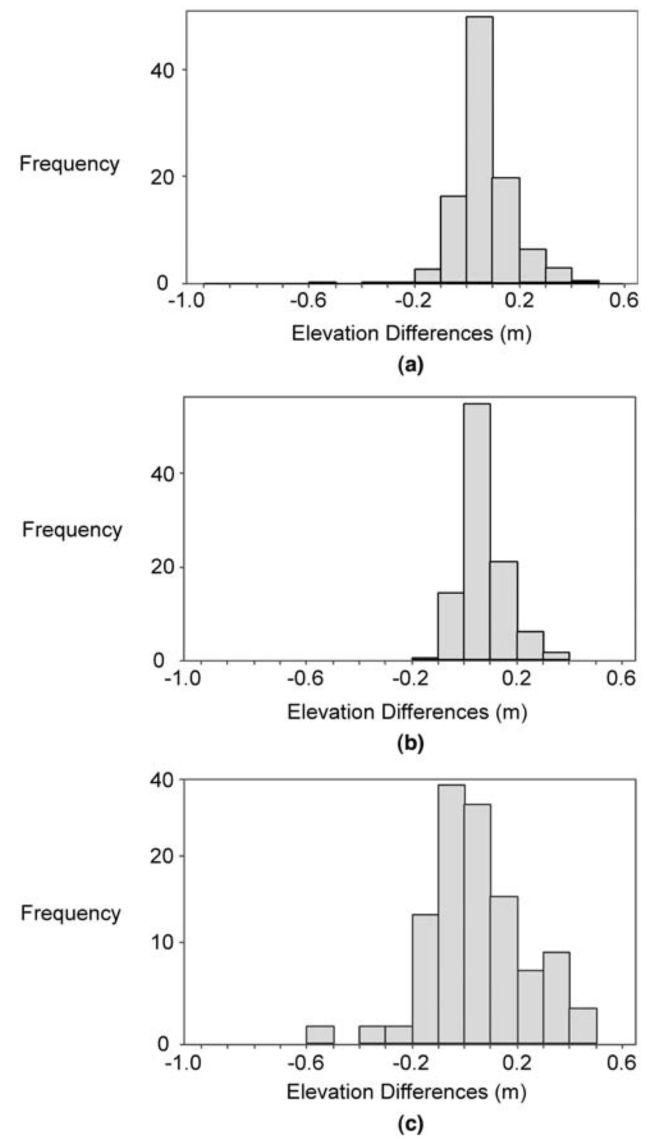

Figure 4. Distributions of (a) combined, (b) platform and (c) creek-only Lidar – RTK GPS data show an approximately normal distribution of elevation differences.

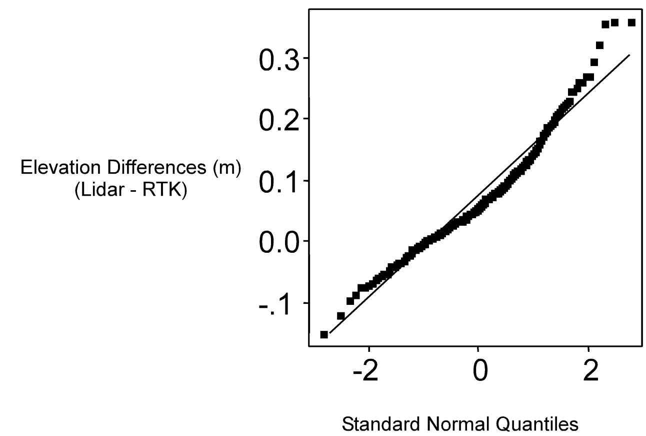

Figure 5. Normal quantile plot of the elevation differences shows a normal distribution provides an accurate model for this dataset.

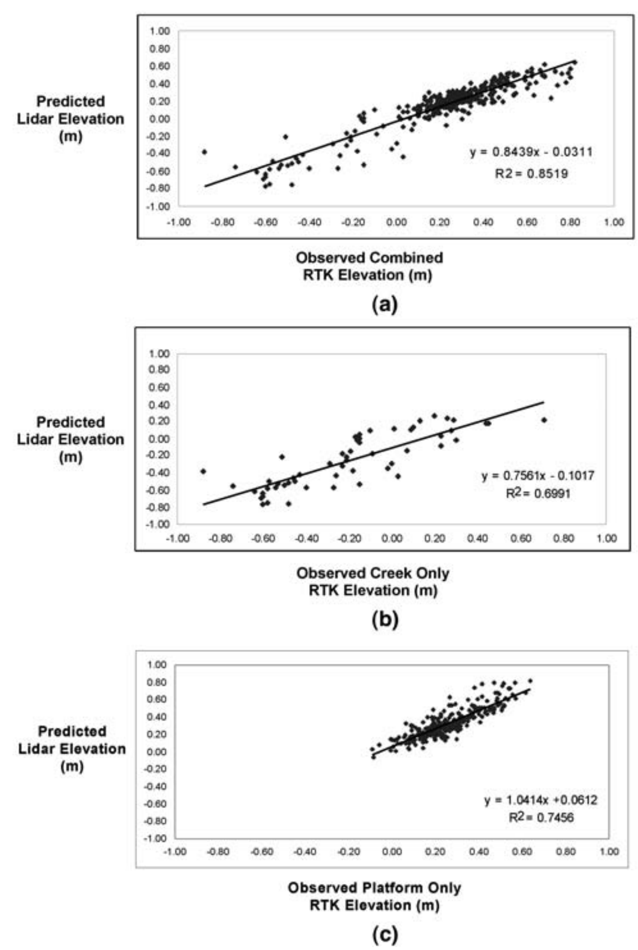

Figure 6. Scatterplots illustrating the overall linear patterns of the elevation differences within the (a) combined, (b) creek-only, and (c) platform datasets.

responsible for the lower irregular scattering and the denser top grouping as the platform-only dataset (Figure 6c). The combined data have a slope of 0.84 and an R^2 of 0.85. The creek-only dataset has a slope of 0.75 and R^2 of 0.69. The data with the best-fit linear relationship were the platform-only where the model equation derived a slope of 1.041, an R^2 of 0.75, and a RMSE of 0.083.

The residual plot for the platform-only data (Figure 7a) does not show any significant deviation from the fitted least-squares line given in Figure 6c. Residual plot for the combined data (Figure 7b) shows a similar pattern to Figure 6a where the irregular pattern of the creek-only data is followed by the dense cluster of the platform-only data. Confidence intervals for 99 percent were used to further constrain the analysis. It was found that the best estimate for the difference between the lidar and RTK data at a single standard deviation was for platform-only data (7.2 cm). The true mean lies within the confidence interval 5.9 cm and 8.5 cm (Table 1). The best estimate of precision of the difference is ±8.3 cm and the true precision lies between 7.5 cm and 9.4 cm. For the combined and creek-only datasets the mean is 6.9 cm and 5.5 cm, respectively.

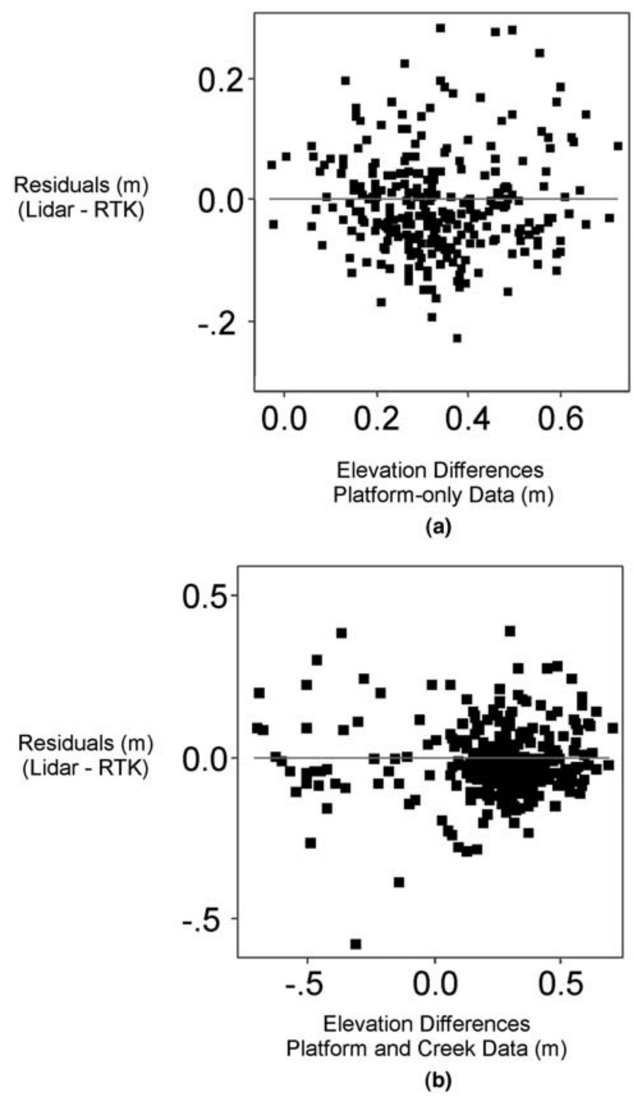

Figure 7. Residual plots for the least-squares regression in (a) platform-only data, and (b) platform and creek data. Unstructured horizontal band centered at 0 shows that the relation is best (linear) for the platform-only data.

Table 1. The Best Estimate for Combined, Platform and Creek-only Datasets, Mean Error and its Precision with Corresponding Upper and Lower Limits of Their 99 percent Confidence Interval

		99% Confidence Interval	
Parameter	Estimate	LCL*	UCL**
Combined Mean	0.0691	0.0537	0.0845
Combined Std Dev	0.1086	0.0987	0.1205
Platform-only data Mean	0.0719	0.0589	0.0849
Platform-only data Std Dev	0.0834	0.0751	0.0935
Creek-only data Mean	0.0551	−0.0127	0.1229
Creek-only data Std Dev	0.1902	0.1523	0.2504

*Lower Confidence Limit.
**Upper Confidence Limit.

Discussion

Very little is known about the quantitative aspects of topography within intertidal zones. Few detailed quantitative field measurements exist to assess the complexity of saltmarsh topographical divides or micro-flow paths on the platform, as well as gradients, channel geometry and subsequent in-creek and overland flows (French and Stoddart, 1992). An accurate depiction of low-gradient topography is fundamental to current and future research in the saltmarsh setting. Technologies used in this analysis of lidar show that for the marsh platform, lidar works well. However, particular care and site ground data need to be included for the creek networks and levees. The data presented here were acquired during times when the creeks were mostly dry; this yielded a difference between the combined and creek-only data of 1.7 cm, which is within instrument error.

Within the target laser footprint, there is a 37 cm horizontal radius that comprised the actual target spot. Taking additional data points within this radius and determining the largest possible elevation change relative to the observed lidar and RTK differences showed that the varying topography within this footprint was negligible. This result was not surprising given the low gradient environment (approximately 0.0008) and a small target radius of <37cm. The least-squares regression suggested that the variability (vertical spread) slightly decreased as the maximum elevation difference for the targets increased (Figure 3). Even though the varying topography in this setting within a small footprint did not seem to have an effect here, other studies completed in areas with larger topographic relief and variable terrain demonstrated that errors may increase with increasing slope (Bowen and Waltermire, 2002; Hodgson and Bresnahan, 2004). In this salt marsh setting we found no distinct correlation between increasing slope and increasing lidar elevation error and therefore, conclude that slope does not affect lidar-derived data accuracy in this setting.

The sample distribution is normally distributed with a slight right skew, indicating larger observation differences fall distinctly to the right of the main body of points (Figure 4a, 4b, and 4c). This slight right skew could be due to the higher and denser vegetation on and near the creek levees. Normal probability plots provide a more sensitive assessment of the adequacy of the normal model for the dataset. This is the recommended tool for assessing normality (Moore and McCabe, 1993) and Figure 5 shows that a normal distribution does provide an accurate model for the data set.

The overall pattern of the least-squares regression describes the platform-only data very well and as expected, the relationship is strongly linear (Figure 6c). The platform-only data R^2 value of 0.75 indicates that in this study, the linear regression explains 75 percent of the observed variation in the elevation differences between the lidar and RTK GPS. Furthermore, an analysis of the residuals (Figure 7a) magnifies the vertical deviations of the data points from the fitted regression line. The line (residual = 0) corresponds to the fitted line in Figure 6c for the regression model of the platform data. The residuals show the irregular unstructured horizontal pattern centered fairly symmetrically about zero (the mean of the residuals), typical of data that do not deviate from the model in any systematic way. A surface plot of the residuals geographically shows where the deviations are between the lidar and the observed RTK GPS data. These deviations are reasonably greatest around the creek network where the higher vegetation interferes with the lidar laser (Figure 8). The majority of the study site where the vegetation is shorter and less dense did not seem to affect the accuracy.

The best estimate for the lidar data accuracy (the average difference between the lidar and RTK data) is 7.2 cm, and the best estimate of the precision of this value is ±8.3 cm from the platform-only data (Table 1). Confidence intervals

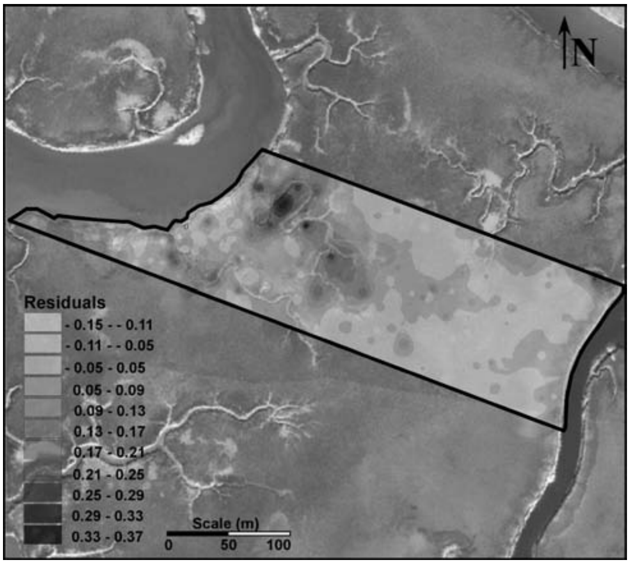

Figure 8. Surface plot of residuals in their geographical location. Darker areas show where the elevation errors are greatest, mostly around the creek network where there is higher and denser vegetation.

used to predict the mean for the entire population of the lidar elevation relative to the RTK GPS ground data substantiate our conclusions by probability calculations. From the confidence intervals calculated there is 99 percent confidence that the true mean (accuracy) and the precision for the platform-only data best estimates are within 5.9 cm to 8.5 cm and between 7.5 cm to 9.4 cm, respectively (Table 1). From this, we can statistically infer with 99 percent accuracy that if our best accuracy estimate (7.2 cm) were subtracted from the platform lidar dataset, we would have a dataset with the increased density given by the lidar technology and the better accuracy of the RTK GPS system. For around the creek networks, the adjustment factor would be 5.5 cm and the combined adjustment value for both the marsh platform and tidal creek networks is 6.9 cm. Despite the dense vegetation, lidar by itself is a useful tool for depicting topographic detail of the marsh surface and (dry) creeks. Lidar-based DEMs have also been found to provide a resolution and accuracy acceptable for many objectives (Toyra *et al*., 2003). However, site ground data should be acquired to ensure verification and report its depicted accuracy.

Conclusions

In this study, the mean difference between lidar-derived elevations and RTK GPS-derived elevations was investigated. Detailed quantitative topographic data are needed to better research, simulate and fully understand intertidal zone processes, development and geomorphology of low gradient salt marshes. Lidar technology has the ability to obtain dense data nearly simultaneously over large areas. Due to the inherent difficulty of conventionally acquiring these data in salt marsh environments, it makes sense to assess the ability of lidar technology to accurately depict this dynamic environment.

The varying vegetated topography did not significantly affect lidar elevation accuracy (Figure 3). The distribution of the elevation errors was reasonably normally distributed (Figure 4a, 4b, and 4c). Linear regressions further show good fit between the predicted lidar elevations and the observed RTK GPS elevations with the best being 1.04 illustrated by the platform-only data (Figure 6c). Residual analysis magnified the vertical deviations between the observed values and the value predicted by the model (least-squares regression analysis), and showed that the data did not deviate from the model in any systematic way for the platform-only data. However, the creek-only data were systematically on the lower end of the graph (Figure 6a and 6b). The best mean difference in the platform-only elevations is 7.2 cm with a precision of 8.3 cm. Confidence intervals were computed for the best estimates to give 99 percent confidence of the probability that the method produced an interval encompassing these parameters. From this we can conclude that the mean value of 6.9 cm may be used as a best estimate adjustment factor for incorporating lidar with other data used in studies and simulations for low gradient salt marshes in this area. For the platform-only or creek-only areas the best estimates of 7.2 cm and 5.5 cm, respectively, should be used (99 percent confidence).

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