Resolution and Accuracy of an Airborne Scanning Laser System for Beach Surveys


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ABSTRACT

Airborne scanning laser technology provides an effective method to systematically survey surface topography and changes in that topography with time. In this paper, the authors describe the capability of a rapid-response lidar system in which airborne observations are utilized to describe results from a set of surveys of Narrabeen–Collaroy Beach, Sydney, New South Wales, Australia, over a short period of time during which significant erosion and deposition of the subaerial beach occurred. The airborne lidar data were obtained using a Riegl Q240i lidar coupled with a NovAtel SPAN-CPT integrated Global Navigation Satellite System (GNSS) and inertial unit and flown at various altitudes. A set of the airborne lidar data is compared with ground-truth data acquired from the beach using a GNSS/real-time kinematic (RTK) system mounted on an all-terrain vehicle. The comparison shows consistency between systems, with the airborne lidar data being less than 0.02 m different from the ground-truth data when four surveys are undertaken, provided a method of removing outliers—developed here and designated as “weaving”—is used. The combination of airborne lidar data with ground-truth data provides an excellent method of obtaining high-quality topographic data. Using the results from this analysis, it is shown that airborne lidar data alone produce results that can be used for ongoing large-scale surveys of beaches with reliable accuracy, and that the enhanced accuracy resulting from multiple airborne surveys can be assessed quantitatively.

1. Introduction

Beach surveys were originally undertaken using traditional surveying techniques, such as the Emery method (Emery 1961), but with the advent of global positioning system (GPS) technology, it has become much simpler to use such positioning devices on all-terrain vehicles (ATVs) as described by Short and Woodroffe (2009). Even so, such vehicles need to be driven in parallel tracks along the beach, and the time available usually dictates the spacing between tracks. Steep slopes caused by storm erosion can also be limiting factors to vehicle operation.

Airborne scanning lasers have major advantages over ground surveys when spatial resolution is important, the terrain has steep slopes, and/or there is a need for repeated surveys over a short time or a large area of interest to be covered. Airborne lidar data can provide near-complete coverage that reduces the need for interpolation. Importantly, the ground and airborne methods complement each other, allowing rapidly repeated surveys, but with high accuracy. The word “run” is used here to describe an airborne survey comprising a single overflight.

Gutierrez et al. (2001) appear to have made the first detailed comparison of airborne lidar with ground survey data, estimating a horizontal resolution of 1 m or less, and a vertical accuracy of 0.10–0.15 m. Sallenger et al. (2003) compared data from a National Aeronautics and Space Administration (NASA) Airborne Topographic Mapper (ATM) flown in a De Havilland Canada (DHC)-6 Twin Otter with three different types of ground-truth topographic data from segments of coastal beach in North Carolina. The lidar equipment, originally intended for monitoring the Greenland ice sheet, was designed and built specifically by NASA. The base station used for GPS corrections was located nearly 50 km from the
survey site. The analysis concluded that ATM random errors in altitude were approximately 0.11 m with means varying from 0.02 to 0.13 m. There was a root-mean-square (rms) error of approximately 0.15 m, including both random and mean errors, when comparing ground-truth data with the airborne lidar data. Sallenger et al. (2003) reported that mean errors vary with location and appear to play a role in degrading data from a number of runs, reducing confidence in the system, and with the mean errors varying with location.

Robertson et al. (2007) evaluated storm erosion, noting the Sallenger accuracy, while Yates et al. (2008) developed a method to eliminate water returns. More recent work by Vrbancich et al. (2011) was also water surface related. Apart from the earlier Gutierrez or Sallenger work, there does not appear to be published in the refereed literature any direct comparison of ground-truth data with airborne data for an actual beach, where small-scale topographic variability or steep slopes may be present.

Recently, Reineman et al. (2009) demonstrated the effective use of a Riegl Q240i lidar with a Coda Octopus F180 + GPS/Inertial Navigation System (INS) to provide position, altitude, and attitude information of the aircraft for a variety of applications including water waves, landslide slippage, and beach survey. Vertical accuracy of the lidar was assessed by comparing data from various hard surfaces (Reineman et al. 2009), but it appears that there was no comparison against beach surface data acquired from surface-based observations. After georectification and topographic evaluation, the elevation accuracy from hard surfaces was estimated by Reineman to be approximately 0.087 m rms and the horizontal position was approximately 0.42 m. Huang et al. (2012) utilized the same lidar equipment to produce estimates of waveform and dissipation around a coral reef; however, they made no further comparisons of elevation accuracy.

In this paper, the authors report on a set of beach topography observations made using an airborne scanning laser system of the same lidar type as used by Reineman et al. (2009), but with different positioning and attitude systems, and compare these data with data acquired using an established ground-based observational technique (Harley et al. 2011). Two methods of data analysis are compared, one being a new method developed that is demonstrated to improve accuracy progressively as additional airborne surveys are undertaken over the same surface. Resolution and accuracy are estimated, and some methods of dealing with multiple runs the same day are discussed. Other work describing the beach dynamics observed during an erosion-inducing storm will be reported elsewhere.

2. The data acquisition system

The airborne system is designed to fit in the rear luggage compartment of a small twin-engine Piper PA44 airplane, which can readily accommodate two scientific operators and a pilot, and has a useful flight endurance of up to 4 h. The system can be configured in 3 hours and decommissioned in less than an hour and, including batteries and data logging computers, it weighs less than 30 kg.

The primary instrumentation is a Riegl laser measurement system (LMS) Q240i laser scanner that utilizes an optomechanical scan mechanism, and pulsed time-of-flight range measurements to measure surface topography at altitudes of up to 500 m above the surface. The maximum scan rate is 80 s⁻¹ and the maximum data measurement rate is 10 000 s⁻¹, while the total scanning angle is 60° (i.e., 30° on either side of track).

Position and orientation within the moving airplane is measured with a NovAtel SPAN-CPT Global Navigation Satellite System (GNSS)/INS. The SPAN-CPT nominal accuracy of 1.5 m at 100 Hz is greatly improved if real-time kinematic (RTK) corrections are used, in which case optimum accuracy (i.e., rms) is specified as 0.02 (horizontal) and 0.05 m (vertical).

The NovAtel system is connected to the top of the lidar, immediately above the scanner system. The GNSS antenna is mounted in the roof of the airplane directly above the NovAtel, and the system is surveyed to determine distances and orientations. Such information is important for the generation of the final georeferenced data, which must also be corrected for aircraft motion, position, and orientation.

Both GNSS/INS and lidar are connected to a base plate, which is connected to the airplane via shock mounts to absorb high-frequency engine vibration. The lidar scans through an approved observation port built into the floor of the rear luggage compartment of the airplane (Fig. 1). Power is provided by portable battery packs, and data are logged onto portable computers. The setup is shown in Fig. 2, which shows the interior of the luggage compartment as viewed from the starboard side of the fuselage.

The lidar scans downward with the scan arc oriented at right angles to the longitudinal axis of the airplane. As the airplane flies along its track, the lidar scanning points describe parallel paths on the earth’s surface running essentially cross track. Resolution along the scanning path (across the flight path) is determined by the sampling rate, and along the flight path is determined by the scanning rate and airplane ground speed. Ground-truth data are acquired using a GNSS/RTK system (Trimble R-6) mounted on an ATV that is driven along the beach.
from end to end in parallel tracks that approximately follow the contours (Harley et al. 2011).

Our expectations of the quality of the data are as follows. Reineman et al. (2009, p. 2631) undertook comparisons of elevation data from flying over the Ramona airport runway and found rms elevation deviation from 17 passes to be 0.087 m, and consistent with on-ground airplane taxiing surveys that resulted in 0.09–0.11 m rms difference in elevation. This is within 1 m \times 1 m horizontal grids. Further, a comparative study between a ground-based GPS survey and the airborne lidar was also undertaken for the lagoon at Lady Elliot Island (their Fig. 14) and showed that the difference was \(<0.10\text{m} \text{rms} \) height for exposed coral head targets. In terms of horizontal accuracy, we note that the SPAN-CPT system has a standard deviation \(<0.02\text{m}\) [Table 5 of Kennedy and Rossi (2008)], which could lead to horizontal differences as low as approximately 0.10 m when flying at 300-m (1000 ft) altitude.

### 3. Data analysis methodology

The binary file format produced by the LMS Q240i is in the Riegl propriety “.2dd” format and needs to be converted to a format with known fields. Fortunately, the Riegl application “3ddTOasc.exe” can carry out this conversion. The software takes the reformatted laser scan file, and the position and attitude file from the SPAN-CPT, and generates a point cloud file in either laser file format (LAS) or plain text (ASCII) format (Mumford et al. 2011). To do this a cubic spline is used to fit the SPAN horizontal position data, which are then interpolated to provide position and orientation for each point of the much denser lidar dataset. The location data in the LAS files are converted to universal transverse Mercator (UTM) coordinates.

An orthogonal (rectangular) horizontal grid is selected, and the data fields for successive airborne lidar runs or ground-based surveys are then interpolated to that grid using natural neighbor interpolation. This produces sets of topographic height data at common grid points that can be used for comparison. Bicubic interpolation and inverse distance weighted and radial basis functions were all investigated, but the natural neighbor interpolation was found to offer the best compromise between filtration of noise, speed, memory requirements, stability, and ability to capture high-frequency details (i.e., beach erosion scarps). The Matplotlib implementation of natural neighbor, which is the standard method of interpolating data to a grid in Matplotlib, was utilized. The interpolated gridcell horizontal resolution was chosen as 0.25 m in order to capture fine details such as scarps. This value was chosen on the basis of estimates of horizontal resolution of 0.10 m of the SPAN-CPT as described by Kennedy and Rossi (2008) and by the manufacturers.

The lidar datasets may include multiple runs from the same day (up to three at any flight altitude, and up to two altitudes with the data described therein). The ATV surveys are limited to one per day due to the time taken to undertake a full survey along the approximately 3.5-km-long Narrabeen–Collaroy embayment, which is located on Sydney, New South Wales, Australia’s, northern beaches. The timing of all runs and surveys is centered around spring low tide to get as much coverage of the subaerial beach as possible. In Sydney this is usually around 1300–1400 local time (LT), so that surveys are achievable in daylight. As the primary interest is in the topography of the beach and sand dunes, but not buildings, the data are filtered to retain only the geographical area of interest. Thus, a grid of lidar-derived beach elevations is obtained at every horizontal gridpoint location \((i, j)\), which is designated here as \(Z_{ij}^{L}\).

Raw ATV height data are typically acquired approximately every 3 m along the wheel track, with parallel tracks separated by approximately 4 m. The accuracy of
such height data using GNSS/RTK has been examined in detail and compared to conventional methods by Harley et al. (2011), who found differences in mean of $-0.03$ m and standard deviation of $0.13$ m. With ATV data, the same analysis method is used to create grid-point height data at the same horizontal resolution and at the same exact horizontal grid points as the lidar data. Only those grid points within $0.25$ m of either side of the ATV data tracks will provide useful data. ATV data at each $(i, j)$ grid point is designated as $Z_g^A$. 

### a. Comparisons of single-pass lidar datasets

Because of the spatial resolution of the raw lidar data, $0.25$ m $\times$ $0.25$ m grid cells (referred to herein as tiles) often do not contain a measurement point, and the resulting interpolated values have increased uncertainty in horizontal height and position. With single runs it is more difficult to detect outliers in data caused by, for example, wave run-up or large seabirds such as pelicans, and there is an advantage in using data from multiple runs.

### b. Comparisons of multiple-pass lidar datasets

When there are multiple lidar datasets (say, $N$ sets from $N$ survey runs), the uncertainties for each tile can be reduced by the following:

1) averaging the $N$ height estimates at each grid point to create the topographic height, or

2) creating a “weaved” dataset. In this case for each grid point with $N$ height estimations all sets of $K$ heights (usually $K = N - 1$) are considered, and the set is chosen with the lowest standard deviation of heights. The mean of that set then becomes the topographic height estimate for that tile. As an example, if there are $N = 4$ sets of data, then there are four possible combinations of choosing $K = N - 1 = 3$ runs (the number of possible combinations of choosing three samples from four is defined by $4C3 = 4$). The set of three having the lowest standard deviation would be chosen and the average height for that set is designated as the topographic height for that grid.

Once the calculations described above are undertaken for each tile, a full dataset of topographic estimates is available. It is then possible to compare an averaged or weaved dataset from a set of runs with a set from another survey—for example, another set of runs taken from the same or different flight altitude, or with a ground-based dataset from an ATV survey.

### 4. Results

The data described here were acquired from Narrabeen–Collaroy Beach, which has been monitored for over 35 years (Turner et al., 2011; Short and Woodroffe, 2009), and is also close to the operational base of the University of New South Wales (UNSW) School of Aviation at Bankstown Airport in Sydney.

Narrabeen–Collaroy Beach is approximately 3.5-km long, 15–30-m wide, and distinctly embayed (or “curved”), so it becomes a difficult task to deal with all the datasets encompassing the entire beach. Therefore, it was decided initially to work with two contiguous segments of beach; that is, segments contiguous in the direction along the beach. These segments were chosen as being typical, having been well covered by both lidar and ATV surveys, and having some changes in topography during the monitoring period. The segments are $200$ m $\times$ $200$ m in size, although the beach is between 30- and 80-m wide, and the masking of location to eliminate areas landward of the dunes is necessary. Later, a comparison of data for the full length of the beach is undertaken. The locations of the beach, and of the two segments, are shown in Fig. 3. The southwestern corners of the two segments are located at UTM coordinates (grid 56H; 342400, 626800) and (grid 56H; 342400, 6267800).

### a. Data point density on the ground

To give the reader an idea of raw data point density on the ground when observed by the airborne lidar scans, data points are plotted in a schematic diagram (Fig. 4). In general, the cross-track distance between data points is determined by (and is proportional to) aircraft elevation above the ground, while along-track distance is determined by scanning frequency and ground speed. Some general idea of the contours is given by the horizontal point density that will change according to the slope of the beach contours. Data point density from 1000-ft flight altitude is approximately one point every 1.6 m².

### b. Comparison of single-lidar data runs with ATV data

Before discussing comparisons of ATV data and lidar data, it is useful to first gain a general idea of the nature of the beach. Figure 5 shows a contour diagram of topographic elevations from a single lidar run at 1000 ft, and an aerial photograph taken concurrently from the same segment. These images provide an idea of the general shape of the beach used in the calculations below, and show the landward dunes to the left of the contoured area and the sea at the middle right of the contoured area.

For the more general analysis of errors and offsets, the following methodology was used. For each lidar survey run, calculations were made for the $200$ m $\times$ $200$ m segments. The calculations included each $0.25$ m $\times$ $0.25$ m tile for which both ATV and lidar data were available, and for each of these tiles values were calculated for mean
and median values of altitude. Calculations were then made for the ensemble of tiles in this segment being:

- The mean value of the height differences: Mean $(\bar{Z}_{ij}^L - \bar{Z}_{ij}^A)$,
- The median value of the height differences: Median $(\text{Median}(Z_{ij}^L - Z_{ij}^A))$, and
- The standard deviation value of the height differences.

Table 1 shows times and altitudes of flights undertaken on 13 July 2011. The results of the analyses are shown in Table 2 for the northern segment. Run 7 is somewhat anomalous, having differences generally more than twice that of every other survey. From the Riegl website, we note that 500-m altitude (1640 ft) is approaching the maximum that would give satisfactory return intensity from a sand surface. Comparison of return relative intensities for each of the runs indicates that the relative intensity was lowest for run 7, which was also at the highest altitude. The low intensity is just one possible explanation of the poor comparison, but it serves as a warning that interpretation of single runs can be problematic, as there is no way of discriminating between outliers and good data.

To provide a comparison, the equivalent data for the next segment south are shown in Table 3. For this segment, the data from run 7 also seem somewhat anomalous in that the differences between lidar and ATV data...
are significantly worse for that run. We conclude that we would not be able to identify, without comparison against ground-truth data, a problematic dataset from a single run. It makes sense, therefore, to sample at altitudes where the return signal will clearly be suitably strong, and to acquire data from multiple runs.

c. Comparison of weaved lidar data runs with ATV data

Having multiple runs allows some additional calculations to improve the lidar-derived elevations, and in this section the advantages of utilizing multiple datasets are outlined. In effect there are five usable survey runs, with run 7 being inconsistent. Calculations are undertaken with the five usable runs separately, and with all six runs to determine mean and standard deviations between the airborne lidar and the ATV data. These are shown in Tables 4 and 5.

Using the weaving technique and analyzing data from two survey runs of the six available, there are 6 choose 2 \( (6C2) = 15 \) combinations for each \( 0.25 \text{ m} \times 0.25 \text{ m} \) tile. For two runs, the only way to estimate the lidar height is by averaging lidar results for each tile and comparing these to the ATV data. Comparisons between the lidar- and ATV-derived elevations for each of the 15 combinations were calculated, and the average and standard deviations for the set of these 15 combinations are presented in Tables 4 and 5.

If three airborne survey datasets are used rather than two, then the total number of combinations for each tile is \( 6C3 = 20 \). In this case, the “weaving” method described earlier that eliminates the point height having the greatest difference from the other two may be chosen. Results for these have also been aggregated, and the mean and standard deviations of these 20 results are also calculated. Averages and standard deviations of these results are shown in Table 4 for the northern segment.

**Table 1.** Lidar flight surveys undertaken on 13 Jul 2011 at Narrabeen Beach. Low tide was at 1212 LT.

<table>
<thead>
<tr>
<th>No.</th>
<th>Start time (local)</th>
<th>Altitude (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1240</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>1244</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>1247</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>1252</td>
<td>1500</td>
</tr>
<tr>
<td>8</td>
<td>1257</td>
<td>1500</td>
</tr>
<tr>
<td>9</td>
<td>1301</td>
<td>1500</td>
</tr>
</tbody>
</table>

**Table 2.** Comparison of lidar data with ATV data from the northern segment for the six runs flown on 13 Jul 2011 at two altitudes, 1000 and 1500 ft. The mean and median are evaluated using the algorithms described in section 4b.

<table>
<thead>
<tr>
<th>Run</th>
<th>Altitude (ft)</th>
<th>Differences</th>
<th>Relative intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (m)</td>
<td>Median (m)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>0.0828</td>
<td>0.0884</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>-0.0360</td>
<td>-0.0445</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>-0.0271</td>
<td>-0.0409</td>
</tr>
<tr>
<td>7</td>
<td>1500</td>
<td>-0.2390</td>
<td>-0.2459</td>
</tr>
<tr>
<td>8</td>
<td>1500</td>
<td>0.0313</td>
<td>0.0338</td>
</tr>
<tr>
<td>9</td>
<td>1500</td>
<td>-0.0163</td>
<td>-0.0159</td>
</tr>
</tbody>
</table>

**Fig. 5.** For 27 Jul 2011, (left) aerial photograph of the northern segment used for analysis, and (right) beach topographic elevations taken from the woven airborne lidar data survey of that segment at 1000-ft altitude. Topographic contour interval is 0.25 m.
To serve as a comparison, the data are also evaluated for the next segment south and are shown in Table 5. A number of features are evident for both segments and these are summarized below.

The 5C1 data
- Excluding the outlier run 7, the mean difference between the ATV and lidar data is less than 0.01 m, with the standard deviation less than 0.05 m. This is a very useful result, as it shows not only an internal consistency between lidar runs, but also that both ATV and lidar data are reliable and repeatable.

The 6C1 data
- Averages and standard deviations of the six runs, designated the 6C1 data (including run 7), show less consistency than the 5C1 data as might be expected, with the average offset now 0.03 m and standard deviations up to approximately 0.11 m. The average offset for the averages for all three sets of mean calculations is approximately 0.03 m, showing that there is still no significant difference between estimates of the offset of lidar and ATV data when one considers the general undulating nature of a beach surface.

The 6C2 data
- The beneficial effects of weaving become apparent, and the significantly reduced standard deviations are evident in all the estimates compared with the 6C1 data. Weaving with two runs is clearly beneficial, as the standard deviations are now comparable to those with the 5C1 data, which excludes run 7.

The 6C3 data
- Standard deviations of the differences of mean remain small and approximately 0.03 m, and are now better than, or as good as, the results of the 5C1 run.

A plot of the distribution of absolute values of the medians for the 6C2 estimates is shown in Fig. 6, and overlaid is the plot of a normal distribution having the same average and standard deviation. It is evident the data are approximately normally distributed.

d. Comparison with datasets from the entire beach

Additional calculations are undertaken using data from the ATV surveys of the entire beach from swash to the vegetated areas, and along the entire 3.5-km length

![Graph showing distribution](image)

**Fig. 6.** Distribution of mean height difference for the 6C2 combinations (solid line) plotted together with the normal distribution having the same mean and std dev (dashed line).
of sand, by comparing against data from the airborne surveys. Both ATV and airborne raw datasets are processed and interpolated as described above, and comparisons are made for the 0.25 m × 0.25 m tiles, where the ATV data had recorded values.

These results are shown in Fig. 7, which depicts the results of the analyses for the entire beach. Here, comparisons are made for 7265 grid points of data acquired on 14 June 2011. In Fig. 7, the x axis shows a measure of the average height of the beach as determined by the ATV, with the sea to the right in the same orientation as in the topographic colored contour diagrams. The origin (zero) shows the mean sea level coastline. The y axis on the top panel is the elevation difference estimated...
between airborne lidar and ATV estimates. No effort has been made to adjust such data to compensate for the impact of swash or to cater for the steep scarp areas. Dots refer to differences as deduced by averaging the airborne data and subtracting the ATV data, while triangles depict differences obtained from subtracting the ATV data from the lidar estimate obtained using the weaving method. The bottom panel depicts the standard deviations evaluated for each of the datasets whose means are depicted in the top plot.

The right-hand group of data between 0.0- and 0.5-m topographic height shows the influence of swash, in that the airborne data shows consistently higher readings of up to 0.2 m, as they measure the swash height that will always be equal to or higher than the sediment height. Standard deviations in this area are approximately equal to the means. In this region weaving reduces mean differences and standard deviations, but it does not eliminate such effects.

Between 0.5- and 3-m topographic height, the beach is gently sloping with a slope of <0.1. In this area, there is a consistent height difference of 0.03–0.05 m, with the airborne data reading lower than the ATV data. This is consistent with the results of Tables 4 and 5. Standard deviations in this area of beach are of similar values of <0.05 m, a better result than that obtained by Reinem et al. (2009) and fully consistent with the instrumental accuracies as specified by the lidar manufacturer and the ATV-acquired data. The weaving method also produces some advantages in reducing both means and standard deviations.

In the areas where the topographic height lies between 3 and 6 m, the effects of grid resolution and the steep topography associated with the scarp become apparent. Mean errors in these areas rise to 0.2 m, and standard deviations vary up to 0.5 m. Beyond 6-m topographic height, the highly variable beach height in and near the public walkways and vegetation appears to be having an adverse effect on data consistency. This area has strong topographic slopes, both perpendicular to and parallel to the mean coastline. There are four points in the standard deviation panel that lie beyond the range of the plot with values of 0.6–1.0 m not shown in Fig. 7.

A summary of the analyses is shown in Table 6, with means and standard deviations indicated for both the averaged and weaved methods. The means lie between 0.12 and 0.14 m; however, the values (which are higher than those in Tables 4 and 5) are affected by the higher values shown in the swash and upper beach areas in Fig. 7. By comparison, the median values are only a few centimeters different. The median appears to provide a more accurate result, and certainly one that is more consistent with the analyses of data within segments.

### Table 6. Comparisons between the methods of averaging differences for multiple runs and using the weaving method that chooses the closest two data points for each tile. The data used here were obtained on 7 Jun 2011 and comprise all data common to the ATV survey for the entire beach, and for the three or four airborne data runs undertaken on that day. The dataset omitted from the three-run estimates was the shortest file on that day, having less beach coverage than the other three datasets.

<table>
<thead>
<tr>
<th>Differences</th>
<th>Mean (m)</th>
<th>Median (m)</th>
<th>Std dev (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three runs (averaging)</td>
<td>0.0119</td>
<td>0.0117</td>
<td>0.0210</td>
</tr>
<tr>
<td>Three runs (weaving)</td>
<td>0.0139</td>
<td>0.0139</td>
<td>0.0282</td>
</tr>
<tr>
<td>Four runs (averaging)</td>
<td>0.0128</td>
<td>0.0128</td>
<td>0.0177</td>
</tr>
<tr>
<td>Four runs (weaving)</td>
<td>0.0130</td>
<td>0.0130</td>
<td>0.0290</td>
</tr>
</tbody>
</table>

Standard deviations are also much higher than as estimated from the segment analyses, again indicative of the likely effects of the higher differences that result from the steeper slopes and upper beach areas, as well as the swash zone.

In summary, even close to the areas of strong topographic gradient, the mean topographic height estimates are reasonably consistent and within 0.2 m, including results for erosion scarps where ATV-mounted equipment cannot proceed, and are remarkably better on smooth, gradually sloping surfaces with means and standard deviations considerably less than 0.1 m, and typically 0.06 m, and are therefore a useful result for studies where strong erosion is occurring, or has recently occurred.

### e. Estimates of horizontal uncertainty

What remains to be done is estimating the horizontal accuracy of the lidar observations. This is done by comparing results from two successive runs, in this case from runs 4 and 5 on 13 July 2011. Subsegments of 20 m × 20 m were chosen for the comparison, with the selection based on having significant elevation differences within each subsegment in both east–west and north–south orientations. Gently sloping beach areas were avoided in this estimation, as the longshore elevation differences are very small within segments on the lower beach. Thus, segments were located in the dune vegetation area where there are also pathways through the vegetation, and there were 15 of these chosen. No comparison with ATV data is possible in the vegetated areas, as no ATV data were acquired there. Segments from each run were then compared using the following method. For each segment in run 4, the partner segment for run 5 is shifted successively in the north–south and east–west directions in 0.01-m intervals, and the sum of squared height differences (SSHD) over the whole segment is estimated for each comparison. A perfect match at any shift would result in an SSHD of zero. For all the calculations for
each segment, the shift having the lowest SSHD score has the differences \( x_{\text{shift}} \) and \( y_{\text{shift}} \) noted, and the diagonal value of the shift magnitude is calculated and designated the absolute shift value.

The absolute shift values were analyzed for the 15 segments, with the average shift being 0.31 m, and the standard deviation being 0.18 m. This gives a practical guide to the horizontal accuracy of the data, which is somewhat less than estimated based on instrumental accuracy, but still useful. It also justifies the use of 0.25 m as a grid size, without which these estimates could not have been made.

For beach surveys where the beach slope is approximately 0.1–0.2, a horizontal shift of 0.5 m would result in a vertical uncertainty of approximately 0.1 m, which is of the same general magnitude as the vertical uncertainty. In summary, vertical and horizontal accuracies are comparable, and the system is not unduly degraded by either vertical or horizontal uncertainties when slopes are small. Care needs to be taken in interpreting erosion scarps, where slopes are often larger than 1.

5. Application of lidar to determine temporal changes in beach profiles

It is not the purpose of this paper to explore the physics behind and/or to develop models for coastal erosion. However, it is useful to show some preliminary results here to demonstrate the effectiveness of the system.

Figure 8 shows the topography of the northern segment surveyed on six days during the period May–July 2011, with contour intervals every 0.25 m. The upper beach and sand dunes are green, the beach itself is yellow and has height contours that are essentially parallel to the beach, and the water level appears as the more randomly contoured darker blue patches. The central part of the upper beach and seaward part of the dune suffers significant erosion of up to 2.5 m between 14 and 19 June, and the beach width narrows, and then grows again by 13 July.

The back dunes remain unaffected by erosion during the survey period while the differences in topography for the central part of the upper beach and seaward part of the dune are shown in Fig. 9. Significant erosion of up to 2.5 m occurring between 14 and 19 June is shown in Fig. 9 (left). The western edge of the dark blue difference contour is located where the contour lines are densest in the contour image in Fig. 8, that is, the erosion is seaward of the scarp. Poststorm recovery of the lower beach at the northern end is evident by the end of July, while the eroded upper beach area remains largely unchanged (Fig. 9, right).

Beach survey data of this temporal and spatial resolution are rare, and it is envisaged that the rapid-response survey method outlined here can provide new insight to better understand and model coastal erosion processes.

6. Discussion

The statistics derived from our multiple runs allow some confidence in the estimation of quality of lidar data overall. For normal distributions, the relation between mean \( \mu \), standard deviation \( \sigma \), and measurements can be expressed approximately as follows:

\[
\mu \pm \sigma \quad \text{spans 68% of measurements}
\]

\[
\mu \pm 2\sigma \quad \text{spans 95% of measurements}
\]

\[
\mu \pm 3\sigma \quad \text{spans 99% of measurements}
\]

This can be used in conjunction with data acquired to estimate likely accuracy.

For example, for single runs (i.e., 6C1; Tables 4 and 5) it is noted that one standard deviation of the average height is less than 0.11 m (and the mean is 0.034 m), so that a general rule of thumb is that a single independent airborne survey will provide estimates within 0.22 m of the actual height with 95% confidence and better than 0.11 m with 67% confidence. Discounting the anomalous run 7 (i.e., 5C1; Tables 4 and 5), the average difference between lidar and ATV data is less than 0.01 m, and the standard deviation of the mean is less than 0.05 m.

By combining two runs (6C2; Tables 4 and 5) the improvement is that one standard deviation of the average is reduced to a little over 0.06 m, and that the rule of thumb is that two data runs will provide estimates within 0.13 m of actual height with 95% confidence, and better than 0.08 m with 67% confidence. This outcome includes the data from run 7, and is arguably a worst-case scenario when considering the data considered here.

Analyses of data comparisons for the entire beach also indicate some lessons. Airborne data acquired from smoother sections of beach with lower gradients may be considered far more reliable than those from the areas of steeply sloping scarps, or other steep areas relating to anthropogenic modifications. Low-gradient slopes have height differences \(<0.06\text{m}\) and standard deviations \(<0.1\text{m}\), whereas steeply sloping surfaces have means \(<0.2\text{m}\) and standard deviations of comparable magnitude. The best way to eliminate swash may be to simply take aerial photographs along with the surveys, as wet sand is differently colored and indicates likely swash activity.

It is suggested that return intensities are logged and mapped over the region to be evaluated, so that poor-quality data may be excluded at the initial stage of
Fig. 8. Series of diagrams of beach contours taken on different days in 2011.
postprocessing. This would suggest flying at or below 1000-ft altitude to ensure that the return signal intensity is adequate. Monitoring intensity during flight is inherently problematic, as each scan will cover some ocean and possibly some road surface, each of which has poor return intensity.

In cases where having accurate data is critical, three survey lidar runs (i.e., 6C3; Tables 4 and 5) allow removal of one set of poor data should it occur, with improvement in the statistics of the outcome to the same level as might be obtained with ground-truth data.

In terms of horizontal accuracy, some benefits would accrue from averaging multiple runs, as is the case for height. In fact, the smoothing of the NovAtel SPAN data to provide estimates of location as well as the natural neighbor interpolation of the ground estimates will both play a role in smoothing random errors caused through higher-frequency airplane movement of angular accuracy. The effectiveness of the comparison in height estimates is also an indirect measure of the accuracy of the horizontal resolution. Overall, the horizontal uncertainties do not contribute to the vertical uncertainties, except in regions of large slope.

In general, it is evident that a two-pass lidar survey of any beach on one day is good practice and that logistically it becomes relatively easy, as surveys can be undertaken both outbound and inbound on a survey along the coast, while four-pass surveys will give optimum results.

7. Conclusions

In this paper, a number of different comparisons have been made between data acquired from surface observations (the ATV data) and from the airborne observations (the lidar data). With data acquired on a number of dates (for which the beach profiles were different) and from differing sections of the beach profile (from the swash zone to near the vegetated areas), there is a range of possibilities for comparisons.

A detailed comparison was made for two selected segments of beach on 13 July 2011 where significant erosion had occurred, leaving a smooth lower beach with a gradual slope and a steeper erosion scarp area in the upper beach. A number of airborne runs were compared to the single ATV run. The results showed that, for four of the six airborne lidar runs, mean differences between height estimates were less than 0.06 m. Some unresolved issues of low return intensity appear to play a role in degrading airborne lidar data for some of the surveys flown at higher altitude.

A new method of “weaving” datasets, where for each grid point the height estimate most different in value from the others is removed, provides significantly enhanced results. Using the weaving method, mean differences between ATV and airborne data drop to less than 0.04 m and standard deviations to less than 0.06 m for each of the two selected segments.

To compare data from the entire beach (from swash zone to upper beach, and along the entire length of the beach) comparisons were made for 14 June 2011 between the six airborne runs and the single ATV run. At this stage significant erosion had occurred on the few days prior, and the erosion scarp had developed almost as far as the vegetation line along much of the beach, and the lower beach was narrow. Combining results from all beach areas shows significant advantages when weaving data using multiple runs, with mean and median differences better than 0.02 m when three or four runs are used.

Analyses of comparisons of datasets from the entire beach results, in terms of locations on different sections of the beach profile, allow a useful interpretation of the
estimated over smooth, gradually sloping beach surfaces to within 0.02 m accuracy (0.06 m with two surveys), with standard deviations in the range 0.06–0.08 m. These results are somewhat better than the estimates of Reineman et al. (2009), but they are undertaken here by a totally different methodology that has dealt with actual beach elevation topographies.

Sandy beaches have undulations caused by natural phenomena such as winds and waves, and also by human use. While very fine changes may be difficult to detect with such undulations always present, airborne lidar provides an effective method to observe significant changes in elevation that occur during storm events. This rapid-response lidar provides the capacity to survey large sections of coastline over a short time, and most importantly to provide time series of these changes over scales and in circumstances where ground-truth data are unavailable.

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