Coastal Dune Surveying Using a Low-Cost Remotely Piloted Aerial System (RPAS)

Authors: Julia G. Moloney, Mike J. Hilton, Pascal Sirguey, and Tom Simons-Smith

Source: Journal of Coastal Research, 34(5) : 1244-1255

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-17-00076.1

Journal of Coastal Research	34	5	1244–1255	Coconut Creek, Florida	September 2018

TECHNICAL COMMUNICATIONS

www.cerf-jcr.org

Coastal Dune Surveying Using a Low-Cost Remotely Piloted Aerial System (RPAS)

Julia G. Moloney†*, **Mike J. Hilton**†, **Pascal Sirguey**‡, **and Tom Simons-Smith**†

†Department of Geography
University of Otago
Dunedin 9016, New Zealand

‡School of Surveying
University of Otago
Dunedin 9016, New Zealand

ABSTRACT

Moloney, J.G.; Hilton, M.J.; Sirguey, P., and Simons-Smith, T., 2018. Coastal dune surveying using a low-cost remotely piloted aerial system (RPAS). *Journal of Coastal Research,* 34(5), 1244–1255. Coconut Creek (Florida), ISSN 0749-0208.

Monitoring coastal morphodynamics is important for understanding the response of coasts to short-term storm events, for understanding coastal response to long-term environmental change, and for managing beach-dune systems. Remotely piloted aerial systems (RPAS), or "drones," present new opportunities for coastal monitoring. They are inexpensive and efficient, require minimal expertise, and provide high-resolution aerial imagery. This paper investigates the efficacy of low-cost RPAS for coastal foredune monitoring. Comparisons among total station, real-time kinematic global navigation satellite system, terrestrial laser scanner, and RPAS surveys were made based on the efficiency of point acquisition, cost, accuracy of the output surface, and the method's sensitivity to atmospheric and environmental limitations. Temporal elevation and volumetric changes in sand were quantified using RPAS photogrammetry and conventional survey methods. An intentionally notched section of foredune was monitored over a 12 month period. The RPAS survey was the most efficient method and had a high level of accuracy. The digital surface model (DSM) derived from the RPAS survey had a vertical root mean square error of 8 cm. However, RPAS was more sensitive to environmental and atmospheric conditions, although the survey rapidity means undesirable weather conditions can be avoided. The RPAS did not accurately quantify total sand deposition downwind of the notches due to an elevational offset caused by vegetation, which is dense throughout the study site. Comparison of the DSMs derived from RPAS surveys indicated a decrease in elevation (between 10 and 20 cm) during the survey period. The method affords the advantages of point acquisition efficiency and flexibility. However, low-cost red-green-blue RPAS is more suited to quantifying the morphology of bare sand or sparsely vegetated areas, quantifying large-scale changes, or for long-term morphologic monitoring due to its inability to penetrate vegetation. It is expected that future sensors capable of penetrating vegetation will become more accessible for low-cost platforms.

ADDITIONAL INDEX WORDS: *Unmanned aerial vehicle (UAV), drone, foredune, coastal surveying, coastal monitoring*.

www.JCRonline.org

INTRODUCTION

Various methods have been employed to monitor the morphodynamics of coastal dunes, including real-time kinematic global navigation satellite systems (RTK-GNSS; Pardo-Pascual *et al*., 2005); total stations (Castelle, Le Corre, and Tomlinson, 2008); laser scanners (Feagin *et al*., 2014; Hilary *et al*., 2002); and photogrammetry/aerial photography (Mathew, Davidson-Arnott, and Ollerhead, 2010). Each method involves trade-offs among the cost of the survey, the speed of point acquisition, and the quality of the data collected (Hugenholtz *et al*., 2013). Remotely piloted aerial systems (RPAS; *i.e*. drones or unmanned aerial vehicles) can be employed to collect low-altitude vertical photographs that are then processed using photogrammetry software to derive digital surface models (DSMs; Turner, Harley, and Drummond, 2016). DSMs can then be used to quantify temporal morphologic changes (Mathew, Davidson-Arnott, and Ollerhead, 2010). RPAS are now affordable and can survey large areas rapidly (Darwin, Ahmad, and Zainon, 2014), whereas ground-based methods (*e.g*., total stations and RTK-GNSS) typically become less efficient as the survey area increases. If low-cost RPAS models can produce accurate DSMs, such technologies could be employed more widely by management agencies for coastal monitoring.

Due to the dynamic nature of sandy coasts, coastal managers routinely monitor coastal foredunes and beaches (Morton *et al*., 1993). Coastal foredunes offer a range of ecological and social services on sandy coastlines where they adjoin metropolitan development (Taylor *et al*., 2015), and they are a natural coastal defense, protecting the hinterland from inundation and erosion (Bochev-van der Burgh *et al*., 2011). Surveying foredune morphology, and quantifying morphologic changes can be useful for identifying trends and patterns, and hence aid in the management of such systems (Morton *et al*., 1993; Saye

DOI: 10.2112/JCOASTRES-D-17-00076.1 received 17 April 2017; accepted in revision 13 October 2017; corrected proofs received 13 November 2017; published pre-print online 8 December 2017.
*Corresponding author: julia.g.moloney@gmail.com

et al., 2005). Morphologic changes in coastal foredunes are indicative of other coastal processes as well, such as the establishment of vegetation in a dune system (Rozé and Lemauviel, 2004); erosion caused by storm waves (Ierodiaconou, Schimel, and Kennedy, 2016); or anthropogenic influences (Martinez *et al.*, 2006).

Several studies have employed RPAS for quantifying morphological dune changes (Gonçalves and Henriques, 2015; Hugenholtz *et al.*, 2013; Ierodiaconou, Schimel, and Kennedy, 2016; Mancini *et al.*, 2013; Scarelli *et al.*, 2016; Turner, Harley, and Drummond, 2016). Gonçalves and Henriques (2015) investigated the use of a SwingletCam RPAS with a low-cost camera for monitoring coastal dune morphodynamics. The study successfully derived DSMs with a ground sampling distance (GSD) of 3.2–4.5 cm, and a root mean square error (RMSE) of 3.5–5.0 cm, and concluded that low-cost RPAS can be employed in the coastal monitoring context and produce accurate results. However, the study also identified the limitations of RPAS platforms during windy conditions. Hugenholtz *et al*. (2013) employed a Hawkeye RQ-84Z Aerohawk for mapping eolian landforms. It was found that the error calculated from the survey was comparable to that of a LIDAR survey of the same site. The author conducted a morphological change analysis between a LIDAR survey conducted 7 years prior and the RPAS survey. The results suggest the usefulness of employing such technology for quantifying morphological dune changes; however, they also suggest that there is error and uncertainty in the camera calibration that need to be investigated further to produce accurate DSMs. A study conducted in Warrnambool, Australia, employed an off-the-shelf RPAS to quantify event-scale beach erosion (Ierodiaconou, Schimel, and Kennedy, 2016). This study focused on the practical ability of RPAS surveying, and the advantages of this method for quantifying changes in coastal dune morphology and sand volume during storm events. The output DSMs had vertical and horizontal precisions of <4 cm, suitable for calculating changes in volume caused by storm events.

The current paper investigates some of the limitations suggested by the aforementioned papers by assessing the efficacy of low-cost RPAS for monitoring coastal dune systems. The application of RPAS surveying is becoming more common for coastal morphology research, and, therefore, the limitations and ability of the method for collecting accurate morphologic data need to be understood. The objectives were to (1) determine the accuracy and cost of RPAS surveys compared with total station, RTK-GNSS, and terrestrial laser scanner (TLS) methods; and (2) to quantify foredune morphodynamics using a low-cost RPAS and understand the potential errors of the method.

METHODS

To address the first research objective, an RPAS survey of a section of foredune was compared with surveys completed using a Leica 307 total station; Trimble R8 RTK-GNSS; and Trimble TX5 TLS. To investigate the second research objective, two RPAS flights were conducted over a second section of foredune, 4 months apart, and DSMs were derived from the data. The two RPAS DSMs were compared to assess how RPAS technology might be used to quantify medium-term (months) foredune morphodynamics. This study took advantage of a parallel investigation designed to evaluate the efficacy of notches to encourage sand deposition in the lee of a foredune. This investigation provided an opportunity to use RPAS to quantify the accumulation of sand in the lee of those notches.

Study Area — St. Kilda, Dunedin, New Zealand

The primary study area was located at St. Kilda Beach, Dunedin, New Zealand (45.9° S, 170.5° E; Figure 1). St. Kilda is characterized by a uniform, stage 1 foredune (Hesp, 1988), approximately 1 km long, 20 m wide, and 12 m high (above mean sea level). The foredune developed seaward and parallel to John Wilson Drive after *Ammophila arenaria* (marram grass) was planted by the local council in 1980. The foredune accreted continually until 2009, when accretion ceased, and the foredune has remained stable since, with occasional episodes of minor scarping.

The field site, area A, is a section of the St. Kilda foredune, approximately 400 m × 85 m. This site was divided into two subsections, area B and area C (Figure 2). The comparison of survey methods (total station, RTK-GNSS, TLS, and RPAS) took place in area B (85 m × 65 m). This site contains a range of topographies (back beach, foredune stoss slope and lee slope, swale) and vegetation types (bare sand, sparse and dense marram grass) with which to test each method. Areas B and C encompassed the foredune "notches" (Figure 3), and these sites were utilized to address objective 2, where the RPAS was used to map and quantify sedimentation in the lee of the notches.

Conventional Surveying Methods

Three conventional surveying methods, total station (Leica 307), RTK-GNSS (Trimble R8), and TLS (Trimble TX5), were compared to RPAS surveying methods. DSMs of area B were derived from each method and compared. Area B was surveyed with the total station and RTK-GNSS using a systematic stratified sampling technique; points were obtained approximately every 1 m over simple topographies and more frequently where the terrain was more complex. The RTK-GNSS surveyed each point with an occupation time of 5 seconds; this was considered to be a reasonable compromise to ensure surveying efficiency. The total station and the RTK-GNSS base station were set up over a known point (45.9074°S, 170.5284°E) located on the northern boundary of the study area.

The points recorded by the total station and RTK-GNSS were interpolated in ArcGIS using the *Geostatistical Analyst* to derive the respective digital terrain models (DTMs). A thin plate spline interpolation was employed, which also conducted a cross validation of the data points, where the elevation of every point in each data set was compared to the elevation at the point location in each DTM. The cross validation reported the RMSE and mean error of the elevation derived in the DTMs.

The TLS was set up at three locations on John Wilson Drive, three locations on the crest of the foredune, and three locations on the beach. The scans were stitched together using Trimble Real Works software, which produced a three-

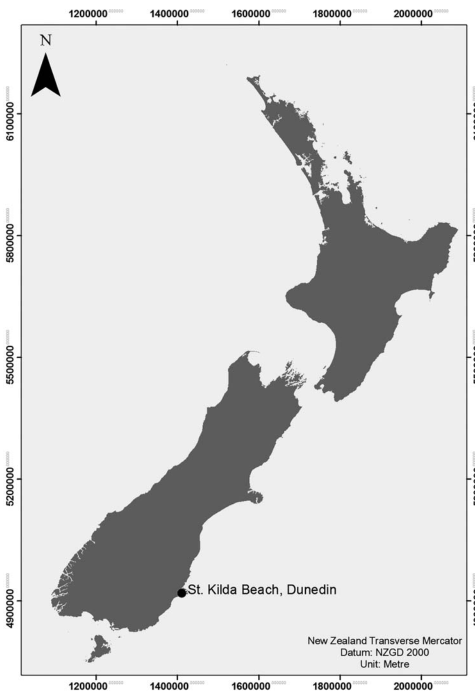

Figure 1. Location map of the study site, St. Kilda Beach, Dunedin, New Zealand.

dimensional point cloud of the area. The point cloud was "cleaned" by removing unwanted points (for example, the ocean) and vegetation. The "cleaned" data set was used so that the resulting model was based on ground elevations rather than the elevation of the vegetation canopy. The point cloud was imported into ArcGIS, a thin plate spline interpolation was employed to generate a DTM, and a cross validation was used to calculate the RMSE and mean error of the interpolation.

RPAS Platform

A DJI Phantom-3 Advanced quadcopter was employed for the RPAS survey. A Sony EXMOR 7.81 mm (1/2.3 in.; sensor size 6.17×4.55 mm), 12.4 megapixel camera was attached, with a field of view of 94° and a 20 mm lens (in 35 mm equivalent) that was focused at infinity. The infinity focus allows the sensor's internal geometry to remain consistent by maintaining the focal length between images. Flight planning software was not employed because the compatible software was not available at the beginning of data collection; photographs were instead captured manually during the flight, which resulted in the individual flight paths differing slightly. The sensor information was used to estimate the "real" focal length, using the following equation:

$$f_{\mathrm{R}} = \frac{(f_{35} S_{\mathrm{w}})}{34.6}, \tag{1}$$

where, f_{R} is the real focal length measured in millimeters, f_{35} is the focal length in the 35 mm equivalent, and S_{w} is the sensor width. The flying height to obtain a GSD of 2.5 cm was determined using the following equation:

$$H = \frac{f_{\mathrm{R}} n_{\mathrm{w}} GSD}{S_{\mathrm{w}}}, \tag{2}$$

where, n_{w} is the number of pixels forming the width of the sensor. To achieve a GSD of 2.5 cm, the RPAS flew at 50 m (± 0.5 m) above the launch site, which was situated approximately 19 m above mean sea level (Figure 4).

The image footprint was calculated to determine the distance the RPAS needed to travel between subsequent photographs to obtain a forward image overlap of 85% and side-lap of 70%, which would satisfy the photogrammetric requirements, while being within the RPAS flight time. Based on the dimensions of each image (4000×3000 pixels), photographs were taken approximately every 10 m alongshore.

A "crosshatch" flight path was not deemed necessary due to the undulating terrain of the study area. The influence of a "crosshatch" flight path on the self-calibration has been identified as insignificant in such circumstances (Gerke and Przybilla, 2016). However, in retrospect, a third flight line may have been beneficial for the accuracy of the output model.

The RPAS survey was conducted over area A, and the subsections (areas B and C) were subsequently extracted; only area B was assessed in the method comparison. The flights were controlled under Part 101 of New Zealand Civil Aviation Authority regulations (2015).

Ground control points (GCPs) were required to orientate the photogrammetric model. In total, 23 GCPs were established along John Wilson Drive, in the swale of the foredune (the area in the lee of the foredune), on the foredune crest, and along the beach (Figure 5). This particular GCP layout was chosen (1) to ensure the points were evenly distributed throughout the study area; and (2) to ensure GCPs were present in the four areas with differing elevations (John Wilson Drive, swale, crest, and the beach [approximately midtide]; Figure 6), hence providing confidence in the accuracy of the output DSM. The GCPs on John Wilson Drive and the crest of the foredune were permanent (road markings and fence posts); the GCPs in the swale and on the beach (ground targets) were established on the day of the survey. The GCPs were surveyed using a Trimble R8 RTK-GNSS unit. The average horizontal precision for the 13 permanent GCPs was 0.011 m, and the average vertical precision was 0.016 m. The temporary GCPs had an average horizontal and vertical precision of 0.009 m and 0.012 m, respectively.

The imagery and GCP coordinates were uploaded into Pix4D Mapper for processing. An inverse distance weighting interpolation was used in Pix4D Mapper to derive the DSMs. A leave-one-out cross validation (LOOCV) was employed to assess the accuracy of the triangulation used by Pix4D to produce the RPAS DSM. LOOCV is an iterative process whereby all of the points except for one are marked as ground control (the remainder are marked as "check points"), and the triangulation is conducted (Sirguey and Cullen, 2014). The process is repeated with a different point marked as a check point, iteratively. This tests the model's reliance on each GCP and supports an independent assessment while

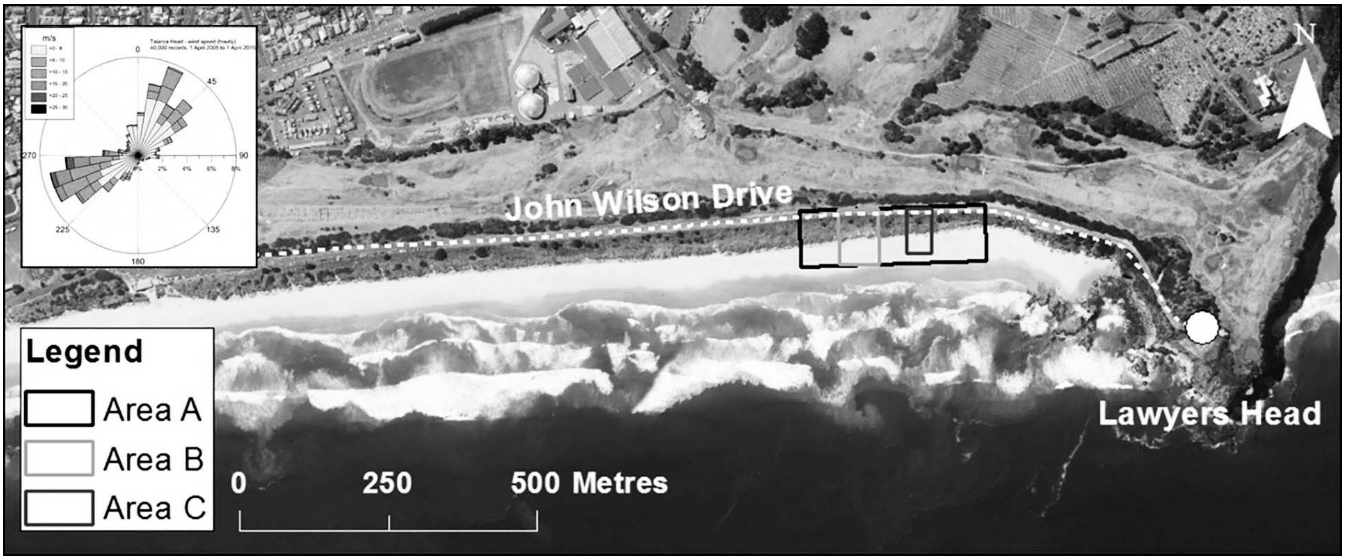

Figure 2. The St. Kilda Beach foredune, and the location of the three study areas. The wind rose is from anemometer data recorded at Taiaroa Head, on the Otago Peninsula (Hilton *et al*., 2016).

allowing the final model to benefit from all points as control points. The model calculates the x, y, z error for every GCP and the check point. The residuals are calculated using the difference between the coordinates of the point produced by the model and the actual (measured) coordinates (Brovelli *et al*., 2006). If the check point residuals are small (relative to the desired accuracy), then it can be assumed that the resulting model has sufficient accuracy. The results can also provide confirmation that the GCP configuration is reliable.

Comparison of Surveying Methods

The three conventional coastal surveying methods (total station, RTK-GNSS, and TLS) were compared with a small, low-cost RPAS surveying tool. Comparisons were based on:

- the accuracy/precision of the DTMs and DSMs produced by each method;
- the efficiency of point acquisition;
- the survey method cost (purchasing equipment *vs*. hiring personnel/equipment); and
- the field limitations of each method.

Area B was surveyed using all four methods, and each survey was used to derive either a DSM (RPAS) or DTM (total station, RTK-GNSS, and TLS). The start and end times of each survey; the number of people required to conduct the survey; the number of points collected during the survey; the atmospheric and environmental limitations of the survey; and the equipment required were all recorded. The data processing and set-up times were estimated.

The accuracy and precision of each DTM/DSM derived from the total station, RTK-GNSS, and TLS surveys were calculated using the mean error and RMSE from the cross validation of the data points used in the thin plate spline point interpolation in ArcGIS. The RMSE and mean error for the RPAS DSM were derived using a LOOCV, which characterized the accuracy of the triangulation, rather than the accuracy of the interpolation.

The efficiency assessment was based on the number of points collected per hour by each method. The set-up and data processing durations were estimated, and the number of people required for each survey and the equipment required were identified. The cost analysis investigated the price of the equipment purchased brand new (based on the cost at the time of this study), the price of hiring a professional surveyor to conduct each survey (based on local quotes), and the cost of hiring the equipment.

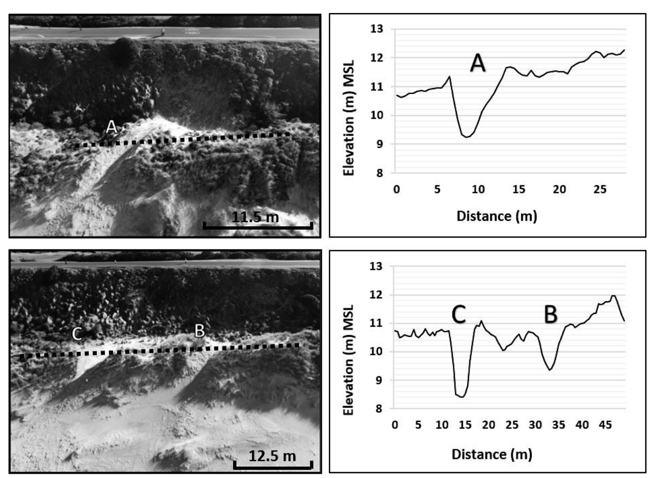

Figure 3. Notches were cut into the St. Kilda foredune to encourage beach-dune exchange in April 2016.

Figure 4. A view along the St. Kilda foredune from the RPAS launch site.

Quantifying Temporal Changes in Foredune Morphology

The RPAS was flown twice over area A to gather vertical photographs of the St. Kilda Beach site, suitable for deriving DSMs to address research objective 2. The first flight was used to collect baseline data and to assess how the GCP configuration affected the quality of the DSM. The GCP layout for the subsequent flight was determined based on the results from the initial flight.

Elevation change surfaces were derived for areas B and C, and these were used to estimate volumetric changes over the 4 month study period. The first flight was conducted on 8 May 2016, and the second was conducted on 10 September 2016. The DSMs derived from each flight were compared to quantify the

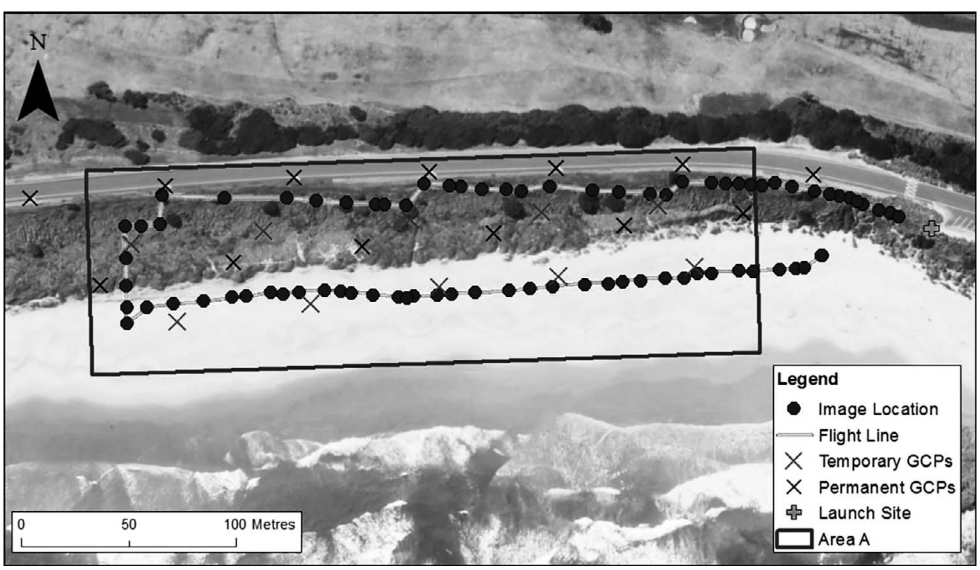

Figure 5. The flight path and GCP layout for flight one at St. Kilda Beach.

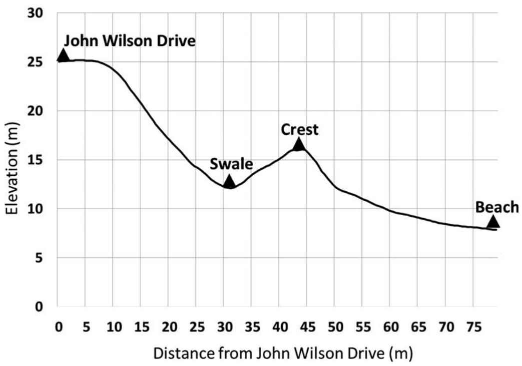

Figure 6. Four lines of GCPs were established for the two St. Kilda Beach RPAS flights: on John Wilson Drive, in the swale of the foredune, on the crest of the foredune, and on the beach.

elevation and volumetric changes facilitated by the constructed notches at St. Kilda Beach.

To derive the elevation change surfaces, the Raster Minus tool from the *3D Analyst* toolbox in ArcGIS 10.2 was used, where the "before" DSM was subtracted from the "after" DSM. The gain, loss, and net change in volume for each notch were quantified using the Cut/Fill tool from the *Spatial Analyst* toolbox. The mean error and RMSE associated with the DSM from the first flight were derived from the LOOCV analysis, and for the second DSM, the error was derived using a check point analysis in Pix4D (Brovelli *et al*., 2006). Nine check points were used (the remaining nine points were marked as GCPs). The elevation change surfaces were adjusted for bias based on the mean error associated with each input DSM.

The precision of the elevation change surfaces (*ECS*) was estimated using the quadratic sum of the standard deviation associated with each input DSM (Hugenholtz *et al*., 2013), derived from the LOOCV for the first flight, and reported by Pix4D for the second flight, using a check point analysis. A 90% confidence interval was used to identify the areas with statistically insignificant elevation change, namely:

$$-Z_{\alpha/2} \times SD_{\mathrm{ECS}} < ECS < Z_{\alpha/2} \times SD_{\mathrm{ECS}}, \quad (3)$$

where, $Z_{\alpha/2} = 1.64$, and SD_{ECS} is the standard error of the elevation change surface. From this, a map was produced that showed the areas of elevation change that were statistically significant. The areas of gain, loss, and no change in elevation in the lee of each notch were mapped and quantified. A 90% confidence interval was then used to determine whether the loss, gain, and net change in volume were statistically significant.

RESULTS

First, the results from the survey method comparison are presented, which identify the differences among the accuracy, efficiency of point acquisition, cost, and atmospheric/environmental limitations of each method. Second, the efficacy of the RPAS method to derive DSMs to report changes in foredune morphology is assessed.

Survey Method Efficiency

The St. Kilda RPAS survey was the most efficient method (Table 1). It had the shortest surveying duration of 10 minutes; however, it took the longest to set up. The RPAS setup required the establishment of GCPs, which added an hour to the overall process. The set-up time for the TLS survey was approximately 30 minutes (which does not include the movement of the TLS during the survey; this was instead included in the survey duration). The total station and RTK-GNSS units took less than 15 minutes to set up. The total station and RTK-GNSS data also took the least time to process (30 minutes), and the TLS data processing was the longest (5–8 hours). The data processing of the RPAS survey took approximately 4 hours. However, the time it takes to conduct each survey and process the data is likely to vary depending on the surveyor.

The total station and RTK-GNSS surveys obtained a similar number of survey points (~2000; Table 1). The TLS and RPAS obtained millions of points. The RPAS survey was capable of obtaining approximately 48 million points per hour. The total station and RTK-GNSS units retrieved 178 and 171 points/h, respectively.

DSM/DTM Accuracy and Precision

The total station and RTK-GNSS surveys produced DTMs, whereas the RPAS surveys produced a DSM. The TLS produced a DSM point cloud; however, the vegetation points were removed to derive a DTM. The total station and RTK-GNSS DTMs showed a similar range in elevation values. The DSM had slightly higher elevations than the corresponding areas in the DTMs (Figure 7).

The total station and RTK-GNSS DTMs had the highest RMSE of 10 cm, and the TLS had the lowest of 2 cm (Table 2). The RPAS had a RMSE of 8 cm and the largest mean error (–3 cm). The TLS DSM had the lowest mean error (0.01 cm). However, it should be noted that the RMSE and mean error of the RTK-GNSS, total station, and TLS surveys were derived from the cross validation in ArcGIS, and, therefore, they characterize the interpolation. Conversely, the RMSE and mean error of the RPAS DSM were derived from the LOOCV, and, therefore, they characterize the triangulation. There are also disparities between the methods due to the density and number of points recorded by each method (and, hence, the grid spacing of each survey), which influence the detail in the output DSMs/DTMs.

Atmospheric and Environmental Limitations

Precipitation was a limiting factor for all survey methods. Precipitation makes it difficult to see through the total station lens, and it makes the ground slippery to traverse with the prism pole. However, surveying with a total station is possible in light showers and rain, but not desirable. In contrast, the TLS and RPAS cannot be operated during precipitation. The RTK-GNSS unit is waterproof, but rain makes the terrain slippery and difficult to traverse with the roving receiver.

Table 1. *Comparison of the efficiency of the total station, RTK-GNSS, TLS, and RPAS surveys.*

	Set-Up Time (h)	Survey Duration (h)	Processing Time (h)	Total Duration (h)	No. of People Required	No. of Points	Points/h
Total Station	0.25	10.9	0.5	11.65	2–3	1936	178
RTK-GNSS	0.25	13.2	0.5	13.95	1	2250	171
TLS	0.5	3.16	5–8	11.66	2–3	5,893,427	1,865,009
RPAS	1	0.16	4	5.16	2–3	981,909	48,141,381

The total station, RPAS, and RTK-GNSS are each affected by wind. The prism and range poles need to be held level when conducting surveys with a total station or RTK-GNSS. Wind generally did not impact the operator's ability to hold the 2 m pole level; however, the 5 m pole was difficult to keep level when the wind speed increased. The RTK-GNSS reports an "excessive movement" error during point measurement if the roving pole is tilted or moving, which prevents measurement (Trimble, 2013). This message appears when the receiver is shaking due to wind, and when the pole is not held steady, which can occur when holding the pole on steep terrain. The RPAS can be flown in wind speeds up to 10 m s^{-1} (DJI, 2015). However, for surveying purposes, winds greater than 5 m s^{-1} are unfavorable, and calm conditions are desirable. All surveys conducted in this study by the RPAS were undertaken in wind speeds below 4 m s^{-1}. The RPAS endurance is approximately 20 minutes; however, this is reduced in higher winds.

Sunlight was limiting for the total station and the RPAS surveys. Due to the orientation of the dune, and the relative location of the total station, the sun was facing the prism at all times. At certain angles, the prism can direct the sunlight into the lens of the total station, preventing the machine from recording a point. Sunlight was also a minor limitation for the drone survey, mainly due to the steep terrain. The sun cast a shadow during winter months, placing the swale and seaward slope of John Wilson Drive in shade. Features in the images can be difficult to differentiate when there are strong variations in illumination. Changes in sunlight throughout the flight caused color distortions in the orthomosaic and saturated the color of the sand in some images.

The topography of the site was a limiting factor for the total station, RTK-GNSS, and TLS surveys. The total station and RTK-GNSS methods required traversing the terrain to collect the data points, which was difficult where the terrain was steep (*e.g.*, the lee slopes of the foredune). Trampling of the study area was avoided by standing behind the reflector pole or GNSS rover (*i.e.* only walking over areas that had already been surveyed). Line-of-sight was an issue for the total station and TLS surveys, which required a prism pole extension for parts of the total station survey, and multiple setup locations (nine) for the laser scanner.

Dense vegetation, *A. arenaria* and *Lupinus arboreus* (tree lupin), presented an obstacle for the total station and RTK-GNSS surveys. The RPAS captured the elevation of the topmost surface. Therefore, in locations with dense vegetation,

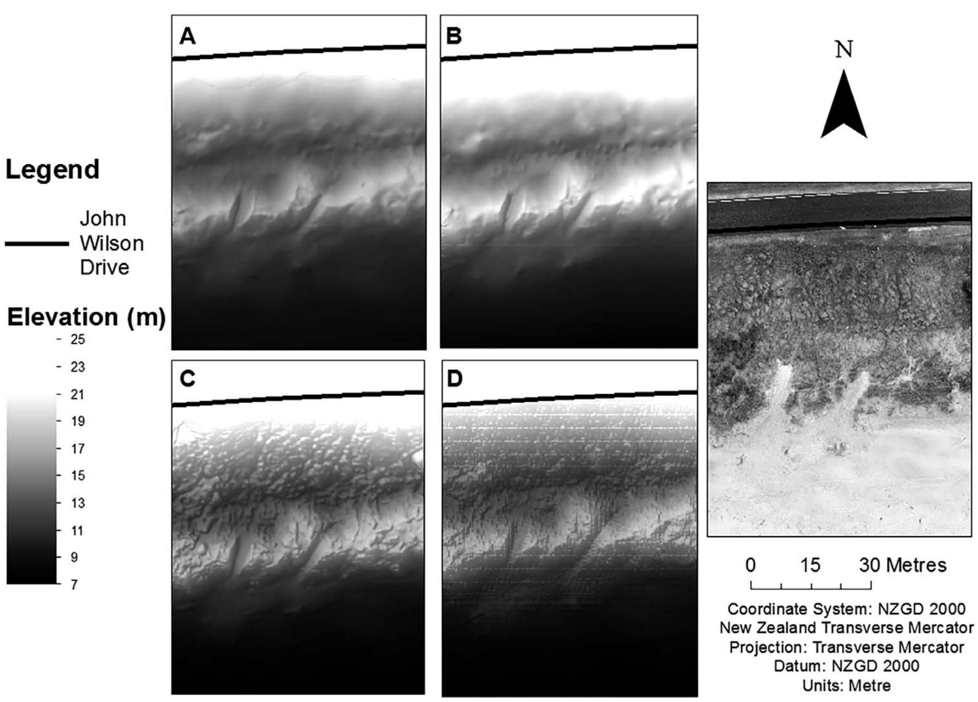

Figure 7. The DSMs and DTMs derived from each surveying method: (a) RTK-GNSS; (b) total station; (c) RPAS; and (d) TLS.

Table 2. *The mean error (ME) and RMSE of each DSM and DTM.*

	ME (m)	RMSE (m)
Total Station	0.002	0.103
RTK-GNSS	0.001	0.100
TLS	0.0001	0.022
RPAS	−0.028	0.080

the top of the canopy was recorded. Conversely, the total station and RTK-GNSS units recorded the elevation of the ground.

Surveying Cost Analysis

The cost of the equipment and the software used to process the data was included in the cost analysis (Table 3). The TLS was the most expensive survey, with a total cost of approximately US$58,654 (Table 3). The total station survey was the least expensive, with a total cost of US$8,640. The total RPAS survey cost included the RTK-GNSS unit because a high-precision surveying method is required to establish GCPs. The TLS survey and the RPAS survey required the most expensive software, which cost US$13,549 and US$8413, respectively. All methods required a means to achieve absolute georeferencing, *i.e*. a benchmark in the data set to tie the survey into a reference system. It should, therefore, be noted that if the survey site does not have a suitable georeferenced benchmark, a high-precision method such as RTK-GNSS may be required to establish a benchmark.

The estimated cost of hiring a surveyor, and the cost of hiring the equipment were also assessed (Table 4). The equipment and surveyor hire costs for the total station, RTK-GNSS, and the surveyor hire for the RPAS are based on quotes from *Overview Surveying* in Dunedin, New Zealand (J. Reeves, *personal communication*). The RPAS equipment hire is based on the current price from the *Drone Hire* website (Mobile Works Ltd., 2016). Purchasing equipment is more expensive than hiring equipment, or hiring personnel to conduct the survey. However, if frequent surveys are required, purchasing the equipment is likely to be more cost-efficient in the long term. Hiring the equipment is the least expensive of the three options, and the total station is the least expensive method. Hiring an RPAS surveyor is the most expensive; however, RPAS can cover large areas rapidly and is, therefore, more cost-efficient for large-scale surveys. Hiring a surveyor to conduct total station or RTK-GNSS surveys was the least expensive per hour; however, these methods are the most time-consuming.

Morphologic Change Assessment

The DSMs from the 8 May and 10 September flights were used to calculate elevation and volumetric changes facilitated by each notch cut in the St. Kilda foredune. The DSMs were corrected for the mean error, and, hence, the output *ECS*s had a mean error of 0. The RMSE of each *ECS* was calculated from the input DSMs, and the RMSE for the *ECS* was 9 cm.

A statistically significant increase in elevation occurred landward of notch A, in the lee of the foredune crest (Figure 8). The analysis indicates that the eastern side of the depositional lobe of sand experienced a decrease in elevation. Prior to this study, a tree directly landward of the notch was cut down, and the debris was placed to the east of the notch in the swale and on the bank of John Wilson Drive, which is visible in the 8 May photograph (Figure 8). The debris was subsequently moved further east, as it became apparent that sand was accumulating on top of the debris. Therefore, the decrease in elevation detected by the *ECS* resulted from the movement of tree debris, rather than coastal processes.

Notches B and C both showed an increase in elevation at the southern end of the depositional lobe (Figure 9). These areas experienced relatively consistent sand deposition during the 4 month study period; however, the calculated elevation change in notches B and C was statistically insignificant.

Over the study period, the depositional lobes in the lee of notches A and B exhibited a net loss in volume, and notch A had the greatest loss of approximately 66 m^3 (Table 5). The depositional lobe in the lee of notch C had an overall net gain in volume of 0.73 m^3. All of the depositional lobes underwent statistically significant volumetric changes, which were calculated based on the cumulative pixel value in the depositional lobe. Conversely, the statistical significance calculated for the elevation change was based on the elevation change in each individual pixel.

The RPAS aerial photography shows that excavation of the notches resulted in the accumulation of sand downwind of each notch. This resulted from onshore steering of beach wind flow and enhanced onshore sand flux. However, the morphologic analysis conducted using the RPAS imagery only captured the sand deposition on the unvegetated surfaces. Vegetated areas (which clearly experienced sand deposition during the study)

Table 3. *Cost comparison among the total station, RTK-GNSS, TLS, and RPAS equipment used in this study, in USD.*

		Equipment Cost (USD)			
Surveying Method	Instrument Cost (USD)	Item	Cost	Software Cost (USD)	Total Survey Cost (USD)
Total Station	$5500–$7000	Tripod	$175	Leica Geo Office $960	~$8600
		Prism Pole	$170		
		Prism	$300		
Trimble R8 RTK-GNSS	$17,500–$21,000	Tripod	$195	Trimble Business Centre $1100	~$23,000
		Range Poles	$457		
		Antenna	$90		
		Bipod	$243		
Trimble TX5 Laser Scanner	$35,000	Tripod ×5	$975	Trimble Real Works $13,500	~$58,500
		Total Station Kit	$8600		
		Sphere Set	$430		
DJI Phantom 3 RPAS	$1400	RTK-GNSS Kit	$23,000	Pix4D Mapper $8300	~$32,800

Table 4. *Cost comparison between hiring the equipment, hiring the personnel, and purchasing the equipment for each surveying method, in USD.*

	Equipment Hire	Surveyor Hire	Equipment Purchase
Total Station	\$100–\$200/d	\$1000/d	\$8600
RTK-GNSS	\$310/d	\$1000/d	\$23,000
TLS	\$700–\$874/d	\$100/d	\$58,500
RPAS	\$94/d	\$2,100/flight	\$32,800

exhibited a loss in volume in the morphologic change analysis. This suggests a "dampening" effect, where sediment that was deposited on vegetated areas pushed the vegetation toward the ground. Hence, even though sediment was deposited, it was calculated as a decrease in elevation.

DISCUSSION

The current study investigated the efficacy of low-cost RPAS for coastal dune surveying by coastal management agencies. Low-cost RPAS methods, in conjunction with appropriate software, allow efficient coastal surveys; however, there are limitations imposed by environmental and atmospheric constraints. Low-cost RPAS surveys offer some advantages over conventional coastal surveying methods, and they have the potential to be employed for monitoring morphological changes. However, RPAS surveying becomes problematic where vegetation obscures the dune surface and/or where the change in elevation between surveys is small. This problem is likely to be insignificant where large-scale changes in foredune morphology occur as a result of significant stoss face scarping or overwash sand deposition during storm and inundation events (Ierodiaconou, Schimel, and Kennedy, 2016).

Efficacy of Low-Cost RPAS Surveying

Coastal dune surveys using low-cost RPAS offer advantages over conventional surveying methods. The current study found that the RPAS survey could be completed more rapidly (7 hours faster) than the other methods, including the setup and processing time. Rapid and responsive surveys are valuable for coastal research (Delacourt *et al.*, 2009; Gonçalves and Henriques, 2015). The dynamic nature of many types of coasts can result in major changes in morphology over short timescales. Such changes in morphology are stochastic. Therefore, it is important that surveys can be conducted quickly and at short notice (Gonçalves and Henriques, 2015). However, environmental conditions may limit the opportunity for RPAS surveys.

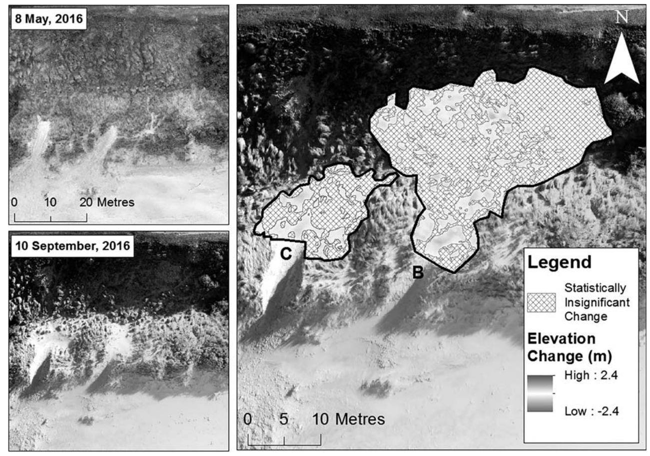

Figure 9. The elevation change through notches B and C between 8 May 2016, and 10 September 2016. The areas of statistically insignificant change, determined using a confidence interval, are shaded.

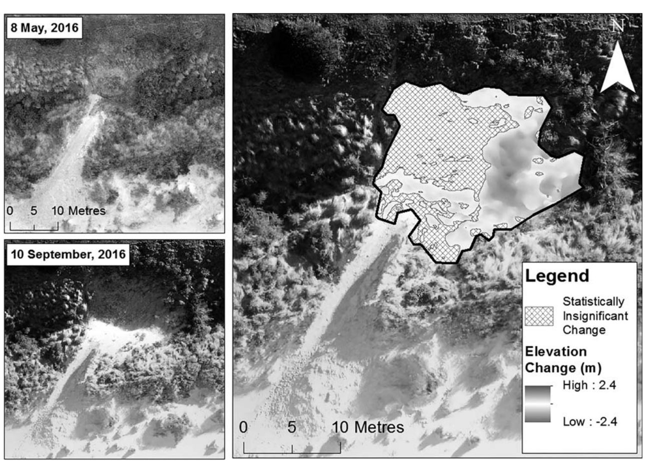

Figure 8. The elevation change through notch A between 8 May 2016, and 10 September 2016. The areas of statistically insignificant change, determined using a confidence interval, are shaded.

Low-cost aircrafts, specifically quadcopters, cannot be operated in the rain. Conversely, imagery can become saturated if there is too much illumination and may not be suitable for processing. This is primarily a result of the configuration of the aircraft. The size and weight (<25 kg) of low-cost RPAS result in low stability in windy conditions (>10 m s^{-1}; Nex and Remondino, 2014). Larger RPAS (>25 kg) models can withstand higher wind speeds (Aber, Marzolff, and Ries, 2010). However, during high wind speeds, the aircraft uses more power to achieve stability (Nex and Remondino, 2014), which can be problematic because low-cost RPAS typically have a battery capacity of <1 hour. This can cause the battery power to decline quickly in windy conditions, which are characteristic of coastal environments. However, the rapid nature of RPAS surveys largely mitigates this problem, making this technology desirable for coastal surveys.

Low-cost RPAS methods typically employ low-cost cameras, which can cause distortion in the imagery captured (Whitehead and Hugenholtz, 2014). Illumination can also cast shadows over areas of the study site, which can ultimately create errors in the point cloud. Higher-quality cameras can overcome some of these spectral issues (Whitehead and Hugenholtz, 2014).

Environmental limitations of low-cost RPAS surveying can somewhat be avoided by planning for conditions with light winds (0–5 m s^{-1}), no precipitation, and high cloud cover (diffuse reflection of light). It is usually possible to meet these requirements because surveys can be completed in a short time period (depending on the climate of the survey area). However,

Table 5. *The gain, loss, and net change in volume through notches A, B, and C, between 8 May and 10 September 2016, and the results from the 90% confidence interval (CI).*

	Notch A		Notch B		Notch C	
	Volume (m^3)	90% CI	Volume (m^3)	90% CI	Volume (m^3)	90% CI
Gain	15.69	(15.65, 15.73)	25.97	(25.91, 26.03)	10.00	(9.67, 10.03)
Loss	81.54	(81.49, 81.59)	38.43	(38.37, 38.49)	9.27	(9.24, 9.30)
Net Change	−65.85	(−65.91, 65.79)	−12.46	(−12.54, 12.38)	0.73	(0.69, 0.77)

this can be difficult when conducting response surveys following storm events.

The RPAS DSM was one of the most precise of the four methods compared in this study, which is likely a result of the dense point cloud. The total station and RTK-GNSS were the least precise; however, each of these surveys contained ~2000 points. In comparison, the RPAS and TLS retrieved millions of three-dimensional points. The total station and RTK-GNSS surveys generally had the highest accuracy and precision; however, the comparatively sparse point cloud makes it difficult for the interpolation to derive a high-accuracy DTM. Deriving a high-accuracy DSM is paramount for quantifying morphologic changes (Mancini *et al*., 2013). The ability of low-cost RPAS to derive a precise DSM over a large area rapidly is desirable for coastal morphology research; the current study shows that low-cost RPAS methods are capable of such surveys.

Low-cost RPAS methods require minimal surveying expertise, especially when flight planning software is employed, which largely automates the survey (Nex and Remondino, 2014). Low-cost RPAS surveying does not require a professional pilot; however, civil aviation regulations (in New Zealand) require pilots to obtain a license to fly within 4 km of an aerodrome. RPAS data processing is largely autonomous, and it only requires a few processing steps to produce a DSM and orthomosaic (Colomina and Molina, 2014). This is beneficial because the method is accessible to a wider range of people (Ivošević *et al*., 2015). However, it is also problematic because the potential errors in the data are not always identified by nonexpert users (Sirguey *et al*., 2016). Modern RPAS photogrammetry employs a self-calibration method to solve both the interior and exterior orientation parameters in the bundle block adjustment, whereas traditional photogrammetry solves the interior and exterior parameters separately. The software finds the best solution for all of the parameters; however, it rarely finds the optimal solution (Whitehead and Hugenholtz, 2014). Previous studies (Ierodiaconou, Schimel, and Kennedy, 2016) have based the accuracy of their RPAS DSM on the RMSE value produced by the self-calibration in the photogrammetry software. However, self-calibration of low-cost sensors can produce systematic errors in the output model, which are not well captured by the RMSE reported by modern photogrammetry software (Sirguey *et al*., 2016).

GCP networks can alleviate some of the systematic errors in the output model. Accurate RPAS photogrammetry is dependent on the GCP configuration (Sirguey *et al*., 2016). The GCPs are used to orientate photographs in space (Gonçalves and Henriques, 2015). The GCP configuration needs to extend beyond the boundaries of the study site to avoid an increase in systematic error in the photogrammetric model. An even spread of GCPs within the area of interest is also required to produce an accurate photogrammetric model (Linder, 2009).

Low-cost RPAS is substantially less expensive than conventional surveying instruments, which is beneficial because it is more accessible to a wider range of people. An RPAS can be purchased for between US$700 and US$70,000. The more expensive models tend to yield better results; however, they also require more expertise to operate. The RPAS in the current study costs approximately US$1400. If the RPAS obtains a small GSD, the GCPs need to be surveyed with high precision (Toutin and Chénier, 2004); therefore, RTK-GNSS or total station surveys are usually employed to establish a GCP network, increasing the total cost of the method. Photogrammetry software employed to process the imagery can also be expensive; Pix4D Mapper, employed in this study, cost approximately US$8400 for an unlimited license. However, less expensive software packages are available, such as AgiSoft Photoscan, which have also been used to derive DSMs from coastal RPAS surveys (Gonçalves and Henriques, 2015).

The cost of RPAS technology is expected to decrease as the technology advances. It is also expected that there will be an increase in availability of different types of sensors (for example, multispectral, hyperspectral, and LIDAR) for low-cost platforms. The application of LIDAR sensors is desirable for morphologic surveys in areas with dense vegetation, because conventional red-blue-green (RGB) cameras cannot penetrate dense vegetation canopies (Harwin and Lucieer, 2012).

Application of RPAS for Coastal Surveying

The DSMs derived from the RPAS imagery did not accurately describe dune morphology in vegetated areas. Low-cost RPAS are generally equipped with RGB cameras that are not capable of penetrating vegetation; therefore, the elevation recorded is not necessarily the ground surface (Hugenholtz *et al*., 2013). This may result in a DSM in coastal dune situations that describes the elevation of the vegetation canopy, or some elevation between the canopy and the ground. In the current study, there were differences of 10 cm to 30 cm between the elevation of the RPAS DSM and the DTMs produced from the other methods in some vegetated areas. This offset resulted from a number of factors, including vegetation height, vegetation density, the spectral characteristics of the image, and GSD.

Coastal dunes typically contain a variety of plant species. At St. Kilda Beach, there are three main species: *A. arenaria* (a grass), *Coprosma repens* (a shrub with dense foliage and clearly defined canopy), and *L. arboreus* (a shrub with spare foliage and a complex canopy). Different plant species vary in height, which may create different elevation offsets. At St. Kilda, *A. arenaria* is typically <0.5 m high. It tends to be dense on the lee slope of the foredune, and somewhat less dense on the stoss face (because of a history of recent scarping). The presence of a variety of species and vegetation densities may make it difficult to accurately survey dune morphology in some situations. The ideal situation would be unvegetated dunes (Hugenholtz *et al*., 2013). However, depending on the quantity of volume change, a sparse grass cover may have minimal impact on the morphological analysis.

Producing accurate DSMs is important when the data are used to calculate morphologic change. In the current study, visible sand deposition occurred in the lee of the constructed notches at St. Kilda Beach. However, the deposition had a dampening effect on *A. arenaria*, and the observed accretion was calculated between the RPAS surveys as a decrease in elevation. The morphologic change assessment, therefore, could not accurately quantify the amount of sediment deposited in the lee of the foredune. Therefore, low-cost RPAS is not suitable for quantifying small-scale (millimeter to centimeter) changes where vegetation is present. In such cases, either a sensor capable of penetrating vegetation should be employed, or the elevation offset caused by the vegetation should be quantified.

For many coastal dune RPAS applications, the effect of vegetation may be insignificant. For example, a management agency may wish to determine the volume of sand eroded from a foredune by waves during a storm event (Ierodiaconou, Schimel, and Kennedy, 2016). In such circumstances, the presence of sparse and short (<1 m high) grasses may not significantly affect the volumetric calculations due to the large loss of sediment. The same applies for long-term changes (years) where the amount of morphologic change is greater than the height of the vegetation.

However, the inability of such sensors to penetrate vegetation can be useful for vegetation studies because approximate vegetation height can be quantified using the output DSM (Li *et al*., 2016), and the vegetation type and distribution can be depicted in the imagery (Kaneko and Nohara, 2014; Reid, Ramos, and Sukkarieh, 2011). In studies where vegetation is present but ground elevation is required, LIDAR will provide a more accurate estimate than an RGB sensor due to its ability to penetrate vegetation canopies and obtain the elevation of the terrain (Hugenholtz *et al*., 2013).

The RPAS method offers the additional benefit of capturing images of the landscape of interest. Obtaining a time series of photographs (both vertical and oblique) can be beneficial for coastal monitoring, as it provides a snapshot of the state of the environment. Photographs are a useful tool for understanding coastal processes, and low-altitude photography enables a unique perspective of the area of interest, using a close-range bird's-eye view. Deriving DSMs and orthomosaics of coastal areas incrementally over time can help to identify long-term morphologic trends and visible changes, including evidence of land-use change. This type of monitoring could help management agencies identify patterns of change, enable a better understanding of the coastline, and predict future coastal change.

CONCLUSION

Low-cost RPAS technology is accessible, flexible, largely automated, inexpensive, and provides both elevation data and high-detail aerial photography. Coastal dune systems can be efficiently and accurately surveyed using low-cost RPAS. The accessibility and flexibility of low-cost RPAS provide benefits over conventional survey methods. RPAS platforms have the ability to access environments that may be difficult to traverse using ground-based methods. This type of RPAS platform does not necessarily require an expert operator, which provides an opportunity for a range of agencies to employ this type of method. However, the systematic errors that are unmodeled by modern photogrammetry need to be understood by RPAS users to produce accurate photogrammetric models.

Low-cost RPAS surveying is ideal for both short- and long-term coastal monitoring due to the ease of conducting repeat surveys. This is especially desirable for quantifying event-scale changes at short notice. However, low-cost RPAS methods are only capable of quantifying small-scale morphologic changes in areas with bare sand or sparse vegetation.

It is expected that this technology will continue to evolve, and aircrafts that can withstand greater wind speeds and precipitation, and that have a greater battery capacity, will be developed. The influence of vegetation cover in RPAS-derived DSMs needs to be addressed further; however, sensors capable of penetrating vegetation are becoming more accessible for use on multiple RPAS platforms.

ACKNOWLEDGMENTS

Julia, Mike, Pascal, and Tom would like to thank the Dunedin City Council and the Civil Aviation Authority (Momona International Airport) for their support and cooperation. Jeff Smart, from the Dunedin Model Aero Club, allowed the author to practice RPAS flying at the model aero club and kindly assisted with the test to gain the "Wings Badge." Julia would also like to acknowledge all of the students that assisted with data collection, and the technical support from the Department of Geography and the School of Surveying at the University of Otago. Special acknowledgement is given to the local dog-walkers at St. Kilda Beach.

LITERATURE CITED

Aber, J.S.; Marzolff, I., and Ries, J.B., 2010. Chapter 8—Platforms for small-format aerial photography. *In:* Aber, J.S.; Marzolff, I., and Ries, J.B. (eds.), *Small-Format Aerial Photography*. Amsterdam, The Netherlands: Elsevier, pp. 91–118.

Bochev-van der Burgh, L.M.; Wijnberg, K.M., and Hulscher, S.J.M.H., 2011. Decadal-scale morphologic variability of managed coastal dunes. *Coastal Engineering*, 58(9), 927–936.

Brovelli, M.A.; Crespi, M.; Fratarcangeli, F.; Giannone, F., and Realini, E., 2006. Accuracy assessment of high resolution satellite imagery by leave-one-out method. *In:* Caetano, M. and Painho, M. (eds.), *Proceedings of the 7th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences* (Lisbon, Portugal), pp. 533–542.

Castelle, B.; Le Corre, Y., and Tomlinson, R., 2008. Can the gold coast beaches withstand extreme events? *Geo-Marine Letters*, 28(1), 23–30.

Civil Aviation Authority of New Zealand, 2015. *Advisory Circular AC101-1*. Wellington, New Zealand. *Civil Aviation Authority of New Zealand Remotely Piloted Aircraft System Regulations,* 15p.

Colomina, I. and Molina, P., 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review, 2014. *ISPRS Journal of Photogrammetry and Remote Sensing*, 92, 79–97.

Darwin, N.; Ahmad, A., and Zainon, O., 2014. The potential of unmanned aerial vehicle for large scale mapping of coastal Area. *IOP Conference Series: Earth and Environmental Science*, 18(1), 1–6.

Delacourt, C.; Allemand, P.; Jaud, M.; Grandjean, P.; Deschamps, A.; Ammann, J.; Cuq, V., and Suanez, S., 2009. DRELIO: An unmanned helicopter for imaging coastal areas. *In:* da Silva, C.P. (ed.), *Proceedings of the 10th International Coastal Symposium*. *Journal of Coastal Research*, Special Issue No. 56, pp. 1489–1493.

DJI, 2015. *Phantom 3 Advanced User Manual Version 1.0*. DJI, 40p. https://www.dji.com/phantom-3-adv/info#downloads.

Feagin, R.A.; Williams, A.M.; Popescu, S.; Stukey, J., and Washington-Allen, R.A., 2014. The use of terrestrial laser scanning (TLS) in dune ecosystems: The lessons learned. *Journal of Coastal Research*, 30(1), 111–119.

Gerke, M. and Przybilla, H.J., 2016. Accuracy analysis of photogrammetric UAV image blocks: Influence of onboard RTK-GNSS and cross flight patterns. *Photogrammetrie-Fernerkundung-Geoinformation*, 1, 17–30.

Gonçalves, J.A. and Henriques, R., 2015. UAV photogrammetry for topographic monitoring of coastal areas. *ISPRS Journal of Photogrammetry and Remote Sensing*, 104, 101–111.

Harwin, S. and Lucieer, A., 2012. Assessing the accuracy of georeferenced point clouds produced via multi-view stereopsis from unmanned aerial vehicle (UAV) imagery. *Remote Sensing*, 4(6), 1573–1599.

Hesp, P., 1988. Morphology, dynamics and internal stratification of some established foredunes in southeast Australia. *Sedimentary Geology*, 55(1–2), 17–41.

Hilary, F.S.; Asbury, H.S.; Jeffrey, H.L., and Rob, A.H., 2002. Estimation of shoreline position and change using airborne topographic LIDAR data. *Journal of Coastal Research*, 18(3), 502–513.

Hilton, M.J.; Hatcher, S.V.; Wakes, S.J., and Konlechner, T.M., 2016. Flow deflection and deceleration across a simple foredune. *In:* Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds), *Proceedings from the International Coastal Symposium (ICS) 2016* (Sydney, Australia). *Journal of Coastal Research*, Special Issue No. 75, pp. 293–297.

Hugenholtz, C.H.; Whitehead, K.; Brown, O.W.; Barchyn, T.E.; Moorman, B.J.; LeClair, A.; Riddell, K., and Hamilton, T., 2013. Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. *Geomorphology*, 194, 16–24.

Ierodiaconou, D.; Schimel, A.C., and Kennedy, D.M., 2016. A new perspective of storm bite on sandy beaches using unmanned aerial vehicles. *Zeitschrift für Geomorphologie, Supplementary Issues*, 60(3), 123–137.

Ivošević, B.; Han, Y.G.; Cho, Y., and Kwon, O., 2015. The use of conservation drones in ecology and wildlife research. *Journal of Ecology and Environment*, 38(1), 113–118.

Kaneko, K. and Nohara, S., 2014. Review of effective vegetation mapping using the UAV (unmanned aerial vehicle) method. *Journal of Geographic Information System*, 6(6), 733–742.

Li, W.; Niu, Z.; Chen, H.; Li, D.; Wu, M., and Zhao, W., 2016. Remote estimation of canopy height and above ground biomass of maize using high-resolution stereo images from a low-cost unmanned aerial vehicle system. *Ecological Indicators*, 67, 637–648.

Linder, W., 2009. *Digital Photogrammetry: A Practical Course*, 3rd edition. Berlin: Springer-Verlag, 229p.

Mancini, F.; Dubbini, M.; Gattelli, M.; Stecchi, F.; Fabbri, S., and Gabbianelli, G., 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: The structure from motion approach on coastal environments. *Remote Sensing*, 5(12), 6880–6898.

Martinez, M.L.; Gallego-Fernandez, J.B.; Garcia-Franco, J.G.; Moctezuma, C., and Jimenez, C.D., 2006. Assessment of coastal dune vulnerability to natural and anthropogenic disturbances along the Gulf of Mexico. Environmental Conservation, 33(2), 109–111.

Mathew, S.; Davidson-Arnott, R.G.D., and Ollerhead, J., 2010. Evolution of a beach–dune system following a catastrophic storm overwash event: Greenwich Dunes, Prince Edward Island, 1936–2005. *Canadian Journal of Earth Sciences*, 47(3), 273–290.

Mobile Works Ltd., 2016. *Drone Hire*. http://dronehire.co.nz/.

Morton, R.A.; Leach, M.P.; Paine, J.G., and Cardoza, M.A., 1993. Monitoring Beach Changes Using GPS Surveying Techniques. *Journal of Coastal Research*, 9(3), 702–720.

Nex, F. and Remondino, F., 2014. UAV for 3D mapping applications: A review. *Applied Geomatics*, 6(1), 1–15.

Pardo-Pascual, J.E.; García-Asenjo, L.; Palomar-Vázques, J., and Garrigues-Talens, P., 2005. New methods and tools to analyze beach-dune system evolution using a real-time kinematic global positioning system and geographic information systems. *In:* Alcántara-Carrió, J. and Tena, J. (eds), *Coastal Erosion*. *Journal of Coastal Research*, Special Issue No. 49, pp. 34–39.

Reid, A.; Ramos, F., and Sukkarieh, S., 2011. Multi-class classification of vegetation in natural environments using an unmanned aerial system. *Proceedings of the IEEE International Conference on Robotics and Automation* (Shanghai, China), pp. 2953–2959.

Rozé, F. and Lamauviel, D., 2004. Sand dune restoration in North Brittany, France: A 10-year monitoring study. *Restoration Ecology,* 12(1), 29–35.

Saye, S.E.; Van der Wal, D.; Pye, K., and Blott, S.J., Beach-dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data. *Geomorphology*, 71(1–4), 128–155.

Scarelli, F.M.; Cantelli, L.; Barboza, E.G., and Rosa, M.L.C.C., and Gabbianelli, G., 2016. Natural and anthropogenic coastal system comparison using DSM from a low cost UAV survey (Capão Novo, RS/Brazil). *In:* Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds), *Proceedings from the International Coastal Symposium (ICS) 2016* (Sydney, Australia). *Journal of Coastal Research*, Special Issue No. 75, pp. 1232–1236.

Sirguey, P.; Boeuf, J.; Cambridge, R., and Mills, S., 2016. Evidences of sub-optimal photogrammetric modelling in RPAS-based aerial survey. *Proceedings of the 8th National Cartographic Conference, GeoCart '2016, and the 4th ICA Regional Symposium on Cartography for Australia and Oceania* (Wellington, New Zealand), Paper 62, pp. 1–8.

Sirguey, P. and Cullen, N.J., 2014. A century of photogrammetry on Kilimanjaro. *Proceedings of the 25th FIG Congress* (Kuala Lumpur, Malaysia), Paper 6959, pp. 1–12.

Taylor, E.B.; Gibeaut, J.C.; Yoskowitz, D.W., and Starek, M.J., 2015. Assessment and Monetary Valuation of the Storm Protection Function of Beaches and Foredunes on the Texas Coast. *Journal of Coastal Research*, 31(5), 1205–1216.

Toutin, T. and Chénier, R., 2004. GCP requirement for high resolution satellite mapping. *Proceedings of the International Society for Photogrammetry and Remote Sensing Congress*, (Istanbul, Turkey), pp. 836–839.

Trimble, 2013. *Trimble Access Software: General Survey, Version 2.10, Revision A*. Sunnyvale, California: Trimble Navigation Limited, pp. 174–292.

Turner, I.L.; Harley, M.D., and Drummond, C.D., 2016. UAVs for coastal surveying. *Coastal Engineering*, 114, 19–24.

Whitehead, K. and Hugenholtz, C.H., 2014. Remote sensing of the environment with small unmanned aircraft systems (UASs), Part 1: A review of progress and challenges. *Journal of Unmanned Vehicle Systems*, 2(3), 69–85.