Title:

Application of UAV techniques to expand beach research possibilities: A case study of coarse clastic beach cusps

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Abstract:

Unmanned aerial vehicles (UAVs) have widely been documented as accessible, low cost, high-resolution coastal monitoring platforms. To date, however, UAVs have primarily been employed in coastal research as an alternative to traditional survey methods, such as beach profiling, despite their capabilities far exceeding such uses. In this contribution, we present UAV surveys as a technique to expand upon previous research possibilities through a case study on coarse clastic beach cusps. Currently no consensus exists regarding the primary mechanism responsible for development of these rhythmic features, not least due to the need for more comprehensive and timely observational data. Previous research on beach cusps is limited to repeat monitoring of a small number of cusps, or monitoring large cusp sets at relatively coarse spatial resolution. Here, repeat UAV surveys along a 600 m transect of composite beach in New Zealand are employed to produce the most comprehensive characterisation of cusp parameters (spacing, amplitude, depth) available to date. Furthermore, the use of UAVs in this mixed sediment environment has made it possible to link cuspate morphology, such as horns and bays, to surface sediment texture. This critical advance provides new opportunities for coupling textural and topographic data in future analyses and modelling approaches. We argue that the enhanced, but still nascent, opportunity to observe morphodynamics using UAV survey methods can be critical to advancing our understanding of complex coastal zone features and changes.

Keywords:

Composite beaches; rhythmic topography; drones; structure from motion; beach topography, survey methods;

1. Introduction:

Beach cusps are crescentic, rhythmic morphological features commonly found on beach foreshores worldwide (Masselink et al., 1997; Nolan et al., 1999). They are most pronounced and noticeable on beaches that comprise some coarse sediment, such as mixtures of sands and gravels. Despite their ubiquity, there is no unifying theory or scientific consensus on how beach cusps form (Coco, 2017). One existing theory suggests that they result from the presence of standing edge waves, which cause systematic longshore differences in wave height and runup (Guza and Inman, 1975). A competing theory is that of self organisation (Werner and Fink, 1993), whereby positive feedback between flow and morphology creates incipient relief and negative feedback inhibits net deposition or erosion on developed cusps.

It is clear that more information on coastal evolution is required in order to fully characterise beach cusp behaviour. Techniques hitherto employed to study coastal topography are characterised by different combinations of scales and/or repeatability limitations, time and cost demands, and/or are intrusive to the point of modifying the features that are being ‘observed’ (Table 1). Since the earliest scientific beach observation, the measurement of cross-shore linear survey lines in the form of ‘beach profiles’ has formed a staple part of monitoring, initially using elevation poles and tape measures (Emery, 1961) and more recently using Real-Time Kinematic Global Positioning System (RTK-GPS) systems (Turner et al., 2016b). When attempting to apply these methods directly to cusp measurement, the rhythmic nature of the feature means that a large number of profiles are required to accurately represent the beach morphology, making fieldwork time-consuming and laborious (Ali et al., 2017; Coco et al., 2004; Masselink, 1999; Nolan et al., 1999; Senechal et al., 2014). The spatial (alongshore) resolution and speed of beach surveys was improved with the advent of RTK-GPS, and particularly the combination of GPS methods with All Terrain Vehicles

(ATVs), but transect spacing on these surveys varies from 3 m (Holland and Holman, 1996) to 40 m (de Schipper et al., 2017). When considering coarse clastic cusps rather than sand beach features, cusps are smaller in length, steeper sloped, and highly collapsible. Given these characteristics, observations derived from intrusive tools, such as ATVs, are likely to struggle with accurately capturing beach cusp features without damaging them. This makes repeat surveys of cusp development, dynamics and evolution difficult. Instead, a number of studies have developed novel methods to measure and monitor beach cusps, with a view to understanding what controls their form and behaviour. However, these experiments have also typically been limited in scope by the observation techniques employed (Table 2), including limits on the number of cusps measured along a beach, and/or the accuracy and resolution of the resulting surveys.

A high resolution, non-invasive, remote survey method is required to accurately describe morphological development and dynamics of cusps through time. Airborne and terrestrial Light Detection and Ranging (LiDAR) techniques have proven useful tools for the creation of digital surface models (DSMs), but Airborne LiDAR is expensive and influenced by weather, while terrestrial methods often require multiple surveys alongshore, and thus more extensive processing, in order to produce accurate topography (van Gaalen et al., 2011). Instead, the rapidly growing availability of low cost Unmanned Aerial Vehicles (UAVs), combined with advances in camera hardware and photogrammetric software, mean that UAV-derived DSMs are an increasingly attractive method of measuring geomorphic change (Cook, 2017).

Table 1. Comparison of the attributes and uses of different beach topography measuring methods.

Approach	Data attributes				Research study attributes				
	Raw data type	Raw data accuracy	Typical processed data products	Data product accuracy	Study area size	Resource issues	Survey repeatability	Intrusiveness[4]	Suitable question types
Beach profiling	Line	sub-meter to cm[1]	Cross-shore profile lines, excursion distances, profile volume changes	Sub-meter to cm[1]	Key locations to 100 km regions	Time consuming	Medium	Intrusive	Broad monitoring of beach trends, detailed cross-shore event dynamics (e.g. storm cycles)
Erosion plates or pegs	Point	mm	Elevations and elevation differences	cm	Few m to few km	Time consuming	Medium	Intrusive	Detailed erosion/accumulation rate monitoring
RTK-GPS (pedestrian or ATV mounted)	Line	cm	DSMs	cm to m[2]	10s m (pedestrian) to few km (ATV)	Slow (pedestrian) to fast (ATV), expensive	Medium	Moderately (pedestrian) to significantly (ATV) intrusive	Moderately broad longshore, cross-shore, and volume dynamics (e.g. to evaluate sediment mining or beach nourishment effects)
Oblique video imagery	Surface imagery	m to 10s m	Spectral surface	m to 10s m[3]	10s to 100s m	Time consuming set up, fast and easy data capture thereafter	High	Remote	Detailed to moderately broad feature location and horizontal dimension dynamics (e.g. to study rip, bar or rivermouth dynamics)
Terrestrial LiDAR	Surface imagery	cm	Spectral surface + DSM	cm	10s to 100s m	Time consuming, expensive	High	Remote	Moderately broad longshore, cross-shore, and volume dynamics (e.g. to evaluate beach trends, or sediment mining or beach nourishment effects)

UAVs (drones)	Surface point clouds	cm to m	Spectral surface + DSM	cm to m	10s m to few km	Fast, cheap to moderately expensive	High	Remote	Detailed to moderately broad longshore, cross-shore, surface and volume dynamics
Aerial LiDAR	Surface imagery	m to km	Spectral surface + DSM	m to km	100s m to 100s km	Expensive	Low	Remote	Broad, long-term monitoring of beach trends
Satellite	Surface imagery	m to km	Spectral surface +DSM	m to km	100s m to 100s km	Free to expensive	High	Remote	Broad near-term monitoring of beach trends

[1] Accuracy varies with tools employed, from ruler, tape measure and compass; through Abney level; to survey total station and prism.

[2] Data coverage and density, and gridding method all affect the accuracy of the resultant DSM surfaces.

[3] Accuracy decreases rapidly with distance from camera location for oblique video images.

[4] Intrusive techniques can preclude analysis of changes in small features such as cusps, since sharp contours and steep slopes may be modified during the survey process.

Table 2. Summary of methodological approaches employed in the measurement of beach cusps.

Method	Coverage	Accuracy	Notes	Authors
Beach profiling	Individual survey lines	O(0.1 m)	Multiple lines to capture horn and bays	Nolan et al. (1999); Masselink (1999); Coco et al. (2004); Senechal et al. (2014); Ali et al. (2017).
Erosion pegs	< 5 cusps	O(0.02 m)		Masselink et al. (1997)
ATV mounted RTK-GPS	Entire beach	O(0.05 m)	Spacing of transects varies from 3 - 40 m	Holland and Holman (1996); Poate et al. (2014)
Video imagery	Entire beach	Not stated	Useful for cusp spacing but not morphology	Almar et al. (2008); Birrien et al. (2013)
Terrestrial LiDAR	500 m	Not stated	11 surveys for 500 m coverage	van Gaalen et al. (2011)

In the last six years, Unmanned Aerial Vehicles (UAVs) have transformed how geomorphology is observed, investigated and understood (Cook, 2017; Gomez and Purdie, 2018; Westoby et al., 2012). The transformation is perhaps nowhere more pronounced than in the study of coasts (Gonçalves and Henriques, 2015; Klemas, 2015; Mancini et al., 2013; Turner et al., 2016a). Here, the high-energy interface of ocean, land and atmosphere provides a unique set of observational and instrumentation challenges. The value of such systems for tracking changes in coastal environments is well documented, with vertical differences of ~0.05 m reported when compared to RTK-GPS surveys (Gonçalves and Henriques, 2015; Mancini et al., 2013). Some key coastal uses of UAVs include rapid post storm surveys (Turner et al., 2016a) and wetland monitoring and management (Klemas, 2015). Most documented coastal applications for UAV monitoring appear to be focussed on broad, general beach surveys, with little published evidence thus far of UAVs being used to monitor and measure small, individual or repeated morphological beach features such as cusps. In contrast to other coastal geomorphology observation approaches, UAVs enable the capture of spatially detailed and accurate data on study areas several kilometres in length for minimal temporal or fiscal cost. They fit into a niche between the accurate but spatially constrained techniques of beach profiling, pedestrian RTK-GPS and terrestrial LiDAR surveys; and the less detailed but spatially expansive applications of aerial and satellite observations; without the intrusiveness of vehicle-mounted RTK-GPS, or bed levelling pegs and plates; nor with the spatial coverage, distortion and dimensional issues of oblique, automatic camera images (Table 1). Does the availability of a technology with these niche characteristics really matter for fully understanding beach morphological change?

More process relevant data is needed on beach cusp morphodynamics in order to resolve the mechansims driving their dynamics, particularly on coasts with a range of grain sizes including gravel (Poate et al., 2014). Therefore, in this contribution we use the case study of beach cusps in composite (gravel and sand) beach settings to demonstrate how UAVs offer new possibilities for measuring, monitoring and, hence, understanding these common but infrequently studied features of coastal environments.

2. Materials and Methods:

This study used a low-cost UAV to investigate the morphodynamics of rhythmic beach cusps at Amberley Beach, a 600 m-long composite beach located in northern Pegasus Bay, on the east coast of New Zealand's South Island (Figure 1a). The contemporary beaches of Pegasus Bay are relatively stable and sandy in the south, which is sheltered from southerly swells by Banks Peninsula; grading to composite; and then mixed sand gravel erosional beaches along the more exposed northern third of the bay (Hart et al., 2008). Amberley Beach is currently erosional, the shoreline retreating by around 15 m over the last 22 years, and the local community and regional council responding with repeated artificial beach renourishments over this period. The beach is predominantly micro-to-mesotidal, with an average tide range of 2 m, and is subject to moderate wave energy (mean wave height H_s = 2 m, mean wave period T_p = 6.5 s (Pitman et al., 2019)) propagating from the south and refracted around Banks Peninsula, as well as locally generated north-easterly wind waves. Amberley Beach is ideally placed for the calibration of methods used in this study since it typically exhibits well-developed and rapidly changing rhythmic beach cusp morphology (Figure 1b), and a transect of 600 m is sufficient to measure in excess of 30 individual cusps.

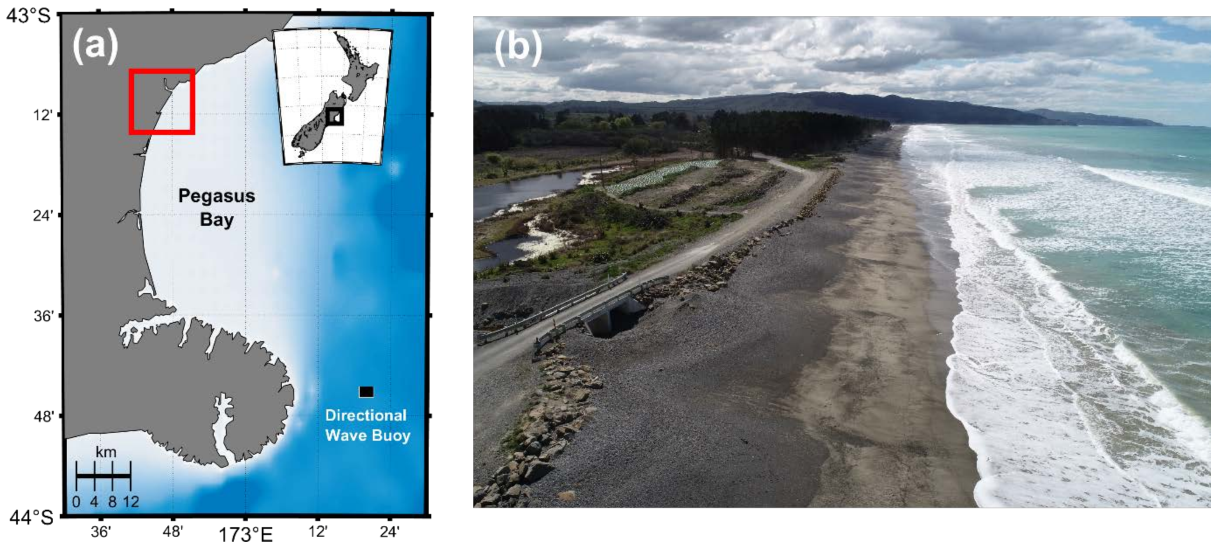

Figure 1. Study site (a) in Pegasus Bay, on the east coast of New Zealand's South Island, with Amberley beach indicated by the red square, and (b) illustrated in an oblique aerial image, facing geographic north, of Amberley beach showing prominent, well-developed gravel cusps and the composite nature of the beach with its gravel backshore and sandy foreshore/nearshore zones.

2.1 UAV and survey methods

This study used a DJI Phantom 4 Pro UAV: a low-cost (US $1,300) quadcopter equipped with a 1" CMOS 20 megapixel RGB camera. DJI provides a number of user-friendly applications, including Ground Station Pro, specifically designed for mission planning (Figure 2). In the GUI for this survey application, the user selects the physical extent of the survey, and some survey parameters such as flight altitude and image overlap. A 60 m flight altitude and 5 ms^{-1} flight speed was used, with 80 % image overlap in the footprint of successive images and parallel transects (side-lap). A field of 18 ground control points (GCPs) were placed across the study area and surveyed in using Trimble R8 RTK-GPS. GCPs consisted of vinyl checkboard targets held in place with pegs, and positioned to span the hinterland (car parks, walkways, etc.), as well as the upper and lower beach. A field of 18 GCPs was sufficient to achieve 100 m spacing at each of these three cross shore zones. Once flight parameters and GCPs were set, the drone flight was largely automated with the operator able to monitor safety and intervene should collision risks or other issues arise requiring temporary mission interruption. Two surveys were conducted two weeks apart (13 and 27 September 2018), and all flights were made in accordance with Part 101 of the Civil Aviation Authority (NZ) rules. In total, the flight time to survey the 600 m study area (approx. 4.6 ha) generally took ~15 min per run, and was achievable on one battery charge. If winds were strong (30 kph) this could double the survey time and battery requirements. The UAV took approximately 200 gridded photos to cover the study area, including a cross-shore extent of approximately 50 m between the swash zone (at the seaward extent), and the consolidated renourishment revetment plus back-beach dunes (inland).

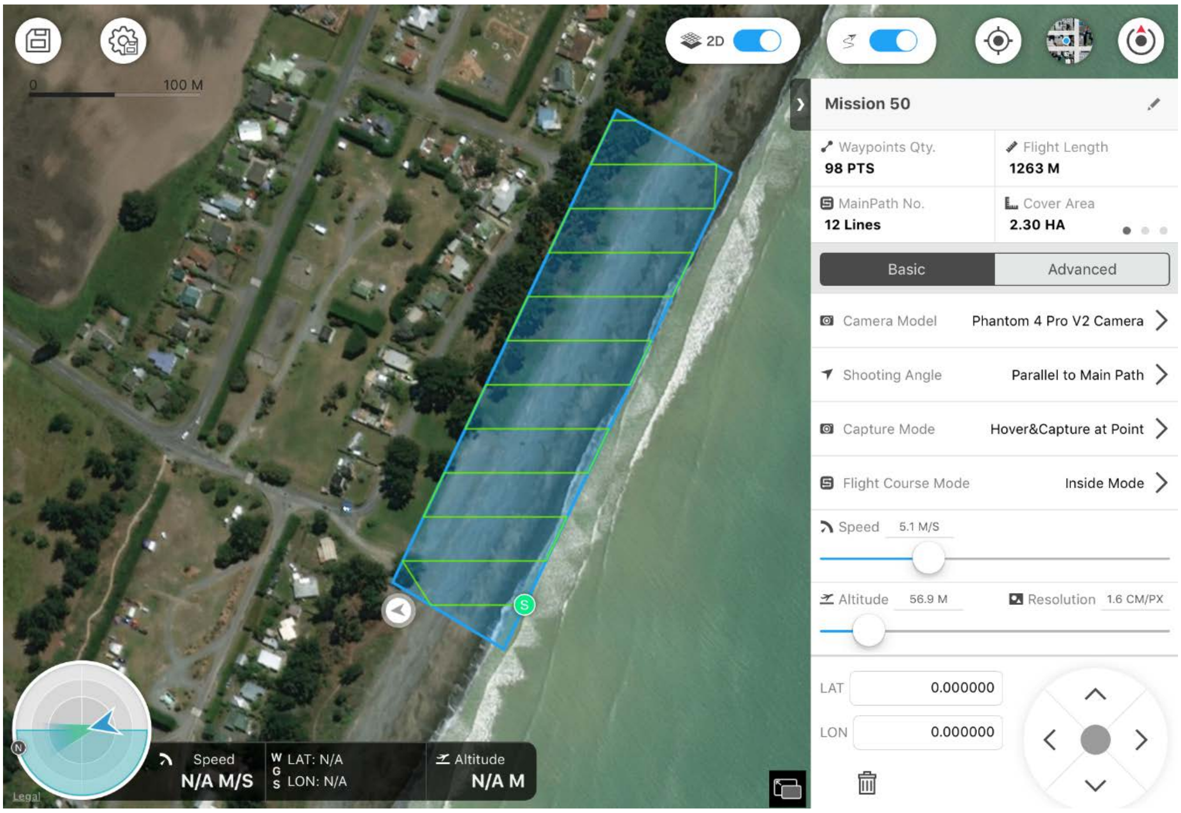

Figure 2. DJI graphical user interface for mission planning over the Amberley beach field area (blue shaded area). The panel on the right was used to select the area of interest, altitude, speed, and image overlap settings, with the app then automatically generating a flight path (green line, starting at S) based on the input parameters.

2.2 Structure from motion

Structure from motion (SfM) is a photogrammetric technique designed to resolve range and 3D surface shape from a series of offset but overlapping imagery. A full overview of the technique and its application to geomorphological studies is provided by Westoby et al. (2012). For this study, the combination of RTK-GPS ground control with the SfM technique allowed for the construction of georeferenced DSMs for each survey. A number of different freeware applications are available for SfM processing, but this study utilised the commercial package Agisoft Photoscan Pro (www.agisoft.com). This software scans all images for conjugate points, creating a point cloud from this information (Figure 3a). The user can then identify the ground control points in the images and assign them their real-world GPS position information, or alternatively convert them to a local co-ordinate system. A multiview stereo algorithm is then used to create a dense point cloud surface, and finally the depth of points is constructed with high precision to create the DSM (Figure 3b). When survey grade GPS positions have been taken, Agisoft can be set to recognise the accuracy of the ground control survey, and will subsequently produce a much higher accuracy DSM. Finally, the software can be used to create an orthomosaic of images (Figure 3c).

To evaluate the utility of the DSMs produced from the UAV survey technique, DSM accuracy was quantified by extracting elevations for 252 independent points distributed randomly across the entire observation area. These points were surveyed on foot using RTK-GPS at the same time as the first UAV survey, with comparisons between the two sets of point data enabling the assessment of the relative accuracy of the new DSM method compared to the more common GPS technique.

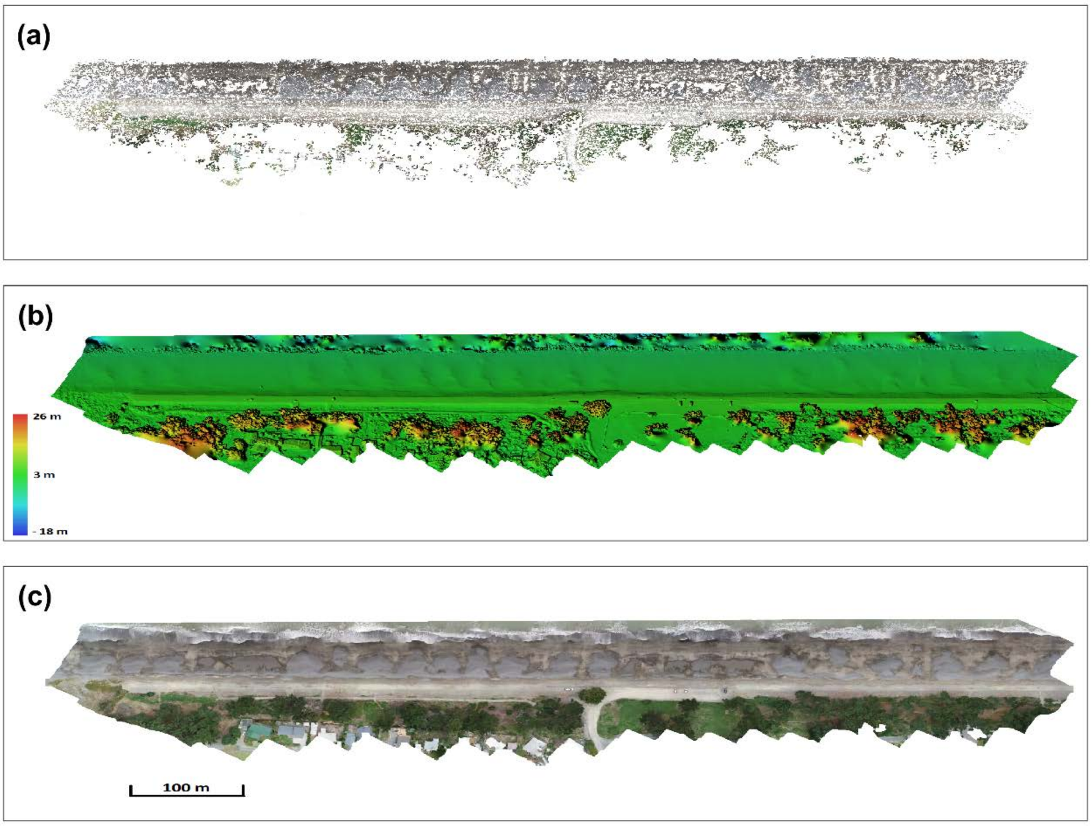

Figure 3. Standard SfM products, including (a) sparse point clouds, showing tie points identified in the imagery; (b) a digital surface model constructed from a dense point cloud; and (c) an orthorectified mosaic of survey images collected.

2.3 Sediment characterisation

The orthomosaic gives an overview of the surface sediment texture across the survey area. In the study of composite beaches and of the mixed grain sizes associated with the different component parts of cusp features, a crucial characteristic to understand is the percentage and location of surface gravel versus sand deposits since previous research links texture to cusp features (e.g. ‘gravelly’ horns versus sandy ‘bays’). The spatial distribution of sediments from these different fractions across the beachface is important in understanding cusp morphodynamics since texture can influence the operation of swash processes. For example, on the one hand increasing deposition may be encouraged by high percolation rates through gravel compared to sand surfaces while, on the other hand, gravel lag deposits can also indicate antecedent erosion.

Field characterisation of the spatial distribution of surface sediment texture is complex and problematic, often requiring either a simple visual estimate of percentage cover; detailed survey transects to isolate areas of sand and gravel; and/or sampling with substantial laboratory processing. Conversely, the orthomosaic technique employed in this study provides a detailed imagery record at sufficient resolution to enable us to visually identify surface sediment textures across the whole survey area. Here, a simple Matlab image segmentation algorithm has been applied to a section of the orthomosaic (Figure 4a) to quantify the proportion of sand versus gravel sediments on the beach surface. The algorithm works in the Hue, Saturation and Value (HSV) colour space, within which we applied simple thresholds suitable for differentiating between sand and gravel based on pixel colour. These thresholds were then used to mask the different sediment fractions (Figure 4b). Exact thresholds are not reported, since changes in factors such as illumination necessitate the review of thresholds on an image-by-image basis to ensure good visual correlation. We then created a binary surface map of the beach face, with the values 0 and 1 representing sand and gravel components respectively (Figure 4c).

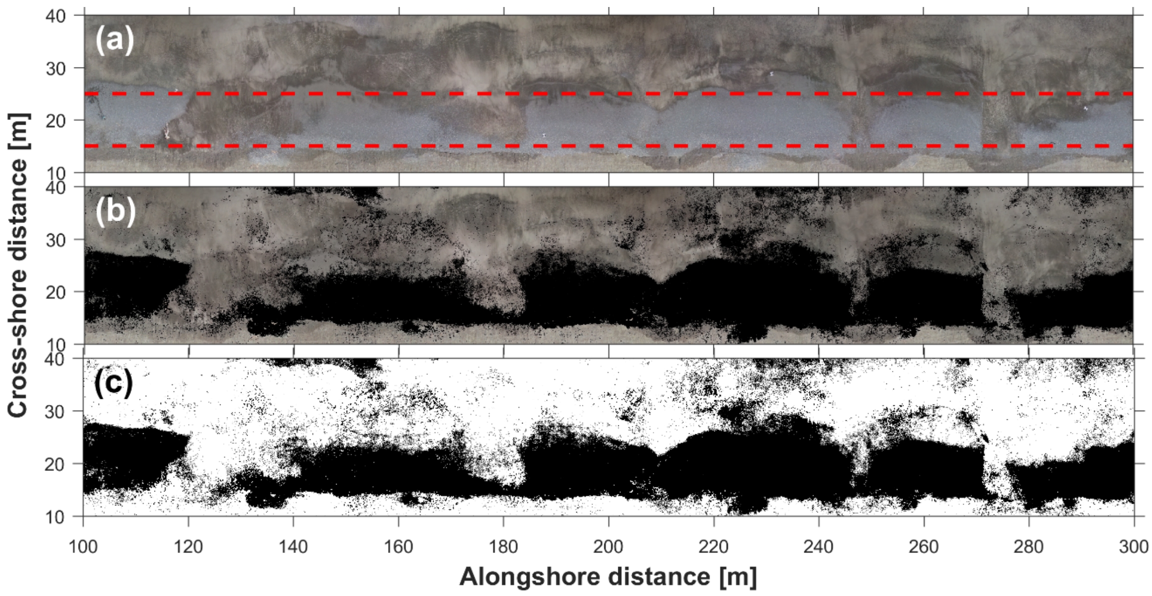

Figure 4. Example image segmentation algorithm used to quantify the percentage of sand versus gravel surface cover. (a) The original orthorectified image, clearly showing consolidated accumulations of gravel in a band between 15 – 25 m (dashed lines) cross-shore. (b) The differing visual signatures of gravel (black) and sand components allow a simple image segmentation algorithm, operating in the hue, saturation and value (HSV) colour space to differentiate between the two sediments. (c) A binary image representing the two different sediment texture categories, which can be used to calculate percentage cover.

3. Results:

In this section we first outline how the DSM derived from the UAV compares to spot heights derived from RTK-GPS systems, we present how this high resolution DSM can then be used to investigate features such as rhythmic coarse-clastic beach cusps, and finally outline some simple spatial analysis steps for the sediment characterisation data.

3.1 Relative reliability comparison of UAV and RTK-GPS survey data

In order to test the relative utility of the Amberley Beach DSMs produced from UAV data, vertical elevation were compared for 252 paired points extracted from both the DSM and RTK-GPS results. The relative accuracy of the DSM data was dependent on the chosen DSM resolution (3, 5 or 10 cm pixels), but overall the results from these two survey techniques proved comparable. The mean elevation difference with the GPS data across all three DSM resolutions was -0.1 cm (Figure 5a – c), with Root Mean Square Error (RMSE) of between 2 and 2.1 cm. DSM error distributions across all resolutions were broadly symmetrical, with a slight left skew. At the 10 cm DSM resolution, the modal error values had a slightly wider distribution, between -2 and 2 cm, though the mean and RMSE were similar to the other DSMs. All DSM resolutions were deemed sufficient for resolving cuspate features on the beachface but given the slight spread in modal vales of the 10 cm resolution DSM, we selected the 5 cm resolution DSM for further analysis, as this represented the ideal trade-off between computing time and spatial reliability. The correlation of points between RTK-GPS and 5 cm DSM derived elevations (Figure 5d) revealed them to be highly similar ($R^2 = 0.999$, $P < 0.001$), and investigation of beach elevation, slope and sediment size (not shown) showed no control on overall fit between the DSM and RTK elevations.

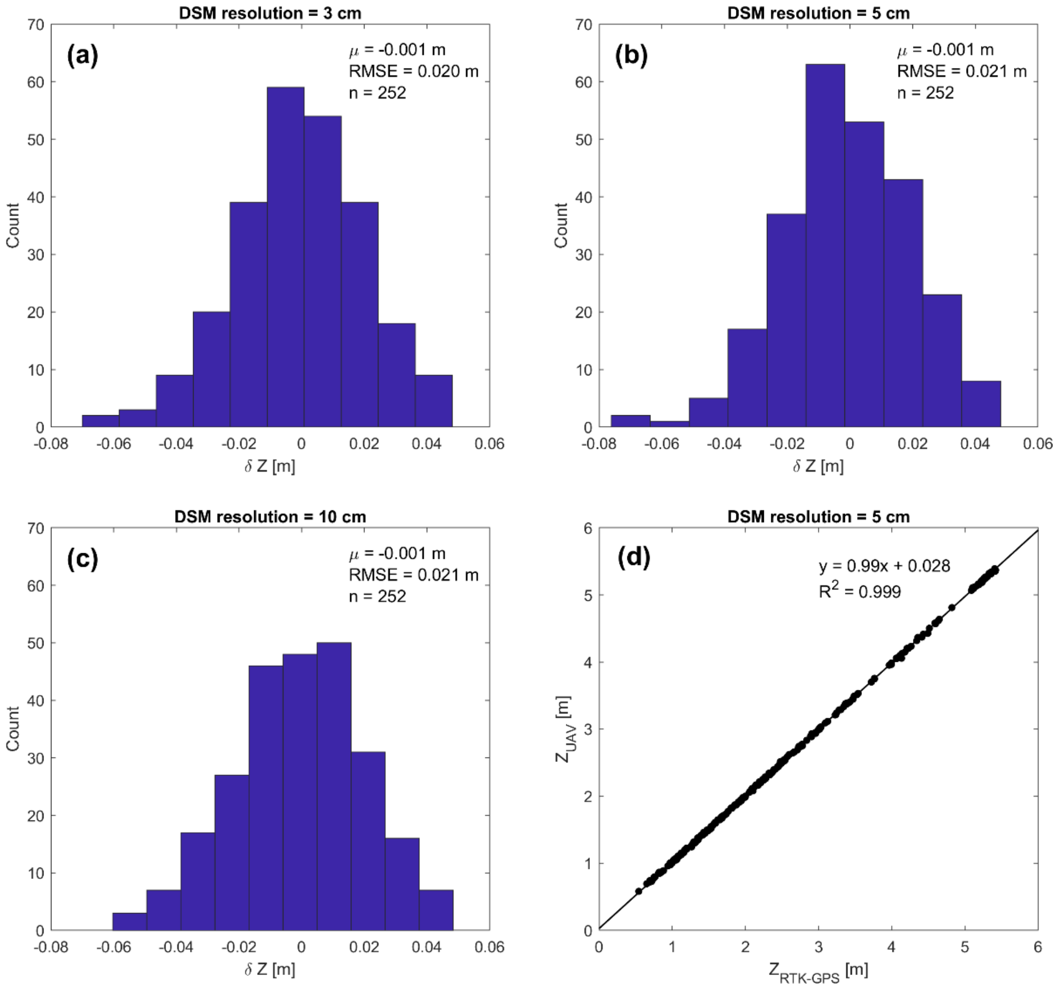

Figure 5. An assessment of elevation correlation and similarity between UAV survey, using (a) 3 cm, (b) 5 cm, and (c) 10 cm resolution DSMs, and RTK-GPS measurements. (d) A correlation of RTK-GPS and UAV 5 cm resolution DSM derived elevations is also presented, as this was the resolution selected for further analysis.

3.2 Cusp morphology

DSMs produced from UAV surveys 2 weeks apart show the existence at the first survey of a well-developed set of 8 cusp horns and bays along a 200 m section of beach, with subtle but clear changes in the contours of these cusps occurring between surveys (Figure 6a – b). Comparisons between these two surveys (Figure 6c) reveal the dominant inter-survey change to have been 0.5 m of erosion of the central to seaward parts of the cusp horns. Slight deposition and accumulation of sediment is evident at the onshore limit of the cusp horns (see cross-shore at 15 m), otherwise most of the eroded sediment appears to have been transported offshore (see cross-shore areas >40 m). With the exception of one cusp bay (see alongshore at 230 m), there appears to have been no infilling of the bays as a result of horn erosion, indicating that net cross-shore sediment transfers were more dominant than those longshore.

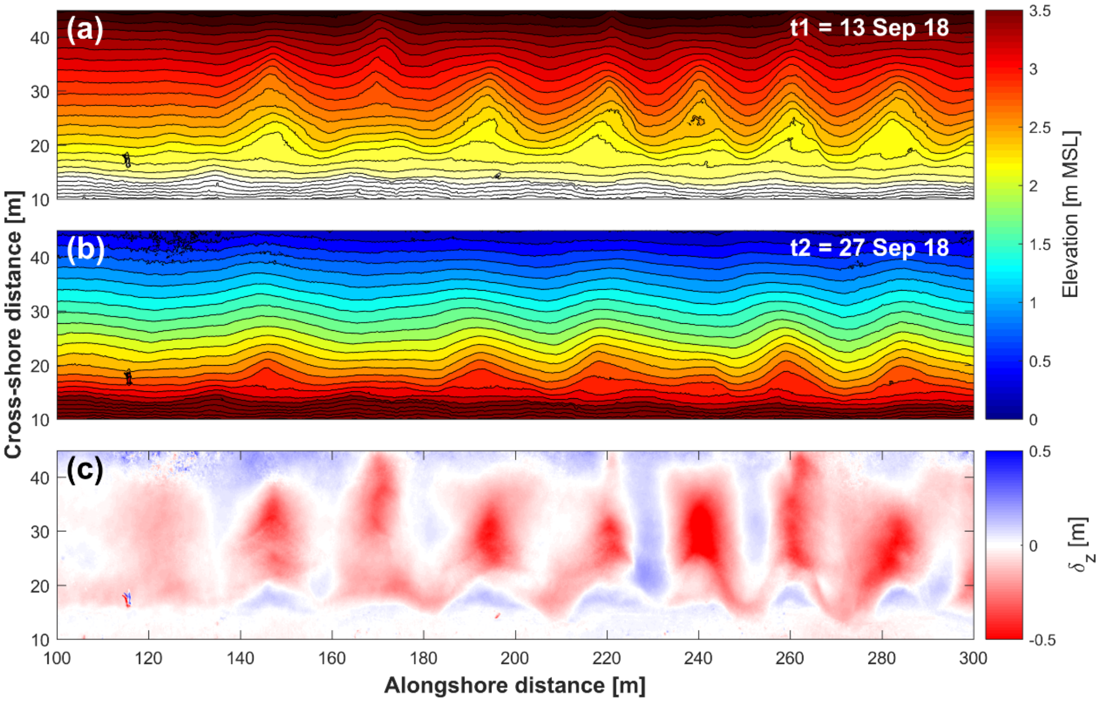

Figure 6. Amberley beach topography on (a) 13 Sep 18; and (b) 27 Sep 18, obtained from SfM DSM, showing rhythmic beach cusp formations. MSL refers to mean sea level. (c) An elevation model showing change in elevation (δ_z) between surveys, highlighting areas that eroded (blue) and accreted (red) respectively.

The construction of DSMs makes it extremely easy to calculate for each survey the four main morphological parameters associated with beach cusps as identified by Nolan et al. (1999): cusp elevation; spacing; depth; and amplitude. A user defined longshore transect through the DSM (Figure 7a) is able to reveal the horn and bay configuration of a beach, with horns appearing as prominent peaks in the elevation signal. The distance between subsequent peaks (i.e. cusp spacing or wavelength) can be detected automatically, using simple algorithms such as *findpeaks* in Matlab, as can the cusp elevation (Figure 7b). Cusp amplitude, defined as the maximum difference in elevation between subsequent horns and bays, is easily identified by comparing the cross-shore profiles extracted from a horn and neighbouring bay (Figure 7c). Likewise, when such profiles are overlaid, measurement of the horizontal depth of the cusps is possible (Figure 6c).

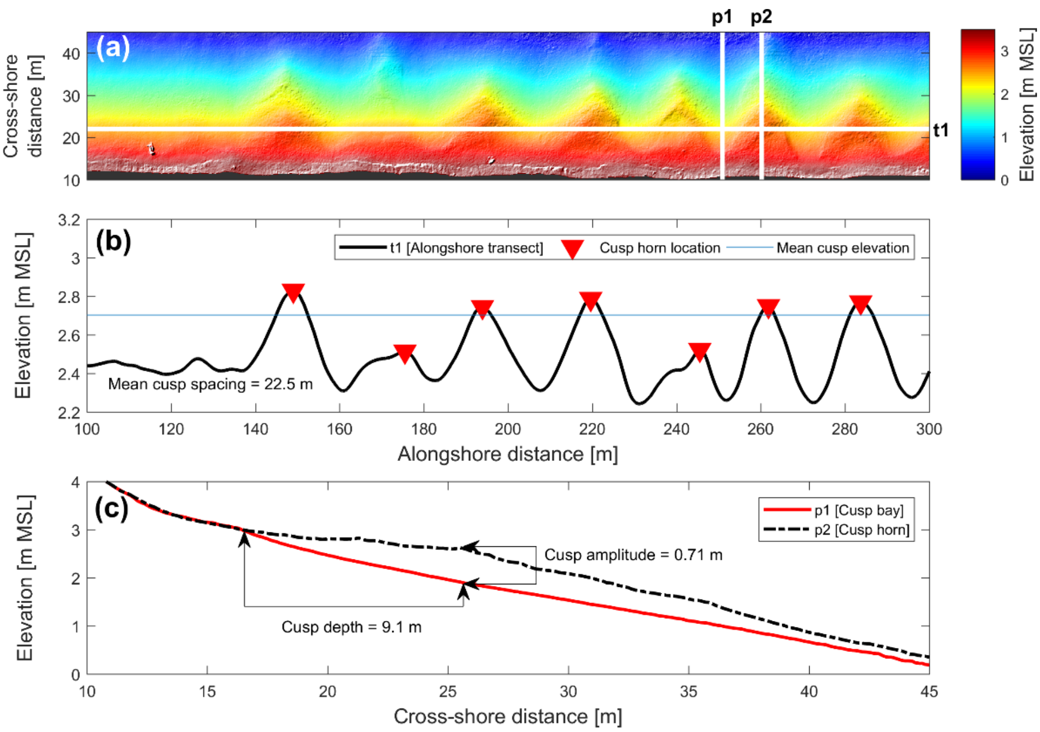

Figure 7. Example analyses of beach cusp characteristics made possible, rapid and reliable using SfM DSM data. (a) A digital surface model for the survey conducted on 13 Sep 18, with two cross-shore profile lines (p1 and p2) and one alongshore transect (t1) selected for further processing. (b) Investigation of the elevation changes along t1 allow the calculation of cusp elevation, and a simple algorithm applied to find peaks in the profile allows calculation of cusp spacing. (c) The comparison of a cross-shore profile through the cusp bay (p1) and the cusp horn (p2) is sufficient to calculate cusp amplitude and cusp depth.

3.3 Sediment characteristics

Thresholding of the orthomosaic into different sediment textures (Figure 4c) facilitates the study of spatial changes in surface cover over subsequent surveys. As pixels are individually classified, it is possible to compute a percentage gravel surface cover for each individual row of pixels in the image (Figure 4c) by counting the occurrence of binary values of 0 and 1, representing sand and gravel respectively. This parameter can be used to look at cross-shore variation in surface gravel cover over time (Figure 8).

In this study, the percentage cover of gravel predominantly reduced over the entire beachface, with the largest reduction (40 %) evident on the lower beachface (Figure 8). Some gain in gravel coverage was observed towards the onshore extent of the profile, which coincides with the small patches of accretion observed in Figure 6c.

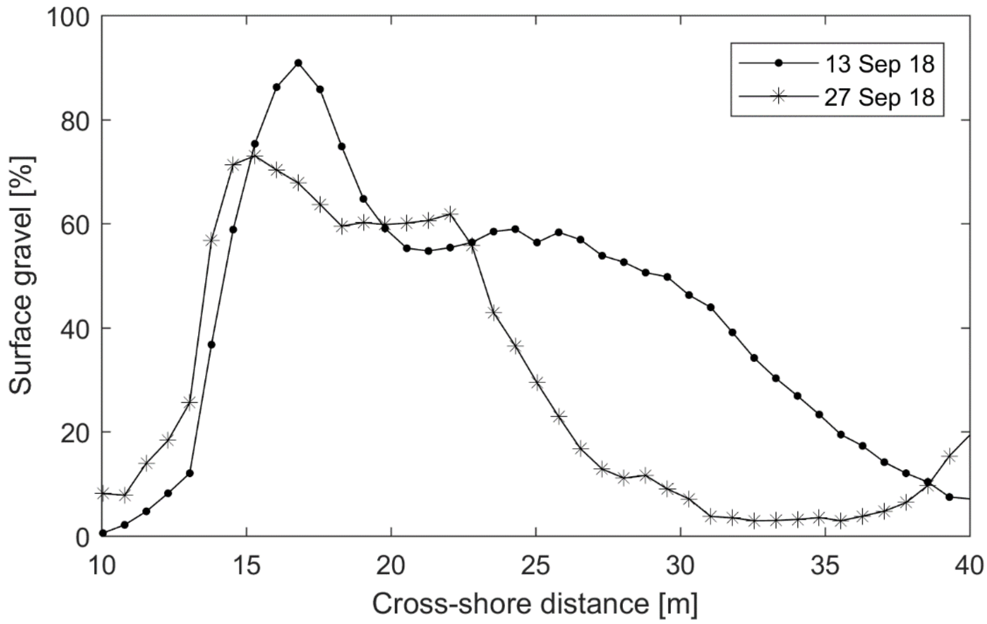

Figure 8. Changes in the percentage surface gravel cover over successive surveys.

4. Discussion:

In this study, accurate cusp surveys were achieved using a low-cost, off the shelf, non-survey grade UAV combined with ground-based survey grade RTK-GPS. This configuration was selected because many coastal monitoring organisations already possess survey grade GPS, such that the additional cost of a simple, complementary UAV system would be low. The ability to resolve beach cusp parameters for entire swathes of beach in the manner outlined here provides significant advantage over traditional beach profile, pedestrian RTK-GPS and terrestrial LiDAR methods, whereby only a few beach cusps can typically be resolved (Masselink et al., 1997; Nolan et al., 1999; van Gaalen et al., 2011). In traditional beach profiling methods there is a high degree of subjectivity in the field as to discerning profile lines that are representative of the cusp horn and bay, whereas the UAV derived DSM allows multiple profiles to be analysed and representative parameters derived quantitatively (such as extracting the maximum horn elevation). This in situ survey scale issue was somewhat addressed by the combination of RTK-GPS with ATVs for increased coverage (Holland and Holman, 1996; Poate et al., 2014). However, the resolution of such surveys is typically still on the order of several metres, with accuracies in elevation reported to be ± 6 cm due to ATVs sinking into, and thus altering, the beachface (Turner et al., 2016a). This would be particularly problematic on coarse clastic and mixed sediment beaches where the break in slope on features such as cusps is highly fragile, and likely to suffer collapse under the weight of an ATV, or even a pedestrian footstep. In contrast, the non-invasive and high resolution sampling of UAVs makes them the obvious choice for morphological mapping of such features (Mancini et al., 2013). Some care needs to be taken with regard to footprints on coarse clastic beaches when setting out GCPs ahead of the survey, but sympathetic routes (i.e. avoiding placing GCPs directly on cusps) was sufficient to negate this risk in our study. The maximum resolution achievable using these methods is limited only by flight altitude and camera optics (Gonçalves and Henriques, 2015). With our relatively low-cost camera, the flight altitude of 60 m resulted in a maximum resolution of 3 cm per pixel. This resolution was limited by the processing steps in Agisoft, but the creation of DSMs from mesh surfaces rather than point clouds could increase this resolution further. When considering resolution versus accuracy, a 5 cm DSM resolution was deemed an appropriate trade-off between computing time and accuracy of the topographic surface. The increased resolution provided by UAV derived DSMs is particularly beneficial when compared to DSMs generated by ATV surveys, where interpolation between transects is a considerable source of error (Parisot et al., 2009).

In addition to the combined spatial resolution, accuracy and repeatability advantages, the ability of the UAV-based beach cusp observation techniques to simultaneously gather data for classifying surface sediment textures is a key advance over all previously employed techniques. It has been previously posited that numerical modelling may provide a good opportunity to resolve the processes responsible for the formation of beach cusps (Coco et al., 2001; Sunamura, 2004), where such models can be calibrated with correct, sufficiently resolved information. On beaches with mixed grain sizes, one crucial parameter affecting morphodynamic processes is surface sediment composition (Buscombe and Masselink, 2006). On such beaches there is large spatial variation in infiltration, and thus markedly different erosion versus deposition potentials (Pedrozo-Acuña et al., 2007). To achieve the binary surface sediment classification of gravel versus sand employed in this paper, only a very basic level of spectral image processing knowledge was required to produce a surface sediment textural classification map. One main limitation to this approach is low elevation illumination (sunrise or sunset surveys), resulting in shadows cast across the beachface. Under these conditions, simple thresholding is not sufficient to derive sediment composition, though, to mitigate a total loss of data under such conditions, individual profiles under constant illumination can be selected and thresholded. For users with more advanced image processing skills, algorithms such as modified fuzzy C-means image segmentation could be applied in an attempt to offset illumination issues (Ma and Staunton, 2007). It should be noted that UAV-based surveys offer many additional possibilities for more detailed optical texture and/or spectral analyses in order to produce more detailed surface sediment classifications, with or without different camera tools and survey resolution choices.

In terms of methodological limitations, the UAV based observation and SfM approach explored in this paper is currently only suited to low tide surveys as the non-static nature of the swash means that SfM methods are unable to detect conjugate points when inundated. Although this low-tide swash zone limitation is comparable to most other survey methods, it does mean that SfM based on non-water penetrating UAV sensors is currently unable to resolve cusp transitions *during* storm events or tidal inundations. Drone mounted water-penetrating LiDAR or fluid lensing sensors (Chirayath and Earle, 2016) may help overcome this limitation in the future but, at present, in situ measurement rigs are still required. The deployment of drones is also generally weather sensitive, with rain and/or winds above 30 kph rendering flights impossible (Gonçalves and Henriques, 2015). This too limits beach change observations occurring during storms. However, the high resource demands and intrusive nature and safety issues associated with in situ measurement rigs offer ample motivation for researchers to pursue solutions to the current methodological limitations of UAV-SfM approaches.

5. Conclusions:

UAVs represent a technology with the potential to transform how coastal geomorphology is observed and investigated. Here we argue that UAV methods should be used to expand upon rather than simply replicate traditional survey approaches. This study has demonstrated how beach cusp topography can be resolved to a 3 cm DSM with vertical accuracies of ± 2 cm, using inexpensive UAV technology and SfM analysis techniques. Unlike traditional high-resolution methods relying on survey lines, SfM techniques allow the rapid measurement of large beach expanses, a crucial advance for characterising the morphological parameters of small three-dimensional and/or rhythmic features such as cusps. In addition to resolving the dimensions of cuspate landforms, we show that the use of UAV surveys in a mixed sediment texture environment has the benefit of facilitating the quick and accurate production of surface sediment textural distribution maps. This allows us to resolve spatial separation of sand and gravel sediments on the beachface and provides for the coupling of surface sediment texture and topographic data in future analysis and numerical modelling approaches.

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