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Short communication

UAVs for coastal surveying

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ABSTRACT

UAVs (Unmanned Aerial Vehicles or "drones") for routine survey applications at the coast have come of age, and are no longer 'the latest thing' more suited to the specialist researcher or amateur enthusiast. Off-the-shelf, survey-grade UAV equipment, data processing and analysis tools are now readily available to practicing coastal engineers, managers and researchers. Within the regulatory constraints that determine their use in many countries, UAVs provide an efficient and cost-effective survey tool for topographic mapping and measurement in the coastal zone. At the practical level, the specialist training required to operate off-the-shelf UAV suited to coastal surveying is now comparable in time and degree of difficulty to learning how to use the equivalent survey capabilities of professional hand-held RTK-GPS equipment. While incremental improvements to both the flight technology and data processing will no doubt continue to occur, from the coastal practitioner's perspective, no more step changes in UAV technology or ease of useability are required. In particular, survey-grade UAVs that incorporate internal RTK-GPS for high accuracy positioning and requiring a single operator only to safely deploy in the field, remove the need for separate and time-consuming on-ground surveying of ground control points (GCPs), previously required during post-deployment data processing. A coastal engineering application of UAV is used here to exemplify the practical use and potential benefits of this now mature survey technology. Over the past 2 years, rapid post-storm deployment of UAV surveying has been successfully integrated into an established coastal monitoring program spanning 4 decades at Narrabeen Beach, Australia. This has extended the scope of this program to include detailed measurements of dune and beachface erosion spanning the full 3.5 km long embayment at a spatial scale and temporal resolution that were previously unfeasible. For both the researcher and practicing coastal engineer, UAVs now provide a practical option for routine coastal surveying.

1. Introduction

Variously referred to in different contexts and aviation jurisdictions as UAS (Unmanned Aerial Systems), RPAS (Remotely-Piloted Aerial Systems), "Aerial Robots" or simply "drones", the practical application of UAVs (Unmanned Aerial Vehicles) for surveying at the coast has come of age. No longer 'the latest thing' more suited to the technical specialist or amateur enthusiast, off-the-shelf (i.e., commercially supplied) UAV survey equipment and data processing methods are now readily available and suitable for use by coastal engineers, managers and scientists. At its core, UAVs use autonomous flight technology combined with recent advances in computer vision techniques, to extend the very familiar and already extensive use of aerial photogrammetry applied to coastal surveying.

In this short communication we provide the coastal practitioner more interested in the survey product (i.e., wide-coverage, high-resolution coastal topography and imagery) than the specific survey equipment used to obtain it, a practical overview of current UAV survey capabilities and requirements. The rapid-response deployment of an off-the-shelf, survey-grade UAV is described, that is being used to extend the scope of a long-term coastal monitoring program underway in southeast Australia, to now include detailed post-storm coastal erosion assessment spanning a full coastal embayment.

2. Brief overview of UAV technology and regulations

For a comprehensive overview of UAV historical development, country-specific regulations and their broader applications to photogrammetry and remote sensing, the reader is referred to the recent review of Colomina and Molina (2014). The current range of civil UAV surveying and mapping applications is diverse, for example: geological resource mapping (Johnson et al., 2014); agricultural watershed analysis (Ouédraogo et al., 2014); mining (Nex and Remondino 2014); archaeology (Rinaudo et al. 2012); fire-fighting (Rufino and Moccia, 2005); forestry (Puliti et al. 2015) as well as a range of more conventional cadastral mapping tasks (Cramer et al. 2013). Published reports of UAV applied to coastal surveying are relatively limited: Mancini et al. (2013) described the trial of a multi-rotor hexacopter UAV to measure the topography of a 200 m section of beach and dune in northeast Italy; while Gonçalves and Henriques (2015) outlined the trial of an earlier generation fixed-wing and very light-weight UAV used to obtain

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a digital surface model at two test areas located on the northwest coast of Portugal. The use of a manually-piloted octocopter UAV to evaluate storm and engineered topographic changes along a 500 m section of beach of the Liguria Region in the northwest of Italy is presented in Casella et al. (2016). In Europe, the USA and Australia, the authors are aware of a number of coastal research groups who are currently exploring the use of UAVs to compliment and extend their coastal measurement programs. Drummond et al. (2015) recently described a range of practical coastal engineering and coastal management UAV applications, including: coastal structure armour volume and damage analysis; beach surveying; as well as estuary and coastal wetland mapping and management. Provided below is a very brief overview of a current off-the-shelf UAV technology that is particularly well suited to topographic surveying at the coast.

2.1. UAV airframes, flight planning & control

A modern, survey-grade UAV contains within the lightweight airframe integrated autopilot and navigation systems, a motor and battery for propulsion, and a digital camera for image capture. For applications extending beyond the specific topographic survey capability that is the focus here, an ever-expanding range of additional ground and atmospheric sensors is also available. The surveyor uses a tablet or laptop to plan, monitor and if necessary alter the survey plan during flight, and a radio link to maintain communication with the aerial vehicle. Extensive description of each of these components (and their various subcomponents) is provided in several recent review articles, including Colomina and Molina (2014) and Nex and Remondino (2014).

Fundamentally, there are two types of UAV airframes: multi-rotor (e.g., 'quadcopters', 'hexacopters' and 'octocopters'.) or fixed-wing. While each system has their particular advantages for specific applications, fixed-wing UAVs are well suited to routine topographic surveying along the coastline, as their naturally 'linear' flight path typically matches the geometry of what is commonly a long (longshore) but relatively narrow (cross-shore) survey region. Where more 'square' than 'strip' surveys of coastal regions are needed, the fixed-wing flight plan comprises a grid pattern spanning the required survey extent. Off-the-shelf fixed-wing UAVs targeted at survey applications can typically weigh of the order of a kilogram (including the camera and battery), and with a total wingspan of around a metre (that is often in two parts and can be additionally separated from the aircraft body), they are very easily transportable to and between survey sites.

Crucially, UAVs developed for the professional surveying market do not require the operator to have any specialist skills to 'fly' the airframe. Instead, a single operator determines the extent of the ground region to be surveyed and the spatial resolution required, and then automated flight-planning software calculates the required movement of the UAV in the air and at what positions to take the multiple aerial images, which is then passed to the airframe's internal autopilot and navigation systems prior to commencing the flight. The operator monitors rather than controls the UAV during flight, but for safety reasons also has the ability via the radio link to initiate several alternative actions mid-flight. These actions can include a temporary return to one or more pre-determined 'safe' waypoints and altitude (for example, if another low-flying aircraft appears unexpectedly), or initiation of automated landing prior to the completion of the full survey. Survey navigation and landing at a specified approach angle and location are all fully automated, and other than the ability to initiate an emergency abort, require no input from the operator. Many earlier generation fixed-wing UAVs relied upon a spiralling approach to the designated landing point, which on a beach of restricted width and/or relatively steep slope can be problematic. The current generation of UAVs describe below now enables a range of automated landing options to be selected, including the ability to precisely align the final approach of the UAV to the local orientation of the shore/dune-line.

2.2. RTK-GPS survey positioning and image data post-processing

The recent major advance in UAV technology that is of particular benefit to the coastal practitioner, is the availability over the past ~2 years of off-the-shelf UAV survey systems that now integrate high-precision RTK-GPS positioning. [Note: while it is recognised that 'RTK-GNSS' is more strictly the correct generic term to use here as it encompasses all global satellite navigation systems, the term 'RTK-GPS' continues to be the most commonly used in this context]. The practical advantage of UAVs with on-board precision positioning is the resulting step change in their practical useability. The RTK-GPS positioning of the camera, combined with the large redundancy of image overlaps, removes the need for any additional ground surveys.

Prior to the availability of RTK-GPS UAVs, it was necessary to separately and independently establish the precise position of a number of ground control points (GCPs) spanning the survey region, in order to proceed with the post-processing of image data to derive topographic information relative to a real-world coordinate system. Temporary GCPs typically comprised marked carpet tiles or other ground targets that were readily identifiable in aerial images. Determining the accurate location of GCPs necessitated additional hand-held RTK-GPS survey equipment and an on-ground survey team.

Removing the need for GCPs has two distinct advantages. First, the time taken to complete individual UAV surveys is substantially reduced. Second, less accessible coastal areas (e.g., wetlands or coastal cliffs) are now as straightforward to survey as an open beach. For earlier users of UAVs where this capability was not available, by far the most time-consuming (and sometime impractical) aspect of completing a UAV survey over larger areas of interest was the pre-flight laying out, accurate surveying, then post-flight collection of temporary GCPs.

A concurrent and similarly time-saving advance in satellite navigation that survey-grade UAVs now incorporate is automatic and seamless access to CORS (Continuously Operating Reference Station) networks via a standard SIM card. Networks of permanent RTK base stations that broadcast corrections over the internet in real-time are increasingly available to surveyors in the field. Whether used in real time or by accessing archived corrections during post-processing, for the coastal surveyor the proliferation of national- and state-based permanent RTK base stations provides the very real benefit that it is no longer necessary to own and deploy at each survey site a base station to achieve RTK calculation and correction.

2.3. Structure from Motion (SfM) — 3-D topography from multiple 2-D images

As noted earlier, the general principles underpinning UAV topographic surveying are very familiar to the coastal practitioner. Stereo-photogrammetry applied to aerial imagery at the coast has been in common use for more than half a century. Recent and significant developments in digital photogrammetry and computer vision have now rapidly advanced the field.

Structure from Motion (*SfM*) is a practical photogrammetric technique that has emerged in the last decade or so, used to derive three-dimensional surface reconstructions from a series of overlapping photographs. First developed in the 1990′s within the computer vision industry, the emergence of *SfM* at that time benefitted from new advances in both motion perception (e.g., Spetsakis and Aloimonos, 1991) and automated feature-matching algorithms (e.g., Lowe, 1999). *SfM* is best suited to a set of images where there is a high degree of overlap that capture the region to be surveyed from a wide number of different positions and orientations, for which a moving camera platform relative to a stationary survey target (hence the name) is particularly well suited. For topographic survey applications, many thousands of matching object and textural features are automatically detected in multiple, overlapping images of the ground surface, from which a high-density point cloud of 3-D positions is then derived. For further technical details of the underlying *SfM* algorithm and related feature-matching techniques, the Reader will easily find in the published literature many technical publications that address the subject. For a comprehensive summary that is presented from a more applied perspective, the Reader is referred to Westoby et al. (2012).

Unlike traditional photogrammetry, the dense point-cloud of individual positions provided by the *SfM* algorithm is generated in a relative 'image-space' coordinate system. Prior to the more recent availability of survey-grade UAV incorporating on-board precision RTK-GPS, the accurate transformation of this 'arbitrary' coordinate system to the required real-world coordinate system necessitated the use of GCPs. For these earlier UAV platforms, the main function of the on-board GPS was for autopilot navigation. But with the advent of on-board precision positioning that is also fully integrated with the UAV's motion and orientation sensors, the precise position and orientation of the camera corresponding to each individual image are known, and from this the real-world ground coordinates of the surveyed ground surface can be reconstructed directly. From the practical coastal practitioner's perspective, commercial suppliers of RTK-GPS UAV designed for the professional survey market will generally bundle appropriate *SfM* post-processing and data visualisation software with their UAV hardware. Standard data products will include orthomosaics, Digital Surface Models (DSMs), 3-D visualisation with fly-through capabilities and often additional automated feature detection and mapping capabilities; plus the option to output point-cloud and gridded data in a wide range of both general and proprietary file formats suitable for existing mapping and analysis software packages.

2.4. UAV regulations

In most countries the rapid development of UAV technology for both professional and recreational use has advanced ahead of regulations to guide and/or control their safe and appropriate use. Around the world, civil aviation regulatory bodies are now dealing (largely retrospectively) with the widespread and rapidly increasing availability of many types of UAVs. National regulatory frameworks for UAV are continuing to be developed and implemented, with the Australian Civil Aviation Authority (CASA) in 2002 issuing the first operational regulation for unmanned aircraft anywhere in the world. The European Aviation Safety Agency (EASA) first developed a policy statement on UAV airworthiness certification in 2009, with an ever-growing list of aviation jurisdictions that have developed UAV-related regulations now including a number of countries in Europe and Scandinavia, Brazil, USA and Canada (see Colomina and Molina, 2014; Nex and Remondino, 2014). The public perception and acceptance of the increasing use of UAVs more generally are presently mixed; Thompson and Bracken-Roche (2015) reported the findings of a survey in 2014 undertaken in Canada, showing that a majority at that time were in general support of the use of UAVs for safety and emergency-response purposes, but not their use for routine surveillance or personal identification.

As an example of the range of practical restrictions that typically apply to UAVs for the type of topographic survey applications that are the focus here, within the Australian context (where the data in the following section were acquired), for professional users the organisation is required to hold a RPA Operators Certificate (UOC) and operators must hold a current Remotely Piloted Air Systems (RPAS) certification (both issued by the Australian Civil Aviation Authority), as well as a current Aviation Radio Proficiency licence. For these types of UAVs, specific operational restrictions that currently apply in Australia include: maximum flight altitude of 400 ft. (approx. 120 m) above ground level; not permitted in controlled airspace (e.g. close to commercial airports); not permitted within 3 Nm (approx. 5.5 km) of a registered aerodrome without prior approval; not permitted over populous areas; the UAV must remain within visual line-of-sight of the operator (typically of the order of 1.5 km in any direction along a relatively open coastline); and the UAV at landing and take-off must be at least 30 m clear of the general public. At the practical level, the training required to operate this type of off-the-shelf UAV is not dissimilar in time and degree of difficulty to what is necessary to effectively operate a hand-held RTK-GPS survey unit, with RPAS training now provided by a range of authorised UAV training organisations.

3. Practical application: rapid post-storm surveying

The rapid-response deployment of an off-the-shelf, survey-grade RTK-GPS UAV is described here, to illustrate the additional capability that this technology is being used for within the context of a long-term coastal monitoring program underway in southeast Australia. Specifically, over the past 2 years the rapid post-storm deployment of UAV has extended the scope of this program to include detailed measurements of dune and beachface erosion spanning the full embayment, at a spatial scale and temporal resolution that were previously unfeasible.

3.1. Field site and existing monitoring program

Narrabeen Beach is a sandy, 3.5 km long open-coast embayment bound by rocky headlands located on Sydney's northern beaches. With routine monitoring having commenced at this site in 1976, it is now one of the longest records of coastal variability and change that are presently available worldwide. Briefly, from 1976 to 2005 beach monitoring consisted of traditional monthly beach profiles at a select number of survey transects spanning the length of the embayment. From 2005 to present, the scope has expanded to incorporate: monthly surveying of the subaerial beach using RTK-GPS mounted on an ATV (all-terrain vehicle or 'quadbike'), coastal imaging using an ARGUS station; Airborne LiDAR; jetski and boat-based surveying of the surfzone and nearshore bathymetry; and most recently the use of a LiDAR system fixed on top of a beachfront high-rise building to continuously monitor surfzone and swash zone hydrodynamics and evolving beachface and dune morphology. Further details of the evolution of the coastal survey tools and techniques at Narrabeen are provided in Harley et al. (2011), with free and open access to the long-term dataset detailed in Turner et al. (2016).

3.2. UAV and image processing

The UAV-derived survey data presented here were obtained using a fixed-wing, off-the-shelf, RTK-GPS UAV (*SenseFly eBee-RTK*) that is commercially manufactured for the professional surveyor market. With a wingspan of just under 1 m and weighing 700 g, approximately 40 min flight-time per battery enables coverage of the order of 2 km^2 in low wind conditions, or lesser areas in wind speeds of up to 45 km/h. The equipment is easily transportable between sites, and the use of multiple batteries is employed when larger surveyed areas are required.

Post-processing of image data to derive the 3-D surveys for storm erosion analysis was preformed using a commercial *SfM* software package (*Pix4D Postflight Terra*) targeted at topographic survey applications, that automates the generation of geo-referenced orthomosaics, DSMs, contour lines, 3-D point clouds and textured mesh models in a variety of formats. For routine coastal survey applications, output of point cloud data from this and other similar software packages includes: ascii files for direct input to generic analysis packages such as MATLAB; or LAS files (the industry-standard LiDAR data format) for use with more specialist GIS and other spatial data mapping packages.

3.3. UAV survey accuracy

Beach surveys of the subaerial beach and dunes at Narrabeen have been conducted at the same time as the routine monthly ATV surveys on a number of occasions, and these concurrent surveys have provided the opportunity to compare and assess the point density and relatively accuracy of these two beach survey techniques. Conveniently, one of these concurrent surveys was undertaken in the month prior to the rapid-response post-storm survey presented below.

UAV and ATV surveys were completed at Narrabeen on 19 March 2015 coinciding with spring low tide. This date and time were chosen so as to expose as much of the subaerial beach as possible. Moving at a speed of ~20 km/h and sampling once every second, the point density of the routine monthly ATV surveys is of the order of 5 m spacing alongshore. Whereas the previous approach to 3-D data processing at this site has been to interpolate the irregularly-spaced and relatively low-density ATV point data to a regular DTM, the enhanced density of UAV point cloud data (with points spaced centimeters, rather than meters apart) removes the need for such interpolation and the inherent data degradation caused by this process. Following the approach described by Lague et al. (2013), comparison between both datasets is therefore undertaken on raw data as follows: 1) for every raw ATV survey point, neighbouring UAV point cloud data within a 1 m radius are extracted; and 2) a local plane is then fit to this neighbouring UAV data and the vertical distance calculated. The 1 m distance around each ATV point from which to fit a local plane is specifically chosen to match the physical dimensions of the ATV and the inherent smoothing of the surface roughness introduced through the ATV collection process (which, due to the rigid four wheels of the ATV, is effectively planar). This therefore gives the most realistic comparison between the two monitoring approaches.

Fig. 1 shows the vertical difference between these two concurrent surveys based on 15,247 point-to-plane comparisons (the total number of data points obtained by the ATV survey). This figure indicates that differences between the two methods are normally distributed, with a mean difference of 0.026 m (i.e., UAV points are slightly elevated) and standard deviation of 0.068 m. The 1:1 comparison of the two surveys also shown in Fig. 1 indicates that they are highly correlated (linear slope = 0.996; $R^2 = 0.998$) and that this does not vary for all surveyed elevations extending from the top of the swash zone across the berm to the foredune. The observed slight mean difference between the ATV and UAV survey methods is perhaps related to the minor sinking effect of the ATV in sand. The magnitude of the elevation variability between the two methods is comparable to the expected vertical accuracy of RTK-GPS in this environment, leaving it unclear as to which of the two survey techniques is the more ‘accurate’.

3.4. Practical example: rapid-reponse post-storm surveying

A rapid-reponse survey completed a month later at Narrabeen illustrates the practical use of UAVs to quantify coastal beach and dune erosion immediately post-storm. On 20 April a low pressure system formed off the southeast coast of Australia following the rapid convergence of two troughs, and by that evening had moved south and deepened into an intense East Coast Low offshore of the central New South Wales coast. During the next 48 h period, the system remained almost stationary and resulted in prolonged onshore winds peaking at a maximum gust speed of 135 km/h (equivalent in this region to a Category 2 tropical cyclone). Energetic conditions began to subside on 22 April when the system moved southwards into the southern Tasman Sea. The deepwater significant wave heights (H_s) measured during this event reached a maximum of 8.1 m and remained above $H_s = 3$ m for a prolonged period of 72 h, with an average peak wave period $T_p =$ 11.3 s.

The UAV was deployed on the late afternoon of 24 April, coinciding with the first low tide after conditions on the beach had subsided sufficiently for it to be safe for UAV survey personnel to operate. Due to this being a period of neap tides, windy and declining light, conditions were far from optimal. A UAV survey was conducted to obtain the immediate post-storm condition of the beach and dunes, the variability in the erosion response observed alongshore, and to determine the net loss of sand from the subaerial beach relative to the UAV survey in mid-March.

The left panel in Fig. 2 shows the orthophotomosaic created from UAV images for the central ~2 km of the surveyed region obtained on 24 April. The area surveyed was slightly more than 1 km^2 in total, comprising approximately 600 individual images and taking approximately 50 min in the air to complete. The top-right panel of this same figure shows one of the individual images obtained by the UAV in the vicinity of an ad-hoc rock revetment that was newly uncovered by the storm, placed on the beachfront several decades ago to provide some protection to private residential properties and public infrastructure.

The UAV flew at an altitude of 100 m above ground level with 80% overlap of individual images, producing an average ground-sampling density of 3.4 cm and resulting in a ~30 million raw point cloud comprising (x,y,z, R,G,B) 3-D coordinates and their associated colour. Shown in the lower-right panel of Fig. 2 is a small section of the point cloud projected at an oblique angle from a position just south and offshore of the same ad-hoc revetment structure. This figure usefully illustrates a number of both advantages and challenges of UAV surveying at beaches. A clear benefit is the high density of data points on the ground surface that can be achieved, as well as the relative ease of surveying difficult or inaccessible terrain such as the dune, the steep and freshly cut storm erosion scarp, as well as the highly irregular topography of the exposed rubble mound revetment structure. An obvious downside is the lack of any survey information below the runup limit, where the *SfM* technique fails due to the non-stationary ground target (i.e. swash). Behind the beach the full details of buildings and other objects is also not

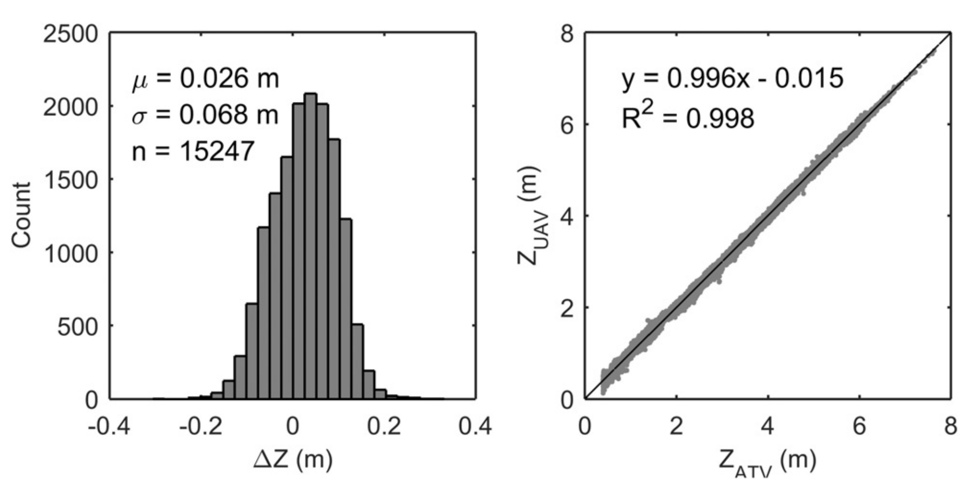

Fig. 1. UAV survey accuracy assed by comparison to concurrent on-ground RTK-GPS ATV survey (March 19, 2015; Narrabeen beach).

Fig. 2. Example post-storm UAV imagery and 3-D point cloud (April 24, 2015; Narrabeen beach).

well resolved, as is the case in small areas of the near vertical dune face and complex rubble mound. The focus of surveys conducted at Narrabeen is of the relatively narrow dune and beach area, and to most efficiently achieve this, the UAV flight path consists of a limited number of parallel passes along the linear length of the beach. Improved survey results of more complex terrain are achieved by instructing the UAV at the flight-planning stage to conduct image collection by following a grid pattern flight path and at different altitudes or angles. This technique results in images obtained from a much wider range of perspectives, better resolving more complex shapes when visualising the 3-D point cloud, and enabling the calculation of their position by *SfM*.

Example results derived from this rapid-response post-storm survey are illustrated in Fig. 3. In the left panel, the change in sand elevation between the March and April surveys (again in the immediate vicinity of the exposed ad-hoc revetment) is quantified. Adjacent to the revetment the sand level can be seen to have lowered in elevation by more than 3 m. Interestingly, even within the short length of the beach that is shown, the degree to which the beachface lowered can be seen to have varied by as much as 2 m. To place these observations in their wider context, the total loss of subaerial sand volume along the full length of the beach was 199,600 m^3, equating to an average subaerial volume reduction of 57 m^3 per alongshore metre. The right panels in Fig. 3 show example cross-sections of the beach at the 3 locations indicated, contrasting pre- and post-storm profiles extracted directly from the two UAV-derived 3-D point clouds. Along the full length of the Narrabeen embayment the beachface shifted an average 19 m landward.

4. Concluding remarks

Off-the-shelf, survey-grade UAV equipment, data processing and analysis tools are now readily available to practicing coastal engineers, managers and researchers. Within the regulatory constraints that determine their use, UAVs provide an efficient and cost-effective survey tool for topographic mapping and measurement in the coastal zone. In particular, the availability of off-the-shelf UAV survey systems that integrate high-precision RTK-GPS positioning removes the need for any additional ground surveying or equipment. The rapid post-storm deployment of UAV within the context of an established coastal monitoring program spanning 4 decades at Narrabeen Beach (Australia) demonstrates the practical use and potential benefits of this now mature survey technology. Detailed measurements of dune and beachface erosion spanning the full 3.5 km long embayment can now be obtained rapidly and immediately post-storm, at a spatial scale and temporal resolution that were previously unfeasible. For both the researcher and practicing coastal engineer, UAVs now provide a practical option for coastal surveying.

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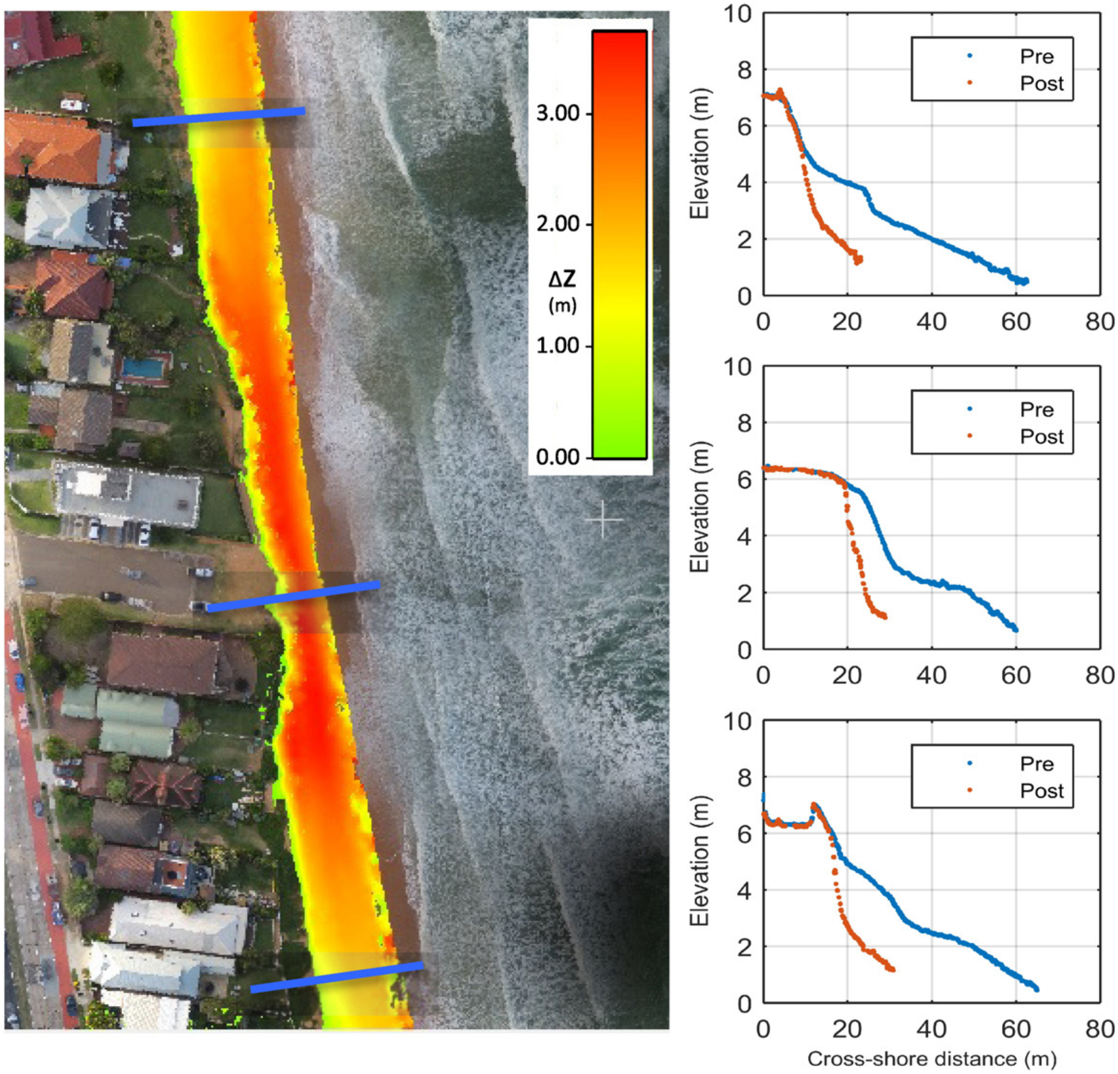

Fig. 3. Beach erosion analysis, by comparison of pre- and post-storm UAV topographic surveys.

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