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Methods for field measurement and remote sensing of the swash zone

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ABSTRACT: Swash action is the dominant process responsible for the cross-shore exchange of sediment between the subaerial and subaqueous zones, with a significant part of the littoral drift also taking place as a result of swash motions. The swash zone is the area of the beach between the inner surfzone and backbeach that is intermittently submerged and exposed by the processes of wave uprush and backwash. Given the dominant role that swash plays in the morphological evolution of a beach, it is important to understand and quantify the main processes. The extent of swash (horizontally and vertically), current velocities and suspended sediment concentrations are all parameters of interest in the study of swash processes. *In situ* methods of measurements in this energetic zone were instrumental in developing early understanding of swash processes, however, the field has experienced a shift towards remote sensing methods. This article outlines the emergence of high precision technologies such as video imaging and LIDAR (light detection and ranging) for the study of swash processes. Furthermore, the applicability of these methods to large-scale datasets for quantitative analysis is demonstrated.

KEYWORDS: run-up, morphodynamics, coastal imaging, video, LIDAR.

Introduction

The beachface is a highly spatially and temporally dynamic zone, predominantly due to swash processes such as wave run up. The foreshore (the intermittently wetted, intertidal area) is the interface between land and sea and is characterised by highly variable hydro- and morpho-dynamic processes. Understanding the evolution of the foreshore is of critical importance to coastal oceanographers, planners and engineers because energy delivered to this region drives the erosive or accretive response of the beach (Stockdon *et al.,* 2006). Swash action is the dominant process responsible for moving sediment cross-shore between the subaerial and subaqueous zones, with a significant part of the littoral drift also taking place in this zone (Masselink and Puleo, 2006). The swash zone (Figure 1) is defined as the boundary between the inner surf zone and the back beach (Ruggiero *et al.*, 2004) and its dominant responses are largely well understood. It is the most energetic zone in terms of bed sediment movement and is characterised by strong and unsteady flows as a result of run up and backwash, within which single events can cause changes of up to 43 mm in bed level (Blenkinsopp *et al.,* 2011). It is important to recognise that this swash zone is part of an integrated system comprising local groundwater dynamics, the beachface and the surf zone, with the feedback from surf to swash of critical importance when considering hydrodynamics (Masselink and Puleo, 2006). It has also recently been shown that swash zone flows exert influence not just locally (overtopping, littoral drift, *etc.*), but they also affect the dynamics of the surf zone itself (Brocchini, 2006).

Run up is described here as a set of discrete water level maxima measured on the foreshore, with respect to the still water level;

that which would occur in the absence of forcing by the incident wave field (Grant, 1948; Guza and Thornton, 1982). The two components of run up; wave swash and wave set-up, operate on very different temporal scales, as a result of the different forcing factors (Senechal *et al.,* 2011).

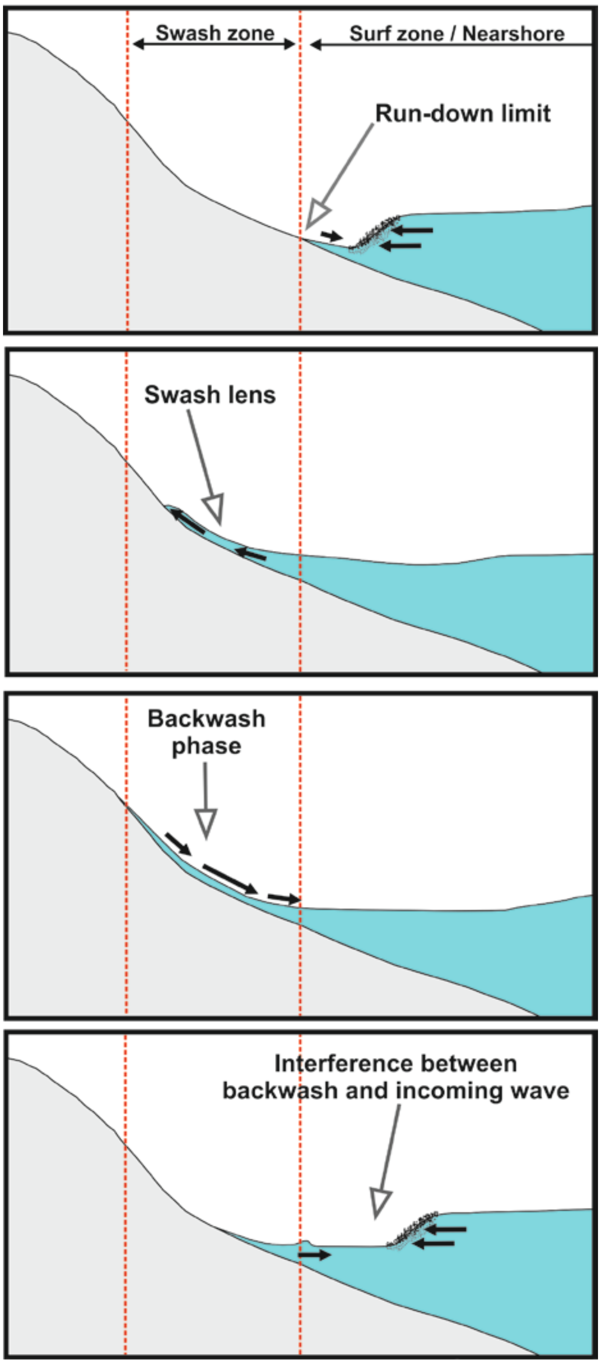

Figure 1: Representation of a typical swash cycle. Arrows represent flow direction with size indicative of relative magnitude. Red lines delineate the swash zone based on limit of backwash (a) and maximum limit of swash excursion (c). Modified from Masselink and Puleo (2006).

Swash, the time-varying, fluctuating component, operates on frequencies comparable to the incident wave field from which it stems, whereas set-up refers to the mean water level as a result of wave breaking (Guza and Thornton, 1982; Nielsen and Hanslow, 1991). The wave run up height is generally normalised by the incident wave height, as they are of the same order of magnitude (Kobayashi, 1997). Set-up is relatively small when compared to swash action on a steeply sloping beach, where there is an appreciable degree of wave reflection (Battjes, 1974). This wave driven run up converts kinetic energy into potential energy as it traverses up the beachface (up-rush phase), before gravity-driven flows act to return the flow down the slope of the foreshore (backwash phase). There is typically interference between subsequent waves, with the backwash of preceding waves colliding with the uprush of the next wave, meaning individual waves do not often complete a full and balanced cycle of uprush and backwash (Erikson *et al.,* 2005). The motion of fluid traversing over the beachface may be affected somewhat by infiltration and/or exfiltration from the beachface. Infiltration will remove water from the swash and generally aids with progradation of the beachface, whereas exfiltration adds water to the backwash and generally aids erosion or scarp of the beachface (Masselink and Puleo, 2006).

When determining various morpho- and hydro-dynamic properties and states of the beach, the non-dimensional Irribarren number or surf similarity parameter is commonly used (Battjes, 1974);

$$\xi = \frac{tan\beta}{(H_o/L_o)^{1/2}} \tag{1}$$

where β is beach slope, L_o is the deepwater wavelength given by linear wave theory and H_o is the offshore wave height. This is often referred to as the dynamic beach steepness parameter (Stockdon *et al.*, 2006), accounting for the antecedent beach slope as well as the incident wave conditions. This property has proved useful in empirically determining run up (Holman and Sallenger, 1985; Holman, 1986; Ruggiero *et al.*, 2004; Stockdon *et al.*, 2006) and illustrates well the dependence of run up on beach slope and wave conditions.

Miche (1951) also provided a formula useful in estimating the maximum swash amplitude;

$$\varepsilon_S = \frac{a_s \omega^2}{g\beta^2} \tag{2}$$

where a_S is the vertical amplitude of the shoreline motion, ω is the angular wave frequency, g is the gravitational component and β is the beach slope. In the Miche equation, maximum swash amplitude is assumed to be related to the limiting amplitude of a non-breaking standard wave on a planar beach slope (Baldock and Holmes, 1997). Miche postulated that an increase in incident wave height would eventually lead to wave breaking, and therefore the amplitude would be saturated as a further increase in wave height simply only increases the amplitude of the progressive component, which would then dissipate through wave breaking with no shoreline amplitude (Ruggiero *et al.,* 2004). This hypothesis therefore proposes that swash heights do not increase with increasing offshore wave height.

When considering swash processes, there are three main hydrodynamic parameters of interest; 1) swash excursion, 2) swash depth, and 3) swash velocity.

Swash excursion refers to the spatial coverage of the varying water surface. This excursion up the beach is typically defined in terms of its vertical elevation, rather than the horizontal extent of run up (Holland *et al.,* 1995). This vertical excursion is usually against the Ordnance Datum (in the UK), which provides a static reference point, especially useful in macrotidal environments. This parameter is of interest because the excursion of swash delineates the area of the beach subject to bed shear stresses, and ultimately sediment transport.

The depth of swash is important because it directly influences how much sediment can be transported in the water column. Thin layers of swash will be confined to transporting sediment as bed load, whereas deeper swash lenses will be capable of transporting suspended sediment as well as transporting bed load. The shape of the swash lens (*i.e.* the swash surface profile) has been postulated as indicative of flow velocities. Early observation of the swash lens during backwash showed that at flow reversal, the leading edge of the swash remains static until a large amount of water mass downslope has moved seaward (Emery and Gale, 1951). Hughes (1992, 1995) identified differing hydrodynamic characteristics within the backwash based upon the free surface profile of the swash lens. He was able to relate these different swash lenses to different methods of sediment transport within the backwash. Therefore, measurement of swash depth across the foreshore may provide clues as to the complicated hydrodynamics at work.

Bed shear stress is the mechanism driving initial sediment motion and is perhaps the most important hydrodynamic parameter of swash motion. It is, however, often replaced with a surrogate parameter in that of flow velocity (Hughes *et al.,* 1997). A degree of asymmetry in swash duration and velocities has often been observed both in laboratory and field investigations (Kemp, 1975; Raubenheimer *et al.,* 1995; Baldock and Holmes, 1997; Power *et al.,* 2011). Of particular interest is the vertical velocity structure (Blenkinsopp *et al.,* 2010), however, the depth averaged velocity is also a useful parameter in estimation of sediment transport.

This paper presents an overview of swash measurement through *in-situ* measurement and the growing shift towards remotely sensed measurements. Measurement of swash processes is often coincident with measurement of sediment movement within the swash zone; sediment transport is covered in Section 3.2.4 and thus not included here. The methods and data presented here, although applicable across the whole spectrum of swash environments, are predominantly collated from the work of Plymouth University (Devon, UK) on Slapton Sands; a coarse grained gravel barrier in SW England.

In-situ **measurement**

Field measurement of the spatial extent, free surface profile and velocity profiles within the swash zone has incorporated a number of *in-situ* techniques, outlined below.

Swash excursion

Some of the first quantitative measurements of swash excursion were undertaken using resistance wires (Guza and Thornton, 1982). This involved two electronic resistance wires, elevated to a nominal distance above the bed. The wires ran cross shore and the swash action running up that profile submerged the wires, shorting out the current path, resulting in different levels of resistance (Holman and Guza, 1984).

The wires therefore recorded the most seaward location at which water depth exceeded the vertical elevation of the wires. This method typically yielded accuracies of *O*(cm) in terms of the horizontal (cross-shore) extent of run up. The wires were calibrated by submerging known lengths in water prior to field deployment (Raubenheimer *et al*., 1995). They were further calibrated after the measurements, as Guza and Thornton (1982) noted resistance gains of 4.5% occurred between pre- and post-experiment calibration. The thin run up lense means this method is extremely sensitive to wire elevation, such that lower wire elevations will indicate a larger total extent of run up (Holman and Guza, 1984; Holland *et al*., 1995). Raubenheimer and Guza (1996) found a 20 cm vertical wire separation accounted for a cross-shore difference in run up excursion of 20 m.

Swash depth

In the same way that horizontal resistance wires have been used to measure the spatial extent of swash, vertical capacitance probes have previously been used to measure swash depth (Waddell, 1976; Hughes, 1992). The probes consist of vertically suspended wires, which when submerged, register an increased capacitance to that recorded in air alone. The change in current is received as an amplitude variation, and these signals can then be calibrated against signals received in known water depths, providing an indication of swash depth in the field (Foote and Horn, 2002).

Instruments deployed to measure bed levels are typically concerned with the change in morphology on the beachface (e.g. Waddell, 1980), however, the same instruments, when set to log at rates of > 1 Hz also give good indication of swash motion over the beachface. The sensors used in this type of instrumentation typically transmit ultrasonic sound toward a target (the beachface) and measure the time before an echo is received back, resulting in high accuracy, high precision measurements (Massa, 1999). The time lag before the echo correlates to distance and is calibrated on the medium through which the sound passes (i.e. air).

Turner *et al*. (2008) described a bed level acoustic array mounted on a scaffold frame that collected data of bed level changes at 4 Hz immediately prior to each swash event. The bed level sensors offered a response from the first non-gaseous surface (i.e. water or sediment). Therefore, the method was appropriate and applicable to measurement of the swash lens. Poate *et al*. (2013) demonstrated the ability of the scaffold sensor array to conduct continuous measurement of swash action through non-daylight hours in energetic conditions.

Pressure transducers (PTs), more commonly used in the surf zone or deep ocean, can also be used to measure swash depth. They measure the pressure applied by the water above and convert this force into an equivalent water depth. PTs give discreet observations, and therefore interpolation is required to make inferences about the swash lens. They are often deployed in conjunction with other sensors, such as run up wires for a more continuous dataset.

Masselink and Russell (2006) deployed 3 rigs, each with 3 PTs attached, in a field experiment investigating flow velocities and sediment transport in the swash zone. PTs are ideally deployed flush with the beachface to give an idea of the total amount of water above the bed. However, this is problematic because saturated sediment washes over and settles upon the PTs, skewing the results. Therefore, Masselink and Russell (2006) set any recorded values of ≤ 0.02 m to zero, and disregarded data in this range.

Swash velocities

Bidirectional current meters in the form of ducted impellors have been used to ascertain swash velocities (Sonu, 1972; Sonu *et al.,* 1974; Teleki *et al.*, 1976). The rotation of the three-bladed impeller in the duct gives output in the form of pulse density and polarity, which is translated to current speed and direction. Sonu (1972) estimated the threshold sensitivity of this method to be 5 cm/sec, with very little signal degradation when the impellor was orientated less than 30 degrees from the mean flow direction. The purpose of the duct on these meters is to protect them from derogatory effects of flows at large incidence angles (Smith, 1978). The impellor current meters are limited somewhat in that they can only ascertain currents in one direction at a time; however, their application to the swash zone is proportionate as generally the swash flow reverses in a depth-uniform manner, unlike the surf zone. Furthermore, the current meters are only able to ascertain meaningful velocity measurements up to a relatively small maximum velocity (Holland *et al*., 2001).

Figure 2: An example of a mobile Argus station deployed by Plymouth University at Slapton Sands for a short field experiment. Two cameras are mounted on a scaffold rig. Checkerboards are placed on the beach, within the cameras field of view to act as ground control points (Photo: S. Pitman).

Electromagnetic current meters (EMCMs) have also been used widely to measure swash zone velocities, although they are more commonly used in the surf zone. The EMCM works by inducing the creation of voltage by movement of a conductor (water) through a magnetic field. Here, the magnetic field is created by a coil inside the head of the instrument (Butt, 1999). The sensors are designed to be used fully submerged, however, with calibration, they can be adapted to suit the continuous emergence and submergence occurring in the swash zone. These meters often have small discus heads, and can be considered to give errors in the region of 8% of actual swash velocities (Butt *et al*., 2001). These sensors need to be mounted at heights of few cm to avoid interference from the bed (Butt and Russell, 1999; Butt *et al*., 2004).

Acoustic Doppler Velocimeters (ADVs) have been used successfully to quantify velocities in the swash zone. These small and robust sensors are effective at measuring oscillatory flows such as those in the swash, typically capable of measuring flow velocities between 0 and 2.5 m/s (Kraus *et al*., 1994). The sensors work by emitting short acoustic pulses into the water and receive a signal back after the pulse is scattered back by reflectors in the water (Elgar *et al*., 2001). The phase shift in these reflectors between several successive returns allows for information on cross- and along-shore velocities, as well as any vertical velocity components to be collected (Lhermitte and Serafin, 1984). The ADV returns can be corrupted by bubbles and sediment in the water column created by breaking waves, but these signals are often distinguishable using a ratio between signal and noise, meaning they can be discarded where appropriate (Elgar *et al*., 2005).

Remote sensing

Predictive formulas for run up are critical for coastal planners, engineers and researchers, because they provide estimation based on relatively easy to measure variables such as the offshore wave conditions and beach slope. However, the *in situ* measurement of swash processes is inherently difficult and complex (Blenkinsopp *et al*., 2011), proving challenging for even the most robust and advanced hydrodynamic equipment (Masselink and Puleo, 2006). This problem seems counter-intuitive as the swash zone is readily accessible when compared to the surf zone or offshore regions; however, the instruments used in the swash zone are often delicate and are exposed to energetic wave breaking and sediment transport regimes. Many coastal processes, especially in the energetic swash zone, are poorly understood because of the difficulty in collecting continuous, long-term and large scale field measurements, especially with high spatial and temporal resolution (Guedes *et al*., 2011, Holman and Stanley, 2007). Remote sensing systems capable of monitoring coastal processes, such as the Argus video imaging system (Holman and Stanley, 2007), have experienced a period of significant interest and development over the past 30 years (Guedes *et al*., 2011; Holman and Stanley, 2007). Progress in this area is largely driven by the aforementioned difficulties in obtaining *in situ* measurement. Coastal imaging systems can be permanent fixtures or can be deployed temporarily to compliment a field experiment (Figure 2). The more commonly employed remote sensing techniques are described below.

Figure 3: Corresponding examples of (a) snap, (b) time-exposure and (c) time-variance images from an Argus camera system at Slapton Sands, Devon, UK. Images courtesy of Plymouth University.

Video image analysis

Time lapse photography has been used in the study of the nearshore for over 40 years (Sonu, 1972; Sasaki *et al.,* 1976). Quantitative data is obtained by interrogating the image for optical signatures that are either directly or indirectly created by nearshore processes, such as the concentration of breaking waves over a submerged bar showing up as a high intensity band in the image (Kingston *et al.*, 2000; Lippmann and Holman, 1989, 1990; Plant and Holman, 1998).The first to directly apply the technique to swash motion were Holman and Guza (1984). They found that manual digitisation of swash events from photographs, although subjective, gave results comparable to those obtained by resistance wires. This method involved frame-by-frame digitisation of the run-up edge in images, as it moves through the uprush and backwash phases, from cameras positioned to look alongshore. The position of this leading edge was converted to a known cross-shore location to create a time series of run up. The authors report times of 30 minutes to digitise a 2048 point dataset. Holman and Bowen (1984) investigated the subjectivity of this method to measure swash height by making replicate digitisations of the same film using different operators. This resulted in errors of between 15 and 20 %.

Aagard and Holm (1989) developed the use of video images further by pre-defining a transect line in the image, and stripping out only the pixels along this transect line in images sampled at 8 Hz. These transects were then used to create a visual timestack which could be digitised and ultimately allowed the backwash phase to be more effectively tracked. An example is given in Figure 4, where 180 s of run up has been recorded at 2 Hz, before being manually digitised. The timestack approach allows researchers to clearly see the leading edge of the swash lens as it propagates across the beach, but it is sometimes harder to pick out the limit of run down.

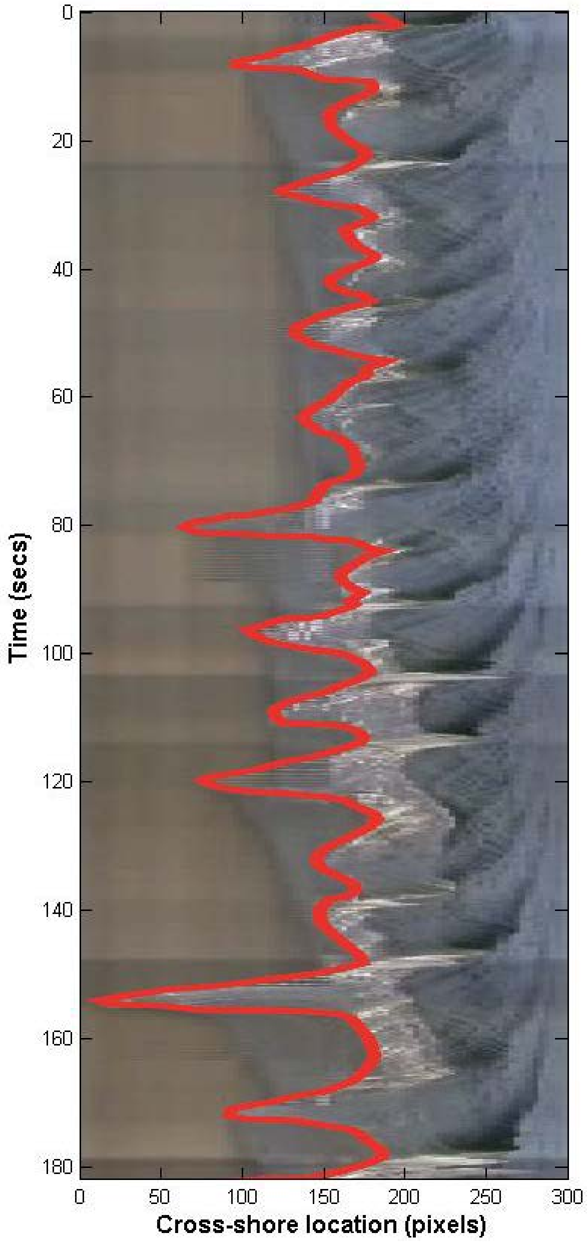

Figure 4: An example of a digitised timestack of run up over 180 s.

Video imaging has also been used as an approach to quantify swash velocities. Particle image velocimetry (PIV) is an approach that uses images sampled at short intervals to track individual particles or clusters of particles, translating the shift in position into a velocity measurement (Adrian, 1991; Grant 1997). Typically, the flow would be artificially 'seeded' with particles (Grant, 1997), however, PIV has been applied to the swash zone where the technique instead tracks the propagation of image 'texture' in the form of naturally occurring foam patterns (Holland *et al*., 2001). A synthetic grid is overlaid onto the area of interest, with the nodes representing the start point of estimated velocity vectors. The technique's output is a trade-off between the size of the field of view, computational time and acceptable error. The resulting data from PIV requires some degree of post processing to remove spurious vectors created by incorrect correlation. This occurs when the automation believes two different particles in subsequent images to be the same, thus creating a vector and velocity measurement between them. Holland *et al.* (2001) successfully adapted PIV to work in the field, applying it to a 25 x 40 m region of the swash zone, with grid points spaced at 0.8 m in each direction. They concluded that the method was effective at measuring flow speeds in excess of 4 m/s and could accurately represent flow structures with large spatial variation.

Meteorological factors influence the ability to remotely sense beach processes. Image quality is highly susceptible to fog, high and low light conditions, rain and temperature variations; all potentially creating images of inadequate quality for quantitative analysis. There are cameras capable of dealing with such adverse conditions, but the expense involved in such systems is generally prohibitive (Holman and Stanley, 2007). Such cameras are primarily based on infra-red imaging and thus can work in fog and low-light conditions.

Extreme sunshine, or sunlight at low incidence angles can create too much reflection from both the water and the beachface. This makes scientific interrogation of pixel intensities in the image challenging, as the high reflectivity obscures the processes of interest. This is demonstrated by Figure 5, where a transect line has been taken across a concurrent timex and variance image. High reflectivity of the beach in Figure 5a obscures the expected intensity maxima. This is a datum postulated by Plant and Holman (1997) to be indicative of the shoreline, located in these images at 60 m cross-shore. In Figure 5a, however, the intensity maxima has been displaced onshore to a location where incident sunlight has created high intensity reflection on the beachface. It could further be postulated that an ill-positioned camera may suffer from reflection of sunlight off of the water during sunrise or sunset, obscuring the trend expected by the shoreline intensity maxima model. This effect appears to be mitigated somewhat by the use of time-variance images as opposed to time-exposure images. This approach has been employed in Figure 5b, where the subsequent pixel intensities (Figure 5c) show much less noise around the maximum intensity values, with a pronounced double peak at 60 m, coincident with the shoreline.

Image collection is also influenced by temperature variations over the diurnal cycle, especially when cameras are mounted on high scaffold frames. Solar heating creates daily shifts in the tilt of the camera by ~3 pixels (Holman and Stanley, 2007). At the furthest extent of the field of view, a shift of 3 pixels in the *y* (*along-shore*) direction could equate to a real-world alongshore shift of *O*(10 m), potentially large relative to scales of swash motion.

Detection and ranging

An emerging method for remotely sensing swash and the near-shore uses light- and/or radio- detection and ranging, or LIDAR and RADAR, respectively. These systems work by remotely sensing the free-surface elevation, normally of the surf-zone (Bell, 1999; Haller and Lyzenga, 2003), but also that of the swash-zone (Blenkinsopp *et al.,* 2010). For the purposes of this discussion, RADAR and LIDAR are grouped together as the mechanism and outputs are largely the same, with the obvious exception that one uses light (laser) and one uses sound (radio waves). Both systems work by emitting a pulse and measuring the round-trip time and known directionality of that pulse in relation to a sensor (Feagin *et al.,* 2014). Generally, the return of such pulses from the water surface would not be sufficient for quantitative analysis unless the incidence angle was almost perpendicular. However, the aerated and turbulent nature of the swash means the free-surface roughness is conducive to ample return signals being created (Blenkinsopp *et*

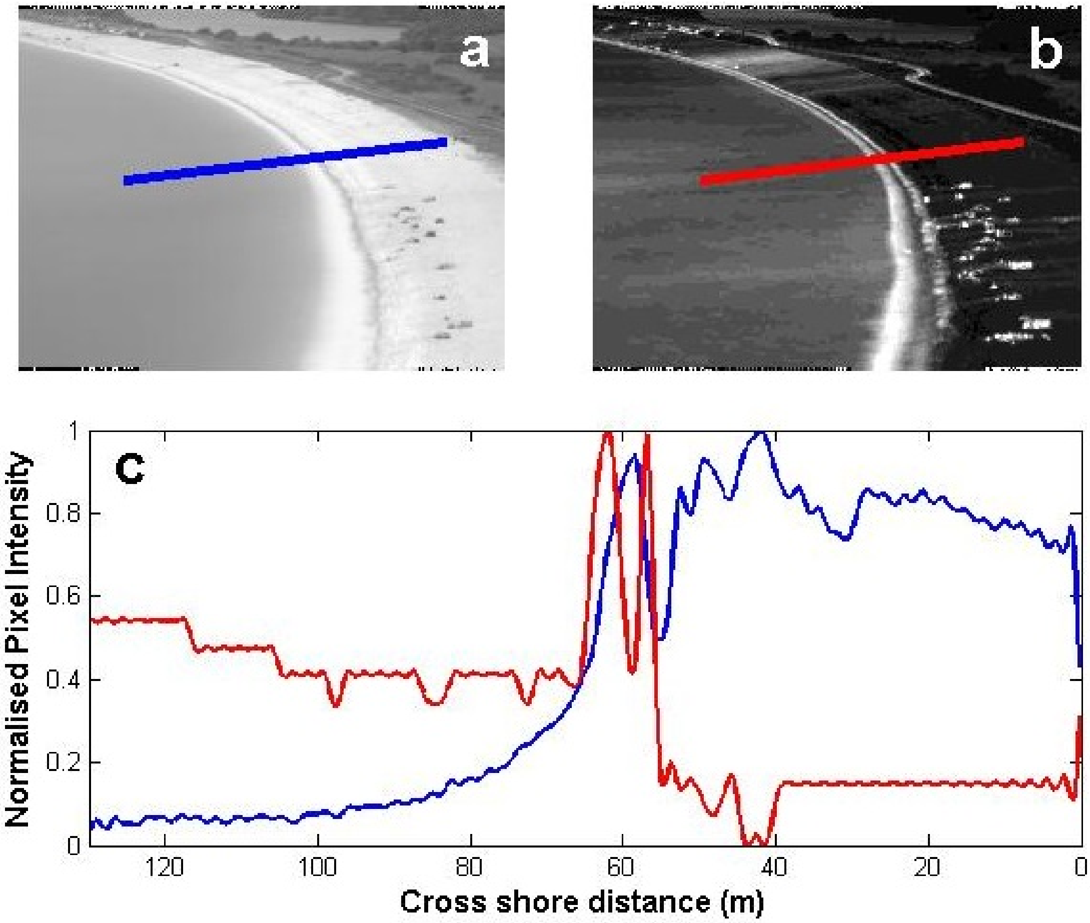

Figure 5: (a) A timex image and (b) corresponding variance image of Slapton Sands, Devon, UK, taken in bright sunshine on 30 Jul 2009. Cross-shore transect lines have been superimposed onto the images. Pixel intensities along this transect were measured, normalised and are presented in (c) with blue and red lines corresponding to the timex and variance images respectively.

al., 2010). It is sometimes useful to apply a time-averaging approach, much in the same way as described for video images. This reduces the scatter from ripples on the ocean surface and instead gives a solid signal back from breaking waves. This method was successfully used by Ruessink *et al*. (2002) to infer sandbar morphology from patterns of persistent wave breaking. A time-variance approach may be useful for detecting swash action on the beachface; the intermittent covering of the beachface by swash could be assumed to create a high variance feedback signal in either of the detection and ranging methods, if sampled at high enough resolution.

Unlike the video imaging approach, detection and ranging methodologies are not limited by daylight and are limited to a much lesser extent by inclement weather (McNinch, 2007). Detection and ranging systems are advantageous in the study of swash processes as they enable rapid data collection, with high spatial and temporal resolution. They are extremely useful for deployment during field studies, but are unable to be left continuously recording in the same way as video imagery. Laser scanning, in particular, is experiencing great interest from the coastal community and is rapidly becoming the tool of choice for surveying (Vousdoukas *et al*., 2014), yet the possibilities for high resolution water surface measurement is still largely unexplored.

Application of methodology

The availability of remote sensing methods to measure swash parameters means that vast datasets, over a wide range of conditions, can be compiled and subsequently investigated. Figure 6 demonstrates the ability of video imaging systems to collect quantitative data of good spatial and temporal resolution, without any need to deploy to the field, once validation has been completed.

Figure 6 shows swash action during a storm on Slapton Sands in April 2008. Swash heights have been extracted from timex images sampled twice hourly, during every hour of daylight in an 85 hour period, spanning the onset of the storm to its decay. Swash heights on the beach were controlled primarily by wave height (Figure 6*a*), with maximum daytime swash heights of 5.9 m recorded. The pre- and post-event beach profiles (Figure 6*b*) show that erosion up to a height of 5.8 m was observed, which corresponds with the maximum height of the remotely sensed swash estimates (Figure 6*c*). Furthermore, the spatial response of the beach can be estimated by investigating other transect lines in the image (Figure 6*d*), with results showing that maximum swash heights correlate well to maximum heights of morphological change. In Figure 6*d*, the bars represent measured maximum elevations of profile change, with the triangles representing the video-derived maximum swash heights. The correlation between the two shows that maximum swash height is a good indicator of effective run-up (i.e. that which has an effect on the beach profile).

This method is applicable to any of the useable hourly images at numerous sites worldwide, provided adequate antecedent morphological data is available. However, often useable images are only collected during calm conditions (i.e. not hindered by weather). The exception to this is when looking at large, flat, dissipative beaches where swash motion under calm conditions is often indistinguishable from the beach face. The effect of higher energy conditions is to create a more energetic swash, ultimately creating a better visible signature in the images.

The combination of multiple methods creates an extremely powerful, accurate tool for assessing small-scale processes such as swash, the measurement of which requires mm scale accuracies. Vousdoukas *et al.* (2014) have recently combined the use of laser scanning and video techniques to reduce root mean square errors in swash elevation on the beachface by an order of magnitude from *O*(10 cm) to *O*(cm). This process involved various forms of sensor calibration and data processing, but ultimately yields a robust method for investigating swash processes.

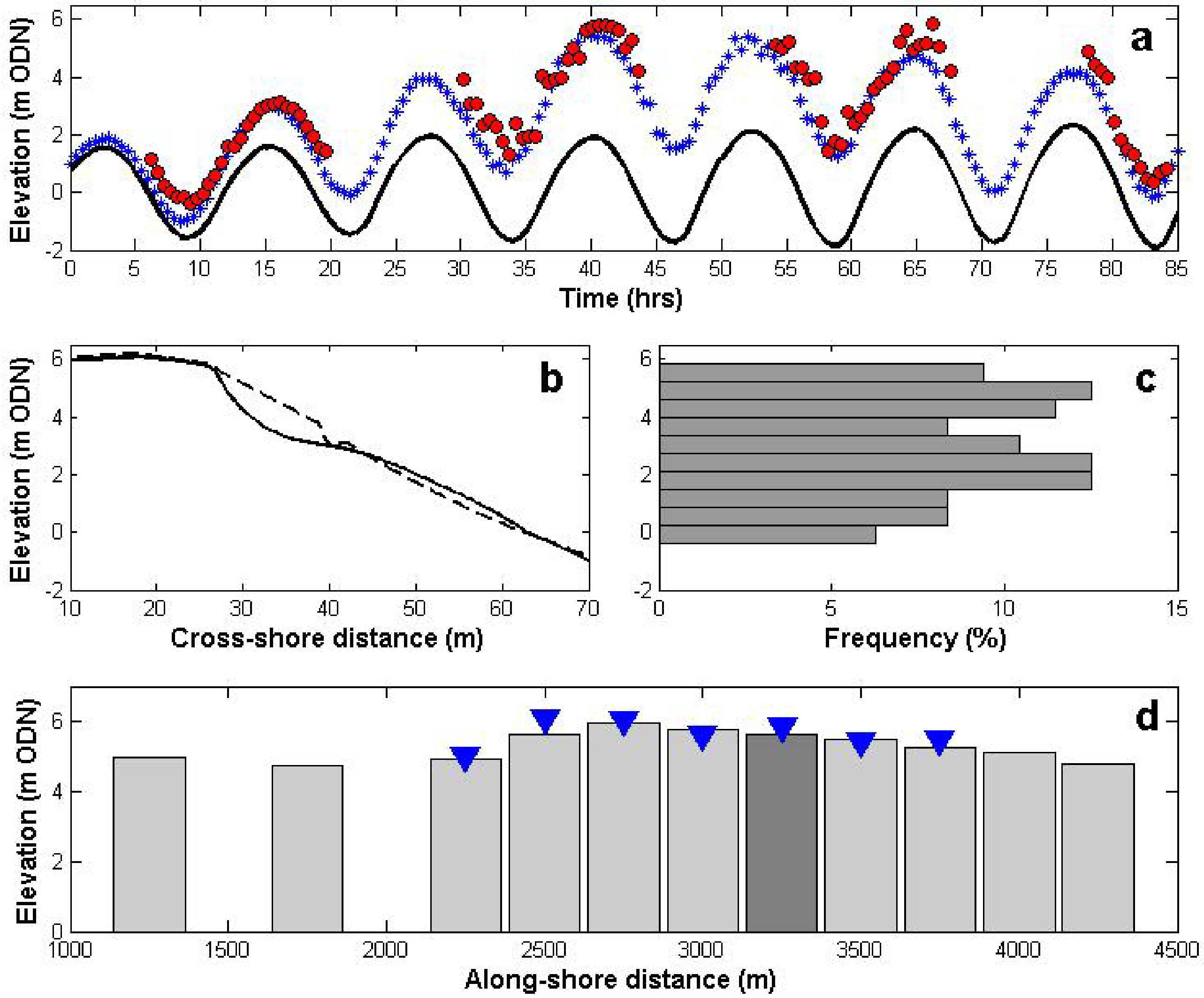

Figure 6: Example of swash extraction from a storm event between 16 and 19 April 2008 at Slapton Sands, Devon, UK. (a) The tidal signal (solid black line) and significant wave height (blue stars) are presented alongside run up derived from video images (red circles) for an 85 hour period. The pre- and post-event beach profile are presented as dashed and solid lines respectively (b) for a position approximately 3200 m alongshore. A histogram of run up heights is presented (c) which shows good correspondence between the maximum run up and the maximum elevation of profile change (effective run up) observed in the post-event profile (b). Run up at various alongshore locations has been presented as bars (d), with the darker bar corresponding to the individual profile presented above. Blue triangles represent video-derived maximum run up at locations that appeared in the field of view of the camera.

Concluding remarks

There is a progressive shift towards remote sensing methods in the study of nearshore processes, however, with the intricate nature of processes such as swash still not fully understood, the collection of *in situ* field data is far from being superfluous. The deployment of instruments into the surf, although sometimes logistically challenging, provides key information on parameters such as the vertical velocity structure of the swash zone. Resistance wires provide a simple and cheap method for measuring both swash depth and also swash excursion. Their simple construction means that even in the event of energetic events damaging them, the fiscal cost to the researcher is minimal. They are able to provide O(cm) accuracy, depending on how they are deployed, in terms of their elevation above the bed. Recently, the advancing state of the art has welcomed a shift to more technically advanced *in* situ methods, such as PTs, bed level sensors and ADVs. The implementation of these instruments has reduced errors in measurement down to mm scales, however, the cost and fragility of the equipment has increased exponentially. The sensors now deployed on these units can not only be fouled by seaweed and detritus, but they are susceptible to damage in the energetic swash. Their suitability to be deployed on calm, dissipative sand beaches is clear, however, the same is not always true for the swash zone of a gravel beach. Indeed, some recent studies (e.g. Poate *et al.,* 2013) have said that much future work on gravel beach swash should be confined to remote sensing methods alone.

The growing availability of remote sensing methods has acted to advance both the understanding of the swash zone and also the capabilities of researchers. Coastal imaging systems can remain in place unhindered for years, with minimal maintenance costs. Their continual logging means that when an event of interest takes place, the data for that event can be interrogated and analysed, without the need to pre-plan a large scale field deployment. Although they are currently limited to day light monitoring and somewhat calm conditions, the reducing cost of technology will increase the availability of systems capable of sampling in the infra-red spectrum, ultimately meaning the imaging system can capture events of interest under any prevailing conditions.

It is clear that advances in technology have been instrumental to studies of the coastal zone. The application of remote sensing methods can create vast databases of swash processes, which can ultimately be compared to incident conditions to help parameterise swash. These data can be used to validate existing equations such as that of Stockdon *et al.* (2006), to ultimately enable coastal planners to utilise the most appropriate equation in their estimation of extreme swash events.

In lieu of new technologies becoming available, the combination of existing methodologies, especially with regard to remote sensing, can vastly help to reduce errors in datasets. The continued development of methods such as that of video imaging, and terrestrial detection and ranging, will be instrumental in bettering our understanding of coastal processes over both spatial and temporal scales.

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