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MONITORING MIXED SAND AND GRAVEL BEACHES USING UNMANNED AERIAL SYSTEMS

PAUL ELSNER¹, DIANE HORN¹, UWE DORNBUSCH², IAN THOMAS³, DAN AMOS⁴

1. *Department of Geography, Environment and Development Studies, Birkbeck College London, Malet Street, London WC1E 7HX, UK. d.horn@bbk.ac.uk, p.elsner@bbk.ac.uk*
2. *Coastal Engineer, Environment Agency, Guildbourne House, Chatsworth Road, Worthing, West Sussex BN11 1LD, UK. uwe.dornbusch@environment-agency.gov.uk*
3. *Project Manager, Pevensey Coastal Defence Ltd, Environment Agency Depot, Coast Road, Pevensey Bay, East Sussex BN24 6ND, UK. pcdl@pevensey-bay.co.uk*
4. *Coastal Cell 4d Data Analyst / Project Manager, Strategic Regional Coastal Monitoring Programme, Adur and Worthing Councils, Worthing Town Hall, Chapel Road, Worthing, West Sussex BN11 1HA, UK. Strategic.Monitoring@adur-worthing.gov.uk*

Abstract: Mixed sand-gravel beaches act as an efficient natural sea defence and are increasingly managed by beach recharge, which can alter the sediment size composition of such beaches and their profile response. This creates an urgent need for better information about the behaviour of mixed sand and gravel beaches after recharge. UAS promise to be a promising novel tool in this context. To test their suitability for routine surveying, we aligned an experimental UAS survey along the standard monitoring schedule that was in operation for a mixed beach in East Sussex, UK. High wind speeds at the time of deployment significantly affected the data collection, but it was possible to generate (i) a surface model using Structure-from-Motion-based photogrammetry and (ii) an image mosaic that clearly identifies the spatial patterns of the sand-gravel mix of the beach. This indicates that UAS offer substantial potential for beach monitoring. However, an unclear legal framework acts and the sensitivity of platforms to high winds sets clear limits for UAS to serve as a stand-alone monitoring tool for beach environments at the present time.

Introduction: monitoring mixed sand and gravel beaches

In a significant number of global locations, beaches that constitute the main defence against erosion and flooding are composed of highly permeable sediments, often a mixture of sand and gravel. Mixed sand and gravel beaches are most common on high-latitude coasts and in temperate latitude coasts which were affected by Quaternary glaciation. These mixed beaches help to protect substantial urban areas and high value agricultural, recreational and environmental assets and are often protected by recharge schemes. Coarse-grained beaches are known to be an efficient form of natural sea defence. The beachface on gravel and mixed sand/gravel beaches is almost always

morphologically reflective, capable of dissipating up to 90% of incident wave energy (Powell 1990). A major advantage of a coarse-grained beach is its ability to absorb wave energy efficiently over a short distance as a result of the large infiltration flow allowed in the beach. This advantage quickly disappears as an increased sand fraction is added to the gravel. Recharge material dredged from offshore, often containing a significant amount of sand, is increasingly used to replenish mixed sand/gravel beaches. A particular problem for management of mixed sand and gravel beaches is that mixed beaches may lose more sediment than a pure sand or gravel beach under similar wave conditions (Lopez de San Román-Blanco and Holmes 2002). The performance of a recharged mixed beach is sensitive to the size distribution of the recharge sediment relative to the size distribution of the position of the natural beach where it is placed. Clarke (2008) described the difference in beach performance that can result from a range of replenishment materials subjected to the same physical processes. He concluded that the difference in performance between fine and coarse sediments was highly significant, not only with regards to the initial losses over the first three years, but also in terms of the presence of undesirable effects such as cliffing, reduction in stable beach gradient, berm erosion and seaward migration of the beach toe. Mason et al. (1997) argued that beach response was controlled by the underlying sand, despite the open-work nature of the surface gravels, and suggested that the additional sand and fines content may be a controlling factor in the profile response of a replenished gravel beach. They concluded that once a mixed beach contains more than about 25% sand by weight in the sediments approximately a metre from the surface, the profile response is more like that of a sand beach than a mixed beach. Other modelling and laboratory experiments suggest that hydraulic conductivity shows the greatest reduction at the point when gravel pore space is just fully occupied by sand. This critical sand percentage appears to be somewhere between 30% and 40%, depending on the compaction of the sediment (She et al. 2006). However, the percentage of sand required to produce a given reduction in hydraulic conductivity will vary with both the size and grading of the gravel material, since both properties influence the void ratio of the bulk sediment. Burgess et al. (2014) found that the size grading of beach nourishment material is inevitably wider than allowed for in modelling, usually with a higher fines content, and noted that the use of a finer grading or more widely graded material would reduce the permeability of the beach and thus reduce the effectiveness of cross-shore performance. From an engineering point of view, there is an urgent need for information about the behaviour of mixed sand and gravel beaches after recharge, in particular to determine the sensitivity of the beach profile and cross-sectional area to variations in sediment distributions (Mason and Coates 2001). Methods which help to reduce the amount of sediment lost from a mixed beach will produce both cost savings and increased beach stability. Accurate characterisation of the sediment and profile variability is important for this purpose.

Sediment size distributions on mixed beaches vary in the cross-shore and longshore direction, vertically through the beach, and over time (over a tidal cycle, seasonally, and over longer time scales). Sediments on a mixed sand and gravel beach can have sizes ranging over three orders of magnitude, from fine sands to gravels to boulders. On some mixed beaches, gravel is found only on the upper beachface and is underlain at depth by sand or mixtures of sand and gravel. Reported sand fractions on mixed beaches range from 15 to 68% sand (Mason and Coates 2001). The surface layer on mixed beaches can be highly unstable with both horizontal and vertical changes occurring within a few metres and pronounced temporal changes occurring over short timescales (She et al. 2010). Even though it is notoriously difficult to achieve a representative beach grading on mixed sand and gravel beaches, Burgess et al. (2014) argued that an appropriate description of beach grain size variation is required. Traditional methods of measuring sediment size require field collection of bulk samples (which need to be very large for mixed sand and gravel) and laboratory analysis; however, it is laborious to collect a sufficient number of sediment samples at an adequate frequency to describe mixed beach sedimentology accurately. This is a particular problem in the cross-shore direction, where sediment parameters of samples only centimetres apart can be quite different.

In addition to rapid changes in sediment texture, mixed sand and gravel beaches also display rapid short-term variability in their beach profiles (Pontee et al. 2004). The cross-shore profiles of mixed beaches are characterised by significant changes of slope over short sections of the beach. Beachface slopes are generally quite steep, ranging typically between 5-15°, with the steepest part of the beachface often approaching the natural angle of repose. Coarse-grained beaches may be fronted by a flatter, dissipative low-tide terrace at the base of the beachface slope. The sediment on the low-tide terrace is usually significantly smaller than the sediment on the beachface. Unless beach cusps are present, much more variation is observed in the cross-shore direction than longshore on mixed beaches (Dornbusch 2010). For example, Thomas (2013) observed significant changes in beach volume that occurred due to the movement of sand across the beach profile, and also noted that the position of the break in slope between the beachface and the low-tide terrace fluctuated by nearly two metres vertically and as much as 14m horizontally.

This extreme temporal and spatial variability presents a challenge for monitoring mixed beaches, which are generally measured using a mix of ground survey techniques and remote sensing methods. Most beach monitoring data is collected at monthly, seasonal, or annual intervals; these measurements represent a snapshot in time and may not be representative of all states of the beach between surveys. Monitoring schemes need to be designed to capture the variability of mixed beaches while measuring beach features with sufficient

resolution and in a cost effective manner. A particular problem for mixed beaches is that the highly variable surface sediment can affect measured elevations, and further work is needed in the evaluation of remotely sensed measurements of beach morphology in relation to surface composition (Dornbusch 2010). Researchers are beginning to use remote-sensing techniques to characterise mixed beaches and UAS promise to be a highly interesting and novel tool in this context. However, we are not aware of any studies using a UAS to collect data on sediment distribution on a mixed sand and gravel beach, nor are we aware of any studies which use a UAS to provide repeated high frequency beach profile measurements.

Use of UAS for beach monitoring

Figure 1 illustrates that UAS can conceptually be understood to bridge a 'missing link' between established remote sensing activities using spaceborne platforms and manned aircraft on the one hand, and ground-based surveys on the other hand. Satellites offer the lowest temporal resolution and essentially no temporal flexibility, due to their rigid revisit cycles. This means that they are well suited to systematic monitoring of larger coastal stretches. However, spaceborne data has comparatively low spatial resolution, and it is not possible to target the capture of individual images to specific weather or tidal conditions. Aircraft offer more flexibility in this respect as their surveying can, in principle, be scheduled to meet data requirements. However, normally such planes are

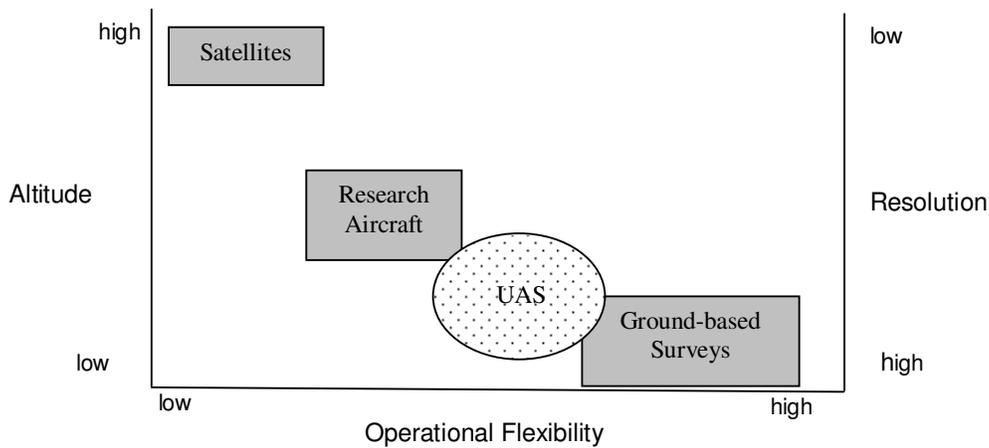


Fig. 1. Conceptual model of UAS providing missing link between traditional remote sensing approaches and ground-based approaches.

operated by large research institutions that have to meet the needs of a larger user community. This means that in practice a survey has to be booked a substantial time before the actual flight and it is often difficult to adjust the data acquisition to tidal and weather conditions on the day. In addition to this, associated costs normally do not allow it to carry out surveys routinely in high temporal resolution to capture weekly, daily and even hourly process dynamics. To date, such processes have to be investigated with field based approaches that are under the control of the researcher in the field, collecting either point data along defined transects or deploying terrestrial laser scanners (Dornbusch 2010). UAS now offer an additional tool that can be deployed directly from the field. A central advantage of this approach is that two data sets can be acquired at the same time: (i) multi-spectral data sets that capture information about the spatial distribution of surface characteristics such as the spatial distribution and patterns of sand and gravel at mixed beaches, and (ii) the development of elevation models using novel photogrammetric approaches such as Structure-from-Motion (SFM) (Westoby et al. 2012). Due to the commonly low flying height of <100 m above ground, the resolution of UAS-based images can provide ‘hyper-resolution’ in the order of a few centimeters.

UAS therefore constitute a low-cost survey tool that can combine the aerial coverage potential of traditional airborne methods with the operational flexibility of field-based approaches.

Case study of a recharged mixed sand and gravel beach

The section of coastline managed by Pevensy Coastal Defence Ltd (PCDL), at Pevensy Bay, East Sussex, on the south coast of England, presents an ideal site to test the potential of UAS for high-frequency coastal monitoring, as a long-term data set is available and the beach profile and sediment characteristics are highly variable. The beach profile at Pevensy can best be described as a composite mixed beach, where the reflective upper beach is composed of mixed sand and gravel rather than pure gravel, fronted by a flat dissipative sand low-tide terrace. Sediment on the low-tide terrace is usually significantly finer than the sediment on the beachface, which can be either pure gravel or mixed sand and gravel. The Pevensy Bay Sea Defences Contract was the first to be undertaken in the UK under the Government’s PPP (Public Private Partnership) initiative, entering into a £30 million contract to maintain the beach above 0m OD in order to provide a 1:400 year standard of protection against breach between 2000 and 2025. The area managed by PCDL consists of a mixed sand and gravel ridge along a 9 km stretch of coastline, containing over 2 million m³ of sediment. The ridge acts as a sea defence which provides protection from permanent flooding to an area of 50 km², most of which is significantly below high tide level. As part of the contractual

agreement, PDCL is required to maintain a 30m beach crest over the whole of the Pevensy frontage. The beach is managed through recharge, reprofiling and recycling of sediment within the frontage. The PCDL frontage is also unusual in that two independent survey programmes have monitored the area over a period of more than ten years.

Beach monitoring on the Sussex coast started in 1973 when Annual Beach Monitoring Surveys (ABMS) were introduced by the Environment Agency. These include 53 cross-shore locations along Pevensy Bay. The ABMS surveys were initially undertaken annually, with profiles extracted from digitally rectified aerial photographs. From May 1999 to March 2001, RTK GPS surveys were carried out monthly, and from 2001 three times a year, with profiles going down to -2.0 OD. The three RTK GPS surveys were replaced by terrestrial laser scan surveys in June 2012 as part of the Regional Monitoring Programme, which the Environment Agency supports. Lidar surveys were flown at low water in the winter of 2007-8, 2010-11, and 2011-12. PCDL has carried out monthly RTK GPS surveys since January 2003 on low water spring tides, going down to -2 or -3 m OD. Comparison of profiles using these different methods of surveying the Pevensy beaches has demonstrated significant cross-shore variation in beach profile, with movement of sediment between the beachface and low-tide terrace. Beach monitoring by PCDL has showed that the beaches in this frontage have suffered a net loss of 80,000 m³ between 2003 and 2013 (Thomas 2013). Further analysis showed significant variability in the lower beach volumes, which Reeve and Karunaratna (2014) attributed to cross-shore movement of sand. They recommended that additional effort should be directed toward monitoring the whole beach profile, particularly the lower beach. They also recommended that future studies should include sediment grading samples taken both across and along the beach. Any engineering measures that might be carried out to stabilise the lower beach are likely to be expensive, with little idea as to whether they would show a direct benefit to beach volumes on the upper beach. However, if sediment continues to be lost at the rate suggested by existing data, and should the presence of this trend be confirmed from further monitoring, the present beach management regime is unlikely to remain sustainable (Thomas 2013). If continuance of such loss of sediment from the lower beach can be verified by more extensive surveys, there would be significant benefit to the long-term management of the Sussex coast. Such verification, however, will require more detailed and frequent surveys than are carried out under the current monitoring scheme. Unmanned aerial systems (UAS) offer a new approach to carry out such measurements.

The potential for the use of unmanned aerial systems for coastal monitoring has been recognised for a number of years and the use of UAS is becoming

increasingly common (e.g. Pereira et al. 2009; Mancini et al. 2013; Casella et al. 2014; Pérez-Alberti and Trenhaile 2014), although not yet for similar purposes.

To test the suitability of UAS for routine monitoring, we designed a field experiment to align our experimental UAS survey with the standard schedule that was in operation for the above-mentioned survey activities at Pevensy Bay, and concurrently to join surveys that were scheduled for around low water spring tide in early October 2014. This meant that our UAS would be deployed alongside the scheduled ATV-based RTK-GPS and terrestrial Lidar scanning surveys that were scheduled for low water spring tide period in early October 2014. In addition to this, the Geomatics unit of the Environment Agency was planning to carry out a new airborne Lidar survey in this tidal window. The overall objective of this project was to assess the quality and uncertainty of the elevation data, using the RTK-GPS and terrestrial laser scanner data. Unfortunately, high winds meant that the Lidar survey was not carried out, illustrating our point above about the inflexibility of aircraft-based surveys.

The UAS and regulatory framework

The UAS platform was a Tarot 680Pro series Arducopter GPS Hexacopter (see Figure 2) that carried a Canon Powershot SX260 12.1 megapixel camera. A 2-axis brushless gimbal ensured that pitch and roll disturbances of the platform were minimized. The hexacopter was equipped with a Pixhawk flight controller that allowed the operator to programme survey missions to be carried out autonomously. The flying time of the system is in the order of 20 minutes.



Fig. 2. The Hexacopter platform deployed in the field trial.

The legal status and regulatory framework of light unmanned aerial vehicles varies significantly across different countries, despite ongoing efforts to harmonize the regulatory framework internationally (Cary 2015). In the UK, the use of an unmanned aircraft is regulated by the Civil Aviation Authority. Currently, platforms of less than 20 kg are in principle allowed (CAA 2012). However, a number of rules limit their deployment. These include the requirements that operation is not allowed over or within 150 metres of any congested area, and within 50 metres of any vessel, vehicle or structure which is not under the control of the person in charge of the aircraft. The aircraft must be kept within the visual line of sight, normally taken to be within 500 m horizontally and 400 ft vertically. Flights that are carried out for commercial purposes are classed as "aerial work" and operators need to be licensed by the UK Civil Aviation Authority (CAA).

The obligation to keep safe distances meant that only part of Pevensey Bay was suitable for testing the UAS approach and the Normans Bay section was identified as the most appropriate field site. A set of automated survey flight paths was defined, using the open software Mission Planner (Oborne 2014). Due to high wind conditions during the entire spring tide period, a low flying height of 40 m was chosen. Considering the focal lengths and the need for at least 60% overlap between individual images, four flight lines with a lengths of 220 m and a spacing of 16 m were defined (Figure 3). However, during actual deployment wind speeds of 25 mph and gusts of >30 mph were present. Such high wind speeds represent the limit of safe operational conditions of a hexacopter. It was therefore only possible to fly a subset of scheduled flight paths, resulting in an incomplete and less coherent data set. The images that were captured during the field trial have subsequently been analysed using SFM algorithms that are implemented in the software package Photoscan. Contrary to traditional photogrammetric methods, SFM approaches can operate with arbitrary images that can be taken from changing positions. The central condition is that a point needs to be visible from least two photos (Agisoft 2014).

Preliminary Results

The versatility of SFM approaches made it possible to generate a surface model, despite limits in coverage and image acquisition systematics. The resulting surface model is illustrated in Figure 4. More rigorous quantitative validation of the elevation data was on-going at the submission deadline of this paper. Qualitative analysis indicates, however, that the model captures beach morphology well and without any apparent distortion.

Figure 5 shows a subset of the beach with a mix of sand and gravel sediment sizes. This complementary product can be analyzed further by standard image processing approaches to develop a grain size classification for sand and gravel. This would make it possible to quantify the overall sand-gravel mix of the beach and to test at high spatial and temporal resolution the extent to which the surface patterns correspond to changing morphological beach responses, as postulated by Mason et al. (1997) and demonstrated by Watt et al. (2008). This could provide information on processes on mixed beaches which could allow models such as XBeach-G (McCall et al. 2014) to be extended for application on mixed beaches.



Fig. 5. Patterns of sand-gravel distribution, as captured by UAS. Clear depiction of ATV wheel tracks and footprints indicates high resolution of imagery.

Conclusions

The initial experiment indicates that UAS-based methods offer substantial potential for beach monitoring approaches. Their versatility and, compared to traditional remote sensing approaches, low cost make them an attractive new methodological proposition. In essence, UAS can combine key strengths of remote sensing approaches such as synoptic data acquisition with the flexibility that are associated with field-based approaches. UAS can easily be deployed from the field and repeatedly monitor the same region with little effort. This makes it possible to capture beach dynamics that hitherto could not be targeted

with remote sensing approaches. Research problems such as quantifying the changes in surface sediment and beach elevation on a mixed sand and gravel beach are likely to benefit from the availability from UAS.

However, the unclear legal situation and regulatory framework for UAS acts as a major barrier. Also, following our experiences and difficulties due to high winds, there seem to be clear limits for UAS to serve as a stand-alone monitoring tool for beach environments at the present time.

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