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A geomatics data integration technique for coastal change monitoring

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Abstract

This paper reports research carried out to develop a novel method of monitoring coastal change, using an approach based on digital elevation models (DEMs). In recent years change monitoring has become an increasingly important issue, particularly for landforms and areas that are potentially hazardous to human life and assets. The coastal zone is currently a sensitive policy area for those involved with its management, as phenomena such as erosion and landslides affect the stability of both the natural and the built environment. With legal and financial implications of failing to predict and react to such geomorphological change, the provision of accurate and effective monitoring is essential. Long coastlines and dynamic processes make the application of traditional surveying difficult, but recent advances made in the geomatics discipline allow for more effective methodologies to be investigated.

A solution is presented, based on two component technologies – the Global Positioning System (GPS) and digital small format aerial photogrammetry – using data fusion to eliminate the disadvantages associated with each technique individually. A sparse but highly accurate DEM, created using kinematic GPS, was used as control to orientate surfaces derived from the relative orientation stage of photogrammetric processing. A least squares surface matching algorithm was developed to perform the orientation, reducing the need for costly and inefficient ground control point survey. Change detection was then carried out between temporal data epochs for a rapidly eroding coastline (Filey Bay, North Yorkshire). The surface matching algorithm was employed to register the datasets and determine differences between the DEM series. Large areas of change were identified during the lifetime of the study. Results of this methodology were encouraging, the flexibility, redundancy and automation potential allowing an efficient approach to landform monitoring. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: **coastal change; data integration; geomatics; photogrammetry; surface matching**

Introduction and Background

The coastal zone provides an environment that has traditionally been hostile to the application of surveying and monitoring techniques, due to the inherent difficulties associated with dynamic processes and large areas. However, this environment is also one of the most susceptible to change, the processes involved not only being of scientific interest but also having a real effect on those living in the coastal zone. It is only in recent times, with increasing populations being sited next to the sea, that it has become important to map and monitor these changes. It is no longer accepted that coastal assets should simply be left to their natural decline; instead, faced with threats to human life and an increasingly litigious society, government and maritime operating authorities are under pressure to predict and react to land movements before they occur (Bray and Hooke, 1997). This may only be accomplished with accurate and current monitoring data, something which is of great importance, but has often been only crudely achieved without a uniform approach (Moore, 2000).

In the UK, the government body responsible for overall management of the coastal zone is the Department of Environment, Food and Rural Affairs (DEFRA). In a DEFRA (then Ministry for Agriculture, Fisheries and Food, MAFF) survey carried out in 1993, 1018 km of England's 3763 km of coastline was found to have some form of defence, whether natural or manmade. In addition to this, a further 135 km of coastline was identified as being 'significantly eroding', but with no form of defence (MAFF, 1994). Individual stretches of coastline cannot usually be separated for individual study, as the prevalent processes can affect the flow of sediment around wide areas; indeed, the construction of defences in one area may compound problems further along the coast (e.g. Pethick, 1984). Consequently, DEFRA manages the coastline based on the concept of sediment cells, comprising smaller sub–cells and management units according to the scale of the processes contained, with a Shoreline Management Plan (SMP) for each (DEFRA, 2001). These SMPs are documents written by consultants and adhered to by the local government authorities to whom execution is delegated. Within are recommendations for the necessary monitoring – from six-monthly topographic surveys to annual aerial photogrammetric sorties. Because of the size of the cells, more than one authority may be responsible for portions of the management; however, areas may be large, presenting a problem of resourcing.

Surveying the coastal zone is often made more difficult by the dynamic processes that occur (Moore, 2000). As a large proportion of the zone is water, surveying becomes multifaceted – requiring a strategy for both land and sea – with few systems being capable of providing simultaneous data in both regimes. Consequently, change measurements are most commonly made along coastlines, the area landward of the shoreline (Bird, 1986). Despite this, the nature of the coastline may still be innately hostile to traditional surveying techniques; often the processes found dictate the methodologies available, and the ease of their application. Because of changes occurring, national large-scale mapping may become rapidly obsolete, with updates too infrequent to accurately portray the changing coastline (Bray and Hooke, 1997). The difficulties of maintaining up-to-date data are therefore detrimental to planning, monitoring or predicting change.

With the wide areas and dynamic processes associated with the coastline, the need for control and datum registration between temporal datasets is paramount. The success of any monitoring scheme is reliant on being able to establish correspondence between the epochs of data collected (Cooper, 1998). This problem is especially apparent in coastal monitoring, as the establishment of permanent monumentation is often a difficult task. This is most readily seen where ground measurements are dependent on the reoccupation of control markers which, of necessity, are located close to the area under study, or where ground features must be identified for use as ground control points (GCPs) in photogrammetric processing.

As a direct consequence of these problems, monitoring schemes have often been restricted to small areas or of a low accuracy (Pethick, 1996), or carried out only in built-up areas where control monumentation is facilitated. In the simplest approach, a series of repeat measurements were carried out on a particular geomorphological feature with reference to an arbitrarily defined datum, usually a survey monument (Gorman *et al.*, 1998) or cliff backscar (Bray and Hooke, 1997). For beach monitoring, low technology approaches have included the use of 'Emery boards' (Komar, 1998), and levelling or total station methods, with profiles measured normal to the shoreline. Cliff measurement has been similarly crude, one technique being to install posts at intervals along a cliff top and record the distance from each post to the cliff edge over time. However, the temporal frequency and physical spacing of such measurements are inefficient and may be insufficient to record change at the short-term, high-resolution intervals required by the geomorphology (Pethick, 1996; Gorman *et al.*, 1998). The value of aerial photography has long been recognized as a means of recording coastal change. Advances in stereo-photogrammetric techniques have made aerial photography a valuable source of data for the Earth sciences (e.g. Chandler and Cooper, 1989; Baldi *et al.*, 2000), but in coastal studies photogrammetry has generally been applied only crudely, with users being warned of the effects of tilt, scale variation and relief displacement affecting the accuracy of their measurements (Moore, 2000). The Environment Agency and local authorities in southeast England have been an exception to this, carrying out aerial surveys and profile surveying (e.g. Thomalla and Vincent, 2003).

More advanced applications of geomatics technology have been reported. Morton *et al.* (1993) used the Global Positioning System (GPS) in kinematic mode as a means of efficiently collecting accurate beach profile data by mounting the equipment on an all-terrain vehicle. Hapke and Richmond (2000) used medium format digital stereo-photography to determine beach volume change. Digital elevation models (DEMs) were measured using automated digital photogrammetric workstation (DPW) routines, though significant errors were introduced due to the poor image texture affecting matching routines (Wolf and Dewitt, 2000). While stereo-photogrammetry is a poor choice for beach studies, due to lack of tonal contrast and wave movement between image frames, for cliff monitoring, the rich detail found in the face is ideal for both manual and automatic measurements to be made (Brunsden and Chandler, 1996; Adams and Chandler, 2002). Innovations in airborne laser scanning (ALS) technology have seen increased applications in coastal zone studies; indeed, ALS is now replacing or complementing photogrammetry throughout the discipline. Although the reported accuracy of ALS is generally higher than photogrammetry (e.g. Huising and Gomes Pereira, 1998; Adams and Chandler, 2002), advantages and disadvantages of each are evident.

Despite the introduction of advanced geomatics techniques to coastline monitoring, no single method has been implemented that is free from some major disadvantage: digital photogrammetry, with both image and DEM data, provides a useful solution but is limited by poor image texture in areas such as beaches. ALS can negate this problem by using an active source laser, but because of the lack of high resolution, image data interpretation is difficult. Kinematic GPS results in the best accuracy at the scale required, but the data are too sparse to provide more than a wireframe surface representation without long field sessions. A further approach, by integration of techniques, is therefore recommended, as favoured by a number of authors (e.g. Schiewe, 2000; Mitchell *et al*., 2002), and it is this concept that is explored in this paper.

Methodology

Instead of relying on a single measurement technique, data integration is used to negate problems associated with each of the component technologies. Because of the complex nature of the coastal terrain, which must be represented at high resolution, techniques providing continuous coverage of the coastal zone allow the most detailed modelling and interpretation to be carried out. Image data, or more importantly terrain surface model data, are therefore required to give the best approximation of the processes under study. Accordingly, DEMs and their integration are fundamental to the proposed methodology. Using DEMs, changes to the coastline under study can be determined, by comparing temporal series with the original surface (e.g. Adams and Chandler, 2002).

Photogrammetry is chosen as the core DEM technique of this monitoring scheme, justified because of its continuous spatial coverage (e.g. Baldi *et al*., 2000), the precision potential of surface measurements (Fryer *et al*., 1994) and the high level of automation available in modern DPWs. Set against these are a number of disadvantages, especially pertinent in coastal regions. Even with expensive GPS and inertial solutions and the bundle block adjustment utilized in contemporary DPWs, large quantities of ground control are required, which may be near-impossible to identify in coastlines where water, vegetation and dynamic processes exist. The lack of image texture on beaches may cause DEM measurement problems for the image matching routines, and the collection of imagery is heavily dependent on tides, weather and atmospheric conditions, and season. These problems may appear debilitating for the successful application of photogrammetry in coastlines. However, instead of conventional large format stereo-photography, this research uses digital small format aerial photography (SFAP) to obtain near-vertical imagery of the coastal strip. Important advantages of this include the use of a lighter camera platform, allowing rapid deployment and a lower flying height for decreased weather dependency (Graham, 1988), faster processing times available with digital imagery, an increased range of camera parameters, and overall system simplicity (Warner *et al*., 1996). However, the identification and quantity of ground control is still problematic and is intensified with the increased number of images needed to capture the coastline strip. Indeed, control is the most inefficient and costly single part of the flowline, constituting between 10 and 50 per cent of project expense (Warner *et al*., 1996; Wolf and Dewitt, 2000).

Instead of using GCPs this method orientates DEMs produced from digital SFAP captured from a microlight platform, using wireframe DEMs acquired with kinematic GPS. The photogrammetric DEMs are matched to the GPS DEMs using a least squares surface matching algorithm to provide control to the reference coordinate system. Use of a separate GPS DEM, independent of the photogrammetric measurements and of a higher order of precision, removes the problem of image texture errors, as the GPS DEM can model the smooth beach areas entirely with only a few carefully selected lines. The combined surface provides the base model for the coastal erosion monitoring scheme, with further epochs of data allowing change detection to be performed.

Component techniques

The selection of kinematic GPS has two uses: for providing control to national and global coordinate systems, useful for coordinating results between government bodies; and for achieving the wireframe model used for orientating the SFAP DEMs. Since its inauguration, GPS has been used primarily for monitoring static points, to give the trend of deformation with utmost precision. However, sophisticated 'on-the-fly' ambiguity determination has simplified kinematic data collection, allowing the trajectory of a roving antenna to be positioned to around the 0·01 m level (e.g. Leick, 1995). This facility is used to form multiple strings of data points which combine together to form a wireframe DEM of the coastline. The precision of each individual epoch is dependent not only on general factors, such as satellite obstruction and multipath, but also, crucially, on the movement of the user or nature of the terrain surface affecting the height of the antenna above the ground. To this end the 'GPSycle' – a standard surveyor's detail pole with mountain bike wheel attached – was developed to keep the antenna height constant (Buckley and Mills, 2001). Repeatability testing of this configuration on a stable test area resulted in a standard deviation in height of 0·014 m. To form the sparse wireframe DEM, breaks in slope, such as the top and toe of the cliff, and features on the cliff top and beach were traversed using the GPSycle. To speed up the data collection process the GPS equipment was mounted on a small all-terrain vehicle, where terrain and environmental concerns allowed.

The use of SFAP has a history dating back to the First World War (Graham, 1988). The huge growth in the digital market has eased the transition from analogue film-based photogrammetry to an almost completely digital solution, allowing total softcopy photogrammetry to be performed. A digital small format solution can be achieved at a fraction of the cost of a large format film camera, one of the digital aerial sensors recently released (e.g. Fricker *et al*., 2000) or, indeed, ALS. The Kodak Professional Digital Camera System (DCS) series has been the main stimulus for research since the introduction of the DCS 100 in 1991. A sequence of high resolution single lens reflex (SLR) bodies has been produced, in collaboration with Nikon, culminating in the DCS 660, 760 and Pro 14n models. Originally developed for photographers and journalists, the photogrammetric community was quick to realize the potential of these cameras for metric work (e.g. Robson and Shortis, 1998). For aerial work, the DCS series has been used in map creation (Mills *et al*., 1996) and revision (Mills and Newton, 1996), direct orientation (Light, 2001) and DEM production (Maas and Kersten, 1997).

Microlight camera platforms have been used previously for SFAP (Graham, 1988; Mills *et al*., 1996). Despite the practical and economic advantages of using digital SFAP for survey work, limitations do exist. For a 35 mm camera, 61 photos would be required to cover the same ground area at the same scale as a 230×230 mm format camera, a value that is increased when stereoscopic coverage is considered, making the use of SFAP unfeasible over large areas. Because a microlight platform is less stable than a conventional survey aircraft, tilts and rotations in the imagery can further reduce the stereo coverage. Associated with the increased number of images is the quantity of GCPs required to give absolute orientation to the photogrammetric block (Wolf and Dewitt, 2000). Even a single coastline image strip would require an inordinate and undesirable number of points to be identified, necessitating the use of the least squares surface matching approach proposed in this paper.

Using a terrain surface to perform absolute orientation allows the control DEM to be collected independently of the unorientated DEM, and the procedure is not reliant on the presence and identification of visible ground features. The problem is instead to register the unorientated model to the absolute coordinate system of the existing ground DEM. Surface matching concepts provide a common and fundamental problem in computer vision (Besl and McKay, 1992). The technique utilized in this monitoring scheme is based on a least squares approach, by minimizing the vertical differences between a fixed and 'floating' surface. For the $2^1/_2$-dimensional topographic surfaces used to represent the coastline, such a technique is accurate enough to perform the adjustment, without the complexity of fully three-dimensional methods (Mitchell and Chadwick, 1999).

This surface matching method is based on the three-dimensional conformal transformation – a standard adjustment in surveying and photogrammetry (Wolf and Dewitt, 2000), requiring the determination of three rotations, three translations and a scale parameter, so that the unorientated DEM is transformed to the coordinate system of the reference surface. The observations in the conformal transformation are the coordinates of control points in both systems; in surface matching no control may be identifiable and instead conjugate patches are used to perform the adjustment. Full details of the algorithm are reported in Mitchell and Chadwick (1999) and Mills *et al.* (2003). Complications with the least squares matching relate to the dissimilar datasets, brought about by disparities between the surface point distributions, data collection techniques and actual surface differences, meaning that no true conjugates may be found and interpolation is necessary. With the complex and disparate datasets resulting from GPS and photogrammetric DEM formation, various numerical and practical problems are apparent (Mills *et al*., 2003). Most outstanding of these is the reliance on surface gradients for a solution to be achieved in all three translation directions; surface texture is therefore crucial, just as it is for image matching in photogrammetric DEM extraction.

The surface matching algorithm is used to integrate the GPS and photogrammetric DEMs, by transforming the photogrammetric data to the global coordinate system of the GPS measurements. A product of the matching is the ability to detect changes, as the residuals from the least squares calculation are the surface separations. If a convergent solution is reached, these disparities may represent errors in the solution – and therefore errors in the object space coordinate system of the transformed surface – or actual differences between the two surfaces. If the two surfaces being matched are representations of the same real-world surface captured at different time intervals, the residuals potentially represent change. A further advantage of this methodology is that the matching algorithm is highly flexible, allowing further DEM data from different sources to be integrated in a modular manner. Indeed, the technique is suited to any Earth surface applications where different technologies may provide individual strengths, where higher accuracy is needed, or where control is problematic (Figure 1).

Case Study

The monitoring methodology was applied to an actively eroding section of coastline at Filey Bay, North Yorkshire, UK (Figure 2). The northeast coastline of England is highly susceptible to erosion, consisting mainly of soft glacial till

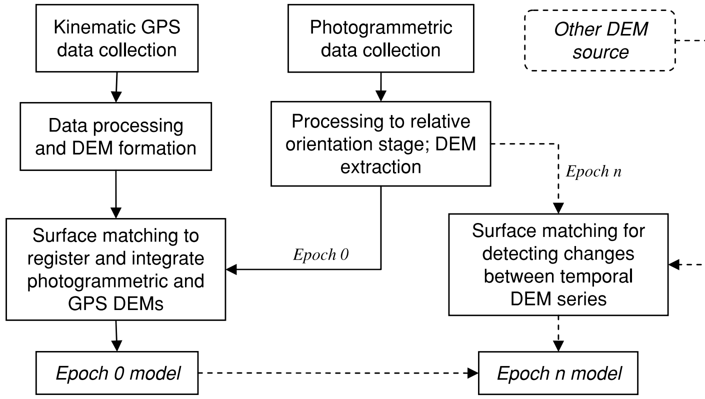

Figure 1. Flow diagram showing major stages of the data integration technique.

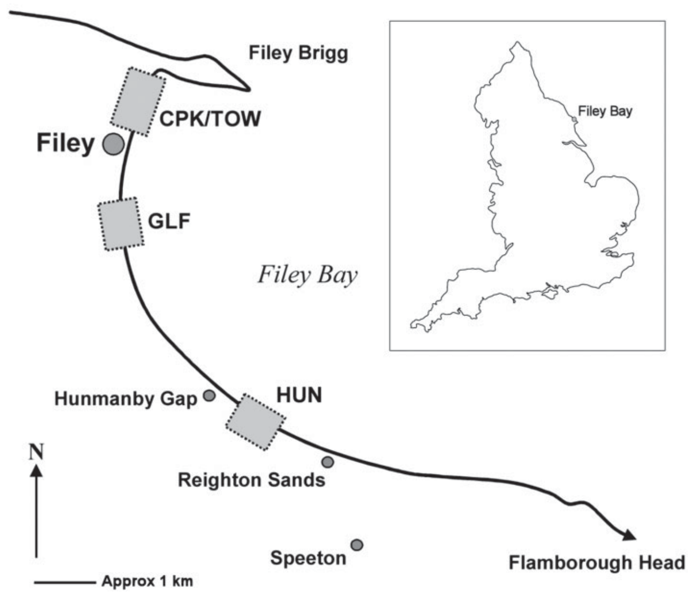

Figure 2. Location plan of Filey Bay, showing test sites used for validating the change detection technique.

depositions that are affected by rain runoff as well as sea erosion. High profile events have occurred in recent years, including the Holbeck landslide of 1993 (Lee *et al*., 2001), problems at Whitby's Abbey headland and at Runswick Bay. Filey Bay has a long history of erosion and, because of the diverse geomorphological processes, ecology and tourism interests, is noted to be '. . . one of the most important coastal sites in the British Isles' (Elliott *et al*., 1991). The geology of Filey Bay comprises steep glacial till cliffs on a limestone base at the north end, gently sloping and vulnerable till cliffs in the centre, and vertical chalk cliffs at the southern headland of Flamborough Head. Previous monitoring within Filey Bay is very limited (Mouchel Consulting Ltd., 1997). Elliott *et al*. (1991) report a former monitoring scheme using cliff-top erosion posts; seven posts were placed around the bay in 1952 by the local authority, observing an average loss of 0·25 m per year. However, this figure reveals nothing about localized variability, which is considerable, with major episodic landslide and slumping events releasing sediment from large areas of the glacial till cliffs. Such events may result in significant realignment of the cliff top and toe, as well as creating backscars tens of metres across where slumps have occurred. The SMP operated by the local authority, Scarborough Borough Council, recommends that six-monthly beach profile surveys and cliff-top erosion monitoring are carried out and that an annual photogrammetric survey is flown (Mouchel Consulting Ltd., 1997) – a sizeable effort for such large

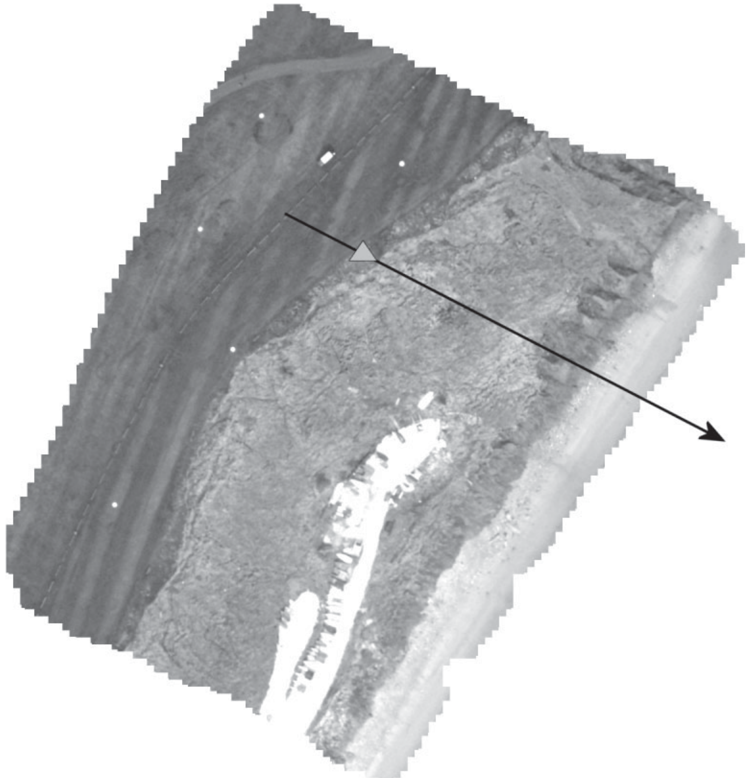

Figure 3. Orthorectified image of CPK test area, showing check profile and control points. Approximate size of test area is 130×200 m.

stretches of coastline. The stipulation for controlled photography further highlights the issues with GCP collection in the coastal zone. As the erosion risk at the southern chalk cliffs was assessed as being low, the remaining 8·6 km stretch of vulnerable coastline was chosen to test this methodology. Because of the large changes occurring at Filey Bay, the SFAP component was ideal for identifying areas of cliff failure, while the high accuracy kinematic GPS measurements allowed more detailed beach changes to be detected.

Data collection was carried out in three epochs over an 18-month period, starting in August 2000, allowing ample time for change to have occurred. Episodic surveys were to be carried out on a six-monthly basis, to conform to the SMP recommendations; however, the foot and mouth disease epidemic affecting British livestock in early 2001 meant that later surveys were postponed to August 2001 and March 2002. Four test sites were established around the bay, used in validating the individual data collection techniques, results of surface matching and changes identified. Within these locations, control points were monumented and check profiles normal to the cliff were measured using total station instrumentation. Areas CPK and TOW were located at the north end of the bay, GLF to the south of Filey town and HUN towards the south end of the bay. Each area was typical of the eroding morphology with vegetated glacial till cliffs, a grassed cliff-top area and a gently sloping beach (Figure 3).

The control markers were observed using static Leica System 500 GPS equipment and referenced to the Ordnance Survey Active GPS station at Flamborough Head, providing results in a global reference frame. The points were used as base stations for kinematic GPS, as well as marking the cliff-top ends of the check profiles. Consequently, the markers were positioned near the cliff edge from where the beach was visible through a total station telescope. Such proximity to the erosion zone created implications on permanency, necessary for repeatability, as described by Gorman *et al*. (1998). However, the stations remained relatively stable throughout the study with only minor change detected by the static GPS reoccupation (maximum differences recorded across the bay in the 18 months of the research were 40 mm in easting, 19 mm in northing and 69 mm in height). The GPS equipment was then used in kinematic surveying; using a combination of antenna mounts – a standard detail pole for the steeper cliff areas, the GPSycle on flatter

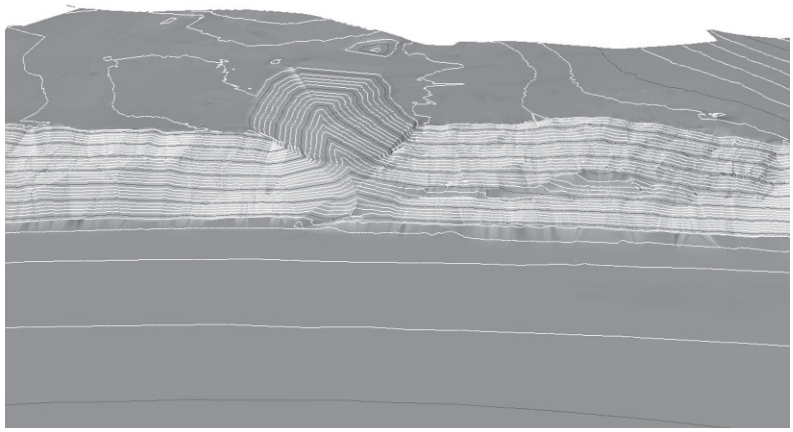

Figure 4. DEM of CPK area formed using kinematic GPS component. Approximate size of test area is 130×200 m (1 m contours).

areas and the all-terrain vehicle on the beach – wireframe DEMs were collected for the study areas, as described above (Figure 4).

Near-vertical imagery was captured using a calibrated Kodak DCS 660 digital camera from a Thruster TST at Epoch 0 (August 2000) and a Thruster Sprint at Epoch 1 (August 2001) and Epoch 2 (March 2002). With a Nikkor 28 mm lens and six-megapixel imager this resulted in an approximate photoscale of 1:22 000, providing a ground pixel size of 0·200 m and, with 60 per cent fore/aft overlap, a base/height ratio of 0·4 and a ground image area of 600×400 m. This configuration provided an expected heighting precision of 0·350 m (Light, 2001). Approximately 50 images were required to give complete stereo coverage of the coastline strip; hence GCP collection would have been undesirable. The Epoch 2 aerial survey was conducted in hazy conditions, with visibility insufficient for a conventional large format survey to be flown. However, when digital processing was applied, the photography was sharp and colours authentic, highlighting the utility of digital SFAP. For each epoch a total station was used to acquire checkpoint profiles; points were observed approximately every metre along the profile, or at significant changes in slope. To ensure repeatability, each profile was measured three times.

The kinematic GPS data were processed using on-the-fly relative phase techniques. The individual profile lines were then merged to form triangular irregular network (TIN) DEMs for use as control in surface matching. Prior to matching, the GPS surfaces were thinned to reduce the number of observations caused by the 1 Hz data collection frequency, so that clusters of points were eliminated and a more even Delaunay triangulation, used by the matching algorithm, ensued (Mills *et al*., 2003). The camera was calibrated and a relative orientation of the digital imagery performed using Leica Geosystems' (now BAE) SOCET SET DPW Version 4.3.1. TIN DEMs of the areas of interest were then created using the automatic terrain extraction facility which, because of the lack of GCP data, were not correctly positioned or scaled in the reference coordinate system.

The means of integrating the data from different sensors for each epoch, and the method of performing registration between the temporal datasets were critical to successfully determining true change. The photogrammetric DEMs for the most recent (March 2002) epoch were matched to their corresponding GPS models and transformed by the resulting parameters. The two models were then merged, with outliers between the surfaces removed so that artefacts were not present to contaminate the change detection (Mitchell *et al*., 2002). The effectiveness of this orientation method was assessed by comparing the merged DEMs with the total station profiles, from which root mean square (RMS) height errors of between 0·273 m and 0·596 m were deduced. Although the cross-sections only show the accuracy of the DEMs along a single line, accuracy of the photogrammetric component was corroborated by the high correlation with the GPS DEMs calculated during surface matching. Further testing of the photogrammetric DEM accuracy, using a surveyed test field of 54 pre-marked independent photocontrol targets located at the CPK site, revealed a post-match accuracy of 0·414 m. This value was used in carrying out change detection between the epochs of data for the Filey Bay test sites, and is worse than the theoretical precision of 0·350 m, suggesting that the DEM extraction using digital SFAP at low flying heights is susceptible to a greater degree of random error than had been predicted (Table I). Nevertheless, with major events occurring at Filey Bay during the study period, this value proved suitable for change detection. It is stressed that the system is modular, with components such as large format photography interchangeable where higher accuracy or more detail is required.

Table I. Expected precisions of survey techniques used in the Filey Bay monitoring scheme

Component	Precision (m)
Kinematic GPS	0·014
Total station	0·100
Photogrammetry from 600 m (theoretical)	0·350
Photogrammetry from 600 m (empirical)	0·414

Table II. Percentage Z differences between confidence interval levels, mean and σ for CPK data

	Epoch 2 – Epoch 1			Epoch 1 – Epoch 0			Epoch 2 – Epoch 0		
CPK1	**–**	**+**	**Total**	**–**	**+**	**Total**	**–**	**+**	**Total**
Change < $\pm 1\sigma$	–30	26	56	–27	24	51	–34	31	65
Change at 95%	–14	14	28	–16	13	29	–12	12	24
Change at 99·7%	–5	6	11	–7	6	13	–4	4	8
Change >99·7%	–2	3	5	–4	3	7	–1	2	3
Mean difference (m)		0.018			–0.047			–0.010	
σ Differences (m)		0.616			0.679			0.560	

Results and Discussion

It has already been established that surface matching is a useful technique for the registration of digital surfaces, without the use of control points. To determine the efficacy of surface matching for detecting change between DEMs, a series of tests was carried out using the three epochs of Filey Bay data. As an example of the methodology, results for the CPK area are presented here. The merged Epoch 2 CPK DEM was used as control, and the earlier surfaces matched to this. Using the most recent DEM as the fixed surface resulted in an RMS error of 0·474 m when the Epoch 1 DEM was matched, and 0·526 m when the Epoch 0 DEM was matched. In both solutions 96 per cent of points were used, the higher RMS value for the Epoch 0 match being a possible indicator of greater change having occurred over the longer time period.

Level difference at DEM observations

With the three epochs of data in the correct object space coordinate system, post-match differences could be determined and analysed for significance. Differences were found by re-running the final matching iteration so that for each point on the matched surface a height value was interpolated on the base surface and the difference deduced. The operation was also performed in reverse so that a value existed for every point in the two DEMs that fell within the union of the surface footprints.

Using the level difference values, statistical analysis was performed to determine significant differences between the temporal CPK surfaces, with the aim of detecting actual coastline change. Identifying accurate changes between datasets relies on some important assumptions about the validity of the data being made, for example that gross and systematic errors have been eliminated so that only the changes remain (Adams and Chandler, 2002). In practice, uncertainty will exist in the data due to random errors in the sensor, difficulties in removing all systematic effects and characteristics of the terrain surface itself. For this reason a critical value is applied, usually based on the measurement precision of the sensor at a particular confidence interval – often multiples of the standard deviation based on the range of the normal distribution (Shearer, 1990; Adams and Chandler, 2002). In this analysis, the measurement precision of the post-match CPK surface (0·414 m) derived above was used as the standard deviation, with multipliers based on the percentage probable errors quoted by Wolf and Ghilani (1997) of 0·811 m (95 per cent), 1·228 m (99·7 per cent) and 1·362 m (99·9 per cent).

Segmenting the data based on these values resulted in a non-Gaussian distribution with fewer than the expected 68·3 per cent of points within the 1σ category (Table II), an indicator that changes or errors were present in the data, though it was expected that change would be manifested as patches of systematic error in the level difference data.

Relatively large point quantities in the upper part of the distribution showed that significant disparities were present between the datasets. Histograms of the differences confirmed that normal distributions existed, expected because a successful match, with outliers excluded, results in a normal distribution with a mean of zero (Mitchell and Chadwick, 1999). Slight skewing towards the negative, when the outliers were included, suggests that overall loss occurred during the study period. Longer tails in the Epoch 2 – Epoch 0 and Epoch 1 – Epoch 0 histograms, compared with the Epoch 2 – Epoch 1 histogram, were indicative of more change having occurred because of the extended time period.

A final statistic calculated was the volume change between the DEM series, calculated by summing the volumes of complex prisms formed between two surface triangulations. For the CPK area a general loss of material was apparent between the years. Despite the vagueness in spatial extent of the volume statistic, it is a main source of geomorphological change information used by coastal managers. A more detailed examination of volume change is possible by comparing specific locations, using only a subset of the prisms.

The level differences between the CPK surfaces were plotted in their correct planimetric positions, resulting in a visual map of the changes (Figure 5), shaded according to the confidence intervals quoted above. As a means of visualizing the location of the differences – an 'end product' that could be used by coastal managers or local government engineers to aid interpretation – perspective scenes of the changes were created, by rendering the DEMs with the differences (Figure 6). The difference plots and perspective scenes facilitate interpretation of coastline change which, with reference to the orthorectified photograph (Figure 3), allow possible sites of erosion or deposition to be identified. Area 1 in Figure 5 continues down the northern side of the CPK test area and represents material lost during the winter of 2000–2001. However, a slump between Epochs 1 and 2 replenished some of this loss, seen by the increase in material. Area 2 in Figure 5 was identified as an accretion of shingle protecting the toe of the cliffs between Epoch 1 and Epoch 2; again, a loss is apparent between 2000 and 2001, which was replenished by March 2002. A general lowering of the cliff profile is apparent between Epoch 1 and Epoch 2, brought about by a slumping over the period 2000–2001, which added material to the cliff (area 3). This was then washed away during the wet summer and the winter, accounting for the large patch of negative differences in Figure 5. Although all of these values are not significant at the 95 per cent level, the overall sign of the surface differences is an indicator of the widespread and ongoing erosion (Figure 7). The GPS component of the merged DEM identified beach loss, which would not have been found using photogrammetry alone, due to correlation errors.

As well as areas of change in the DEMs caused by genuine coastal erosion, further areas were identified as being caused by human activity or vegetation change which influence all comparisons made using the affected data. Most recognizable of these are vehicles parked on the cliff top (area 4). The interpreter must therefore be wary of trusting difference plots blindly, without some form of verification; ideally such visible surface artefacts should be removed from the DEM during photogrammetric editing. Modifications to Filey Sailing Club were also apparent from the level differences; between Epochs 0 and 1 a new clubhouse was built and the dinghy park levelled (area 5), the old clubhouse being removed before the Epoch 2 survey, explaining the large DEM differences at this point.

The final differences that existed in the temporal DEM series were gross or systematic errors in the datasets, arising from a number of different sources. These were harder to detect and had the potential to affect all areas of presumed change, making interpretation difficult. By far the most likely source of error affecting DEMs derived from digital photogrammetric means are those brought about by poor image texture, resulting in image matching errors. The effect of these is systematic over- or under-estimation of the true surface level, or an increase in surface noise where the local grey-level minimum is unclear. Correlation error is apparent in the CPK DEMs as a number of invalid areas of difference (areas 6 and 7 in Figure 5). Area 6 was located on the beach area, a featureless expanse where matching failure was expected. The most worrying error was found in area 7, where a large patch containing systematic error (approximately 50×30 m) close to the boundary of the Epoch 0 DEM had been measured. This resulted in an overestimation of the model greater than the final 99·9 per cent confidence interval, and was caused by poor image texture of the grass surface of the car park. Without knowledge of the issues affecting the data quality, or some form of supplementary data (Gooch and Chandler, 2001), it would have been easy to categorize this area as an actual change, making further work based on such results flawed.

Validation using total station profiles

The final stage of the difference detection involved verifying the interpretations made above, to ensure that changes found were authentic. This was performed using the total station check profiles used previously for assessing surface matching results. Sections of the merged DEMs were taken for each data epoch. These were compared, as shown in Figure 8, indicating that the position of the merged surface after matching and the integrity of the correlated DEM was good. Areas of real change are identified on the cliff that conform well to the corroborating total station data, despite different spatial sampling. However, areas of correlation error are also apparent for the beach in both the 2001 and

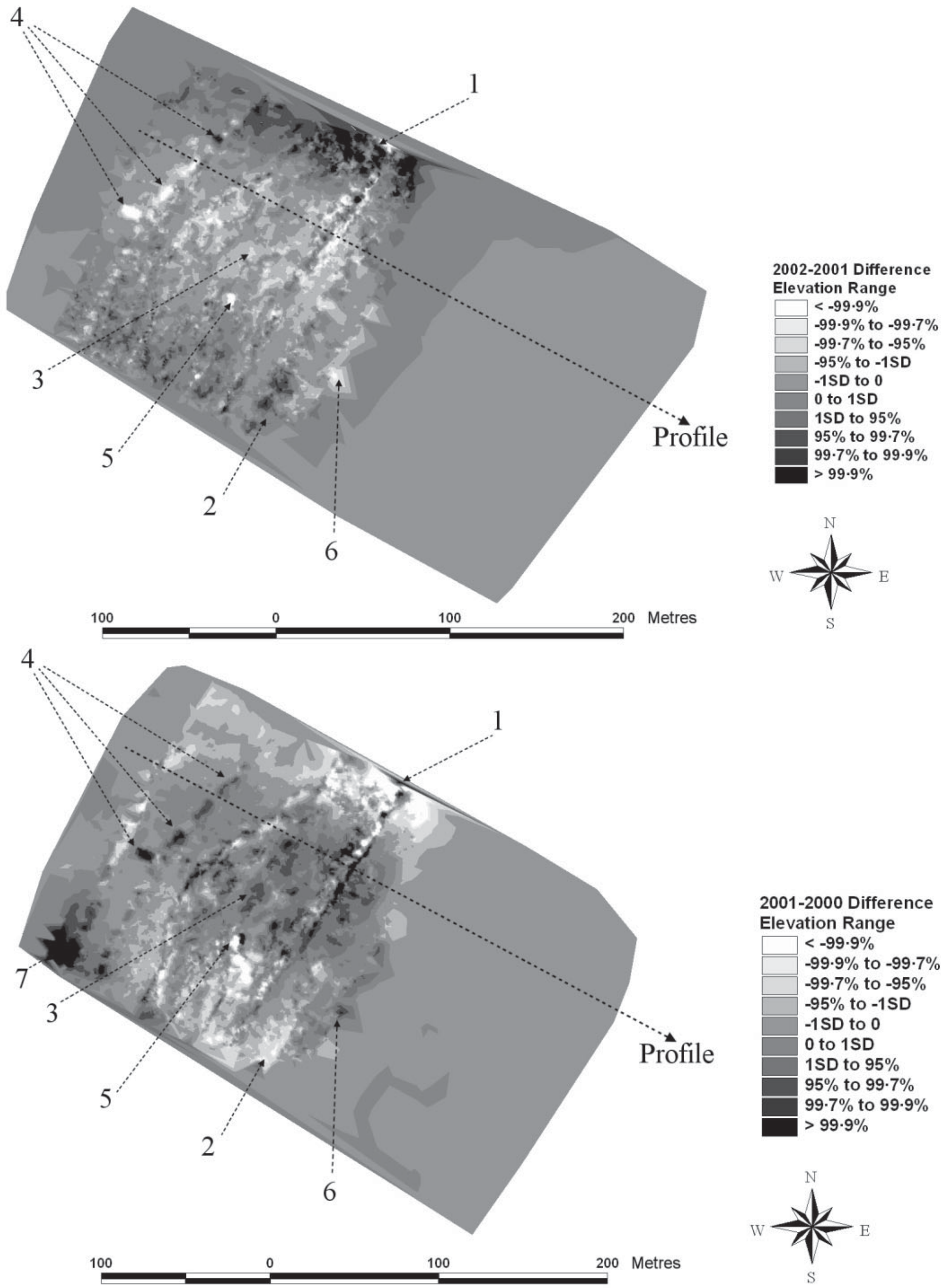

Figure 5. Level difference plots for CPK test area.

2002 DEMs, and the cliff top in the 2000 DEM. The merged surfaces contain more noise than the total station data, represented by small surface artefacts, though this is reflected in the established precision of the photogrammetric measurements. High match accuracies are implied in RMS profile differences of 0·468 m, 0·374 m and 0·275 m for the Epoch 0, Epoch 1 and Epoch 2 data respectively, suggesting that the surface matching technique is valid for conducting change detection in such terrain monitoring applications. However, the interpreter must be critical of results, as

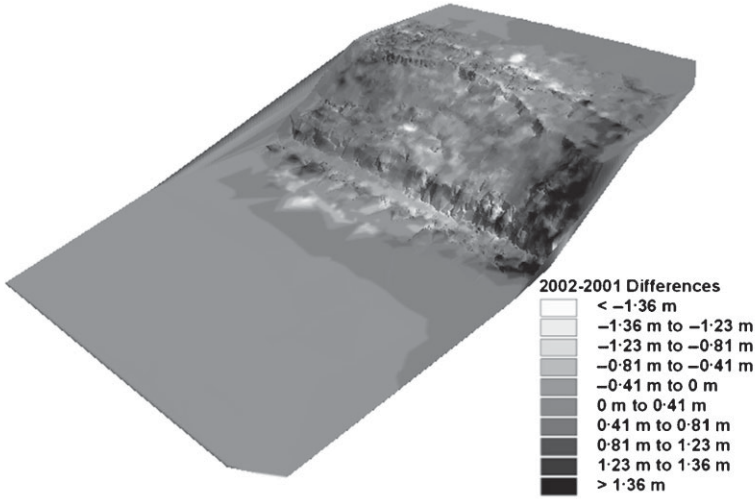

Figure 6. Perspective view of Epoch 2 – Epoch 1 DEM differences for CPK test area.

Figure 7. CPK test area photographed during Epoch 2 survey, showing ongoing erosion.

errors in raw data processing, DEM structure and surface matching may be present in the epoch differences, affecting the ensuing change detection.

Conclusions

This paper has addressed the important issue of coastal change monitoring, using the integration of geomatics techniques to form accurate representations of the coastline, with high spatial resolution and efficiency. The use of terrain data is seen as the optimum approach to change detection in landforms, particularly in the coastal zone where dynamic processes and lack of identifiable features are often detrimental to the monumentation of individual control points. Examining the current status of the geomatics discipline revealed that while a number of techniques were applicable to the task, none was capable of providing a full solution. The integration approach adopted in this paper therefore combined the best of the component techniques.

Central to the development of this methodology was a surface matching algorithm, used to register and calculate the differences between DEMs derived from different data sources at different temporal epochs. The advantages of such a

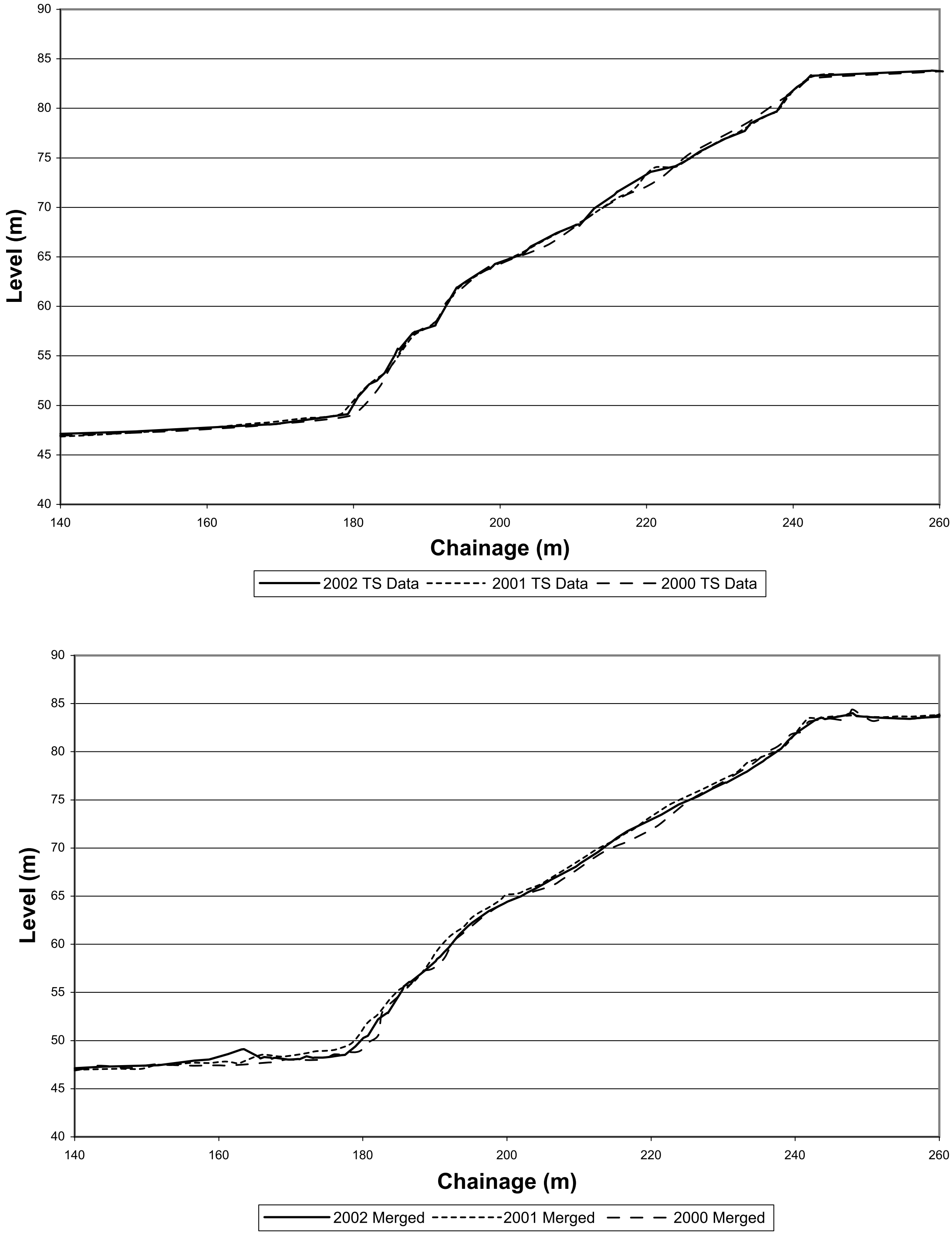

Figure 8. Total station (top) and merged (bottom) profile comparisons for CPK test area.

system are readily apparent, allowing the introduction of multiple terrain data in a modular approach. The flexibility of the matching algorithm was demonstrated by its use in two stages of the monitoring methodology: in registration of the core DEM components, and in later change detection, with high levels of redundancy and reliability. However, further issues remain and, as in all change detection methods, responsibility ultimately falls on the user to assess whether the results given by the system correspond to reality, and that errors in the data sources or registration are not falsely categorized as change. Despite this warning, the methodology presented here has proven to be effective and flexible, suitable for many DEM sources and Earth science applications.

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