SYNERGY OF GPS, DIGITAL PHOTOGRAMMETRY AND INSAR IN COASTAL ENVIRONMENTS*

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ABSTRACT

Coastal zone management is becoming increasingly important to government authorities who are charged with monitoring changes to the coastline brought about by phenomena such as erosion, marine flooding or landslides. Previously, monitoring techniques have often been crude and inefficient, due to the inherent problems associated with the wide areas and dynamic processes existing in the coastal zone. This research is developing a faster, more accurate and more efficient monitoring system, by deriving synergy from three integrated measurement technologies. Elevation models derived from the Global Positioning System (GPS) and digital photogrammetry are merged to form an episodic coastal change model at a high spatial resolution; this information is then updated regularly using spaceborne synthetic aperture radar interferometry (InSAR) data. The integrated model, with high spatial and temporal resolution, forms the basis for understanding coastal processes.

1. INTRODUCTION

The issue of coastal zone management is becoming increasingly important to government authorities who are confronted with problems of erosion, marine flooding, landslips and other phenomena that affect the existence of coastal assets within their administrative boundaries. Faced with legal consequences of not predicting or reacting to land movements, it is imperative that accurate monitoring systems are regularly deployed to record the evolving coastline. Of England's total coastline of 3760km, it is estimated that 30% is susceptible to varying levels of erosion, with 860km of coastal defences being in place to protect important areas (MAFF, 1994). In Britain, Shoreline Management Plans (SMPs) have been set in place by the Department of Environment, Food and Rural Affairs (DEFRA), a government body, to manage each individual coastal system, or 'sediment cell'. The SMP lays out a strategy for each sediment cell, defined by the inputs and outputs from sediment processes, based on the natural and man-made assets in each strip of coastline. One of the problems faced by the SMP administrators, the local government authorities, and coastal managers is the actual quantification of erosional and geomorphologic processes occurring in each cell, as required by the SMPs.

In the past it has not been uncommon to make use of field survey techniques. Beach profiles have been measured using a rod and transit or cruder approach (Komar, 1998), as well as standard total stations. Limitations with these approaches are apparent due to the large time budget required for data collection over wide coastal areas. For government authorities who have many kilometres of coastline to monitor, use of such small-scale techniques is inefficient and unfeasible. The introduction of GPS has facilitated the measurement of beach profiles (Morton et al., 1993), but gives only a sparse indicator of change over the whole coastal strip. For many years aerial photography has provided a more continuous coverage, episodic photogrammetric measurements allowing landform change models to be developed (Brunsden and Chandler, 1996). In addition, recent advances in the field of digital photogrammetry have allowed more automation in model orientation and the creation of high resolution digital elevation models (DEMs). However, slow film processing times, analogue to digital conversion and ground control requirements still make for an inefficient solution. Developments to LIght Detection and Ranging (Lidar) have

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meant increased usage in coastal environments, the rapid acquisition and high data quantities allowing detailed DEMs to be produced, albeit with associated errors depending on terrain type (Huising and Gomes Pereira, 1998).

This paper describes a new method of monitoring coastal erosion, one that derives synergy from three measurement technologies, GPS, digital photogrammetry and interferometric synthetic aperture radar (InSAR). Individually, each technology is capable of providing a partial contribution towards monitoring; together an improved solution, in terms of spatial coverage, precision, accuracy, time and expense, is the result.

2. METHODOLOGY

The primary component technology is digital photogrammetry, utilising a small format digital camera mounted on a microlight platform. Small format cameras have been used previously for aerial survey (Graham, 1988), providing a cost-effective solution for small-area surveys. Advances in the field of digital camera technology have resulted in high resolution sensors, comparable in usage with small and medium format film and with the added practicality of instantly available imagery. Use of a microlight camera platform reduces costs and enables air survey to take place rapidly, from nearer to the coastal strip than a conventional aircraft. Because a microlight is fast to scramble and can fly below the cloud base, it is less dependent on weather conditions, giving a larger flight window (Warner et al., 1996). Although the ground coverage of a small format camera is small when compared with conventional large format photography, for narrow coastal strip surveys where only one single strip is needed, this problem is minimized.

The use of small format digital imagery results in a large number of images covering the coastal strip, having implications on the amount of ground control required to transform the stereomodels into an absolute coordinate system. Because of modern aerial triangulation methods employed in digital photogrammetric workstations, the amount of control, formerly a minimum of two plan and three height points per stereopair (Rosenholm and Torlegård, 1988), has been greatly reduced. However, a difficulty associated with surveying in the coastal zone is that few natural or man-made features exist that are easily identifiable (Warner et al., 1996). A common solution to this problem is the use of pre-fabricated ground markers, positioned and coordinated before a flight takes place, but the added time and expense, combined with tidal patterns and unpredictable weather conditions still makes the absolute orientation process the least efficient and most costly in the photogrammetric processing chain.

Orthodox photogrammetric processing follows a set workflow: interior orientation, where image space and camera parameters are defined; relative orientation, where stereomodels are formed by identifying homogeneous points in the overlapping images; and absolute orientation, where the stereomodel is scaled and orientated into an object-space reference coordinate system (Wolf and Dewitt, 2000). Using conventional ground control, a least squares adjustment is performed transforming the coordinates of a set of points in the model space to known control in the object space using a scale factor, a translation vector and a rotation matrix.

Instead of using ground control points to give absolute orientation to the strips of digital imagery, this research instead uses independently collected DEMs to scale and orientate the elevation model produced from the relative orientation stage of photogrammetric processing. A least squares three-dimensional surface matching algorithm is used, based on the above transformation, in a similar manner to image matching methods employed elsewhere in digital photogrammetry. Rosenholm and Torlegård (1988) introduced the theory of least squares surface matching, and applied it to the absolute orientation of blocks of aerial photography using coarse national-level DEMs. Karras and Petsa (1993) and Mitchell and Chadwick (1999) used surface matching for ultra small-scale medical and dental applications, where the comparison of digital surfaces at different epochs was required, but the use of control markers was both undesirable and unethical. As no control points are used in surface matching, the procedure is instead to register two DEMs, which may have differences due to data collection methods or differences caused by deformation, by a set of transformation parameters, so that the vertical differences between the surfaces are minimized.

To remove the need for costly ground control, the floating photogrammetric surface produced from the relative orientation stage of processing is fused with a DEM collected using GPS. Early GPS research was used primarily to observe and monitor single point positions. However, with the development of modern on-the-fly kinematic post processing algorithms, GPS can equally be used to record strings of points using a roving receiver. Dual frequency GPS receivers are used to acquire a coarse wireframe DEM of the beach, cliff and cliff top areas, by following the breaks in slope, thus defining the shape of the terrain surface with the least amount of data. Where possible the GPS antenna is mounted on an all-terrain vehicle to speed up data collection and improve efficiency.

The merged GPS and photogrammetric DEM forms the base model of the coastal zone. A product of the least squares surface matching approach is the ability to detect differences between surfaces (Mitchell and Chadwick, 1999). These show up as residual points that differ greatly in the match. By examining the residual plot it is possible to identify areas of surface difference. Because GPS measures to the ground height and photogrammetry measures to the highest part of the terrain, some of the residuals can be identified as differences in data collection, with vegetation, buildings and vehicles being the most common. The photogrammetric survey is repeated episodically in development of a temporal model of the coastline. By matching the new DEM on to the old DEM, true surface differences can be identified, indicating change may have occurred.

The integrated surface provides a single epoch of data, in essence a ‘snapshot’ of the coastline at the time of collection. However, to increase the temporal resolution of the model, SAR Interferometry is used to detect changes occurring between photographic surveys. Although the spatial resolution of radar imagery is poor, interferometric processing allows a change detection sensitivity of millimetres between coherent image pairs. During development of the InSAR technique, applications in earthquake displacement studies (Wright et al., 1999), subsidence monitoring (Strozzi et al., 2001) and landslide detection (Kimura and Yamaguchi, 2000) have been researched. The all-weather nature of radar allows frequent images to be acquired - based on the orbit rate of the satellite - without the need for field survey.

3. CASE STUDY: FILEY BAY, YORKSHIRE, ENGLAND

The North Yorkshire coastline of England is highly susceptible to erosional processes, as it is comprised largely of glacial till – an inherently unstable material. In recent years the local government authority, Scarborough Borough Council, has initiated many schemes to counter the actions of coastal erosion. High profile cases of erosion have been seen with the Holbeck Hall Hotel collapse at Scarborough in 1993, the Runswick Bay sea wall movement throughout the late 1990s, and ongoing problems in Filey Bay, the site chosen for testing this coastal monitoring research. Filey is a small town of around 7000 inhabitants on the North Yorkshire coast of England, situated in a 12km bay. The northern 8.6km of the bay are comprised mainly of the same glacial till as much of the Yorkshire coastline, subject to erosion by runoff caused by rain, as well as erosion by the sea. A fault line splits the bay, with stable vertical chalk cliffs at the southern end; because of this the larger glacial till stretch of the bay was chosen as a test site. A report commissioned in 1991 estimated that an average erosion rate of 0.25m a year was present in the bay (Elliott et al., 1991). However, this information was based on only seven erosion posts distributed along the bay, and conceals a more complex periodicity of cliff failures related to storm events and beach dynamics. The SMP identified the monitoring of cliff processes and beach levels as key issues for the management of Filey Bay, and recommended strategies for each sub-cell within the bay itself, based on the levels of natural and human assets. During the development of this methodology three sets of fieldwork have been carried out at Filey Bay, in August 2000, August 2001 and March 2002, allowing a temporal change detection model to be initiated. For each of these three fieldwork periods, GPS and photogrammetric data were captured, along with total station cliff profiles for verification of both the surface matching and change detection results.

Leica System 500 dual frequency receivers were used to traverse the breaks in slope, creating a wireframe DEM of the beaches and cliffs (Figure 1). On the smooth and unobstructed beach a small all-terrain vehicle was used to reduce data acquisition times. In other areas the GPSycle (Buckley and Mills, 2001) – a standard surveyor's detail pole with a mountain bike wheel attached – was used. Multiple height repeatability studies of this methodology were carried out along a known baseline, resulting in a standard deviation of 0.014m, better than the expected precision of photogrammetric measurements. Individual lines of GPS data were merged into a single DEM for the later surface matching procedure.

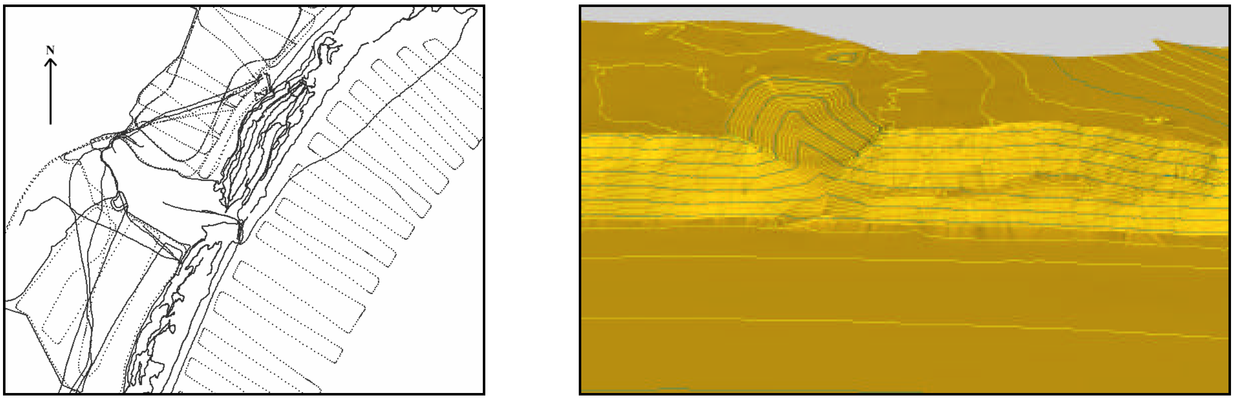

Figure 1. Plan View (Left), and 3D View (Right) of GPS DEM Created for Filey Country Park, 2001 Survey

Digital imagery was acquired from a Thruster Microlight platform (Graham, 1988), using a Kodak DCS 660 camera. The Kodak DCS 660 is one of a successful series of high resolution SLR cameras that have been employed for mapping (Mason et al., 1997; Mills et al., 1996) and surface modelling (Chandler et al., 2001). With a six megapixel charge-coupled device (CCD) and 9µm element size, the DCS 660 provides a cost effective approach to aerial survey, especially when used in conjunction with the low-cost microlight aircraft. At a flying height of 2000 feet (600m), the camera was set at ISO200 and f/4 with an exposure time of 1/400s. A Nikor 28mm lens was used, giving an approximate photoscale of 1:22,000. Overlap of 60% was achieved, this configuration providing a ground pixel size of 0.2m and an expected heighting precision of 0.35m (Light, 2001). The non-metric nature of the DCS 660 meant that calibration was needed to give accurate internal orientation; this was performed using 54 ground markers laid and coordinated before the flight took place. Because of the small format of the camera, around 50 images were required to give complete stereo coverage of Filey Bay (Figure 2). From this it can be seen that even with sophisticated aerial triangulation algorithms a correspondingly large amount of ground control would have been needed, increasing the time and expense of the monitoring scheme.

Imagery was processed in LH Systems' SOCET Set version 4.3.1, a digital photogrammetric workstation capable of performing model orientation and automatic DEM extraction. Because of the nature of the triangulation algorithms in SOCET Set, some ground control is required to give initial approximations of the block, as both the relative and absolute orientation stages are performed simultaneously. To bypass this, three approximate points were scaled from existing mapping and measured in one stereopair. The remaining images in the Filey Bay strip were then added to this first pair using tie points, until the end of the strip was reached. With the strip orientated, DEMs were then automatically extracted and edited within SOCET Set. The resolution of the DEMs created varied according to the nature of the monitored features. Coarser DEMs were measured of large stretches of coastline, and then smaller, finer models added in areas of more detailed processes, such as landslides or embayments.

Figure 2. Near-Vertical (left) and Oblique (Right) Images of Filey Country Park, Captured Using DCS 660 Camera

As only three ground control points were used in the transformation of the model into the absolute reference coordinate system, the accuracy of this transformation decreased along the strip as the distance to the control increased. As a result of this, a comparison with the GPS surface towards the strip end showed that the photogrammetric DEM was rotated slightly and was around 60m below the 'true' surface level (Figure 3); hence surface matching was crucial in removing this transformation error and merging the two data collection techniques. Photogrammetric DEMs were matched to the corresponding GPS areas using the least squares surface matching algorithm, resulting in integrated surfaces (Figure 3), more accurate than when using a single technique alone. Total station cliff profiles were measured at six 'control areas' along the 8.6km coastal strip; these were used in match verification, showing correlation values up to 0.98 between the merged GPS and photogrammetric surfaces.

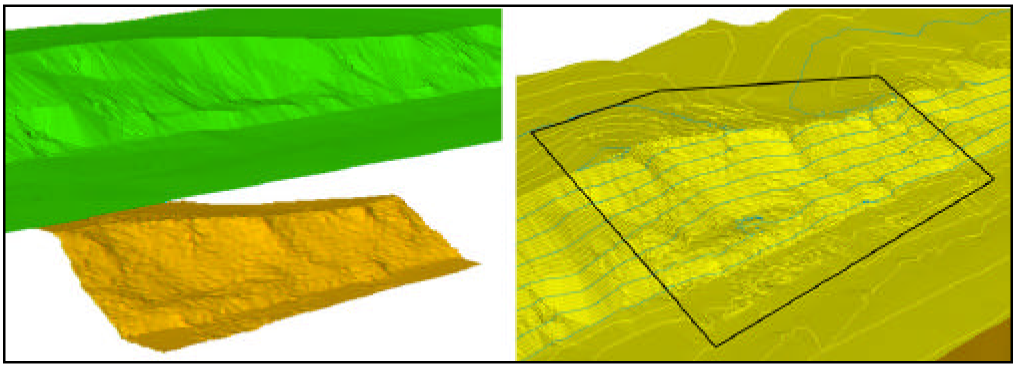

Figure 3. Unmatched Surfaces at Southern End of Strip (Left), Showing Photogrammetric DEM Below GPS DEM, and (Right) Merged Surface (1m Contours)

The merged GPS and photogrammetric DEMs will provide an high resolution surface for InSAR processing. Unfortunately, since this research project began, the European Space Agency's ERS-2 satellite has suffered a loss of gyro stabilisation meaning that the repeat orbits required for interferometry have not been possible. In addition the replacement to ERS-2, ENVISAT, has still not been launched, making the proposed temporal update to the coastal model impossible. However, to prove the concept, archival radar imagery has instead been chosen from before the problems with ERS-2 occurred, coinciding with the start of this project and the time of the first fieldwork (May to November, 2000). Current work is being carried out to process these images (Figure 4) which, if successful, will give an historical insight into the erosional processes of Filey Bay. Areas of coherence between image pairs will highlight areas of small coastal changes, whereas it is expected that incoherent areas may be indicative of larger changes having occurred, requiring field inspection or further survey work to be carried out.

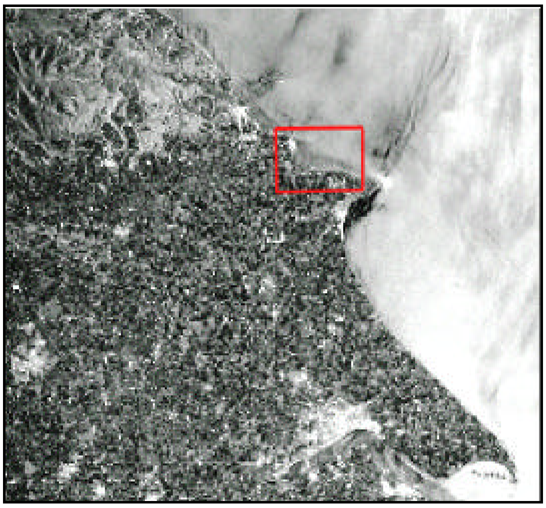

Figure 4. SAR Scene of North Yorkshire, England, Acquired by ERS-2 on 15th May, 2000. Filey Bay is Boxed

4. CHANGE DETECTION

With merged DEMs of Filey Bay already created for the 2000 and 2001 datasets some preliminary change detection has been possible. As stated above, an outcome of the surface matching process is a matrix of residuals defining the error between the two surfaces being matched. Statistical analysis and visualisation of this can highlight areas of large surface error, where change may have occurred. In addition, transforming the matched surface into the coordinate system of the control surface by the post-match parameters and analysing the differences can also identify areas of potential change. The 2000 merged surface was held fixed as the reference surface, and the 2001 data was matched on to this. The resultant surface differences can be seen in Figure 5 for Filey Country Park, situated at the north end of the bay.

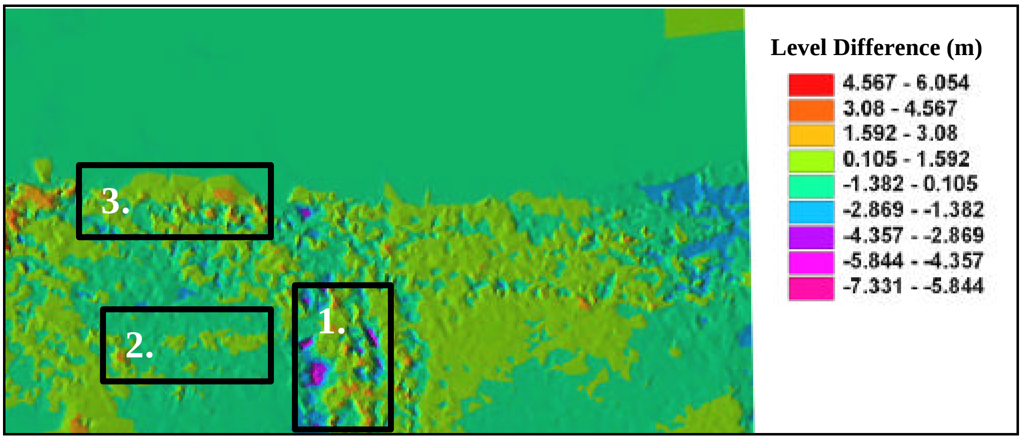

Figure 5. Level Difference Map of Filey Country Park Between 2000 and 2001 (See Text for Explanation)

From Figure 5 it can be seen that surface differences are apparent between the 2000 and 2001 datasets. However, it must not be immediately assumed that all the differences are due to deformations to the coastline; indeed, on close examination of the differences and the related 2000 and 2001 images, it is possible to reject areas due to artefacts on the terrain surface. This can be demonstrated in Figure 5, where vegetation changes in a wooded ravine (Box 1) and vehicles in a car park (Box 2) can contribute to misleading results. Nevertheless, possible cliff toe erosion can be seen (Box 3). Because only the photogrammetric DEM is orientated during surface matching, the imagery still remains in the incorrect coordinate system meaning that orthophotos produced are also incorrectly orientated. Therefore, further work is required to transform the photographic block by the post-match parameters, so that change data may be superimposed on to a correctly orientated orthophoto, aiding interpretation.

5. CONCLUSIONS

An ongoing project to develop an optimum solution to the problems of monitoring coastal erosion has been described. In the past surveying techniques have often proved difficult and expensive because of the inherent problems associated with the wide areas and dynamic processes in the coastal zone. By incorporating the high positional accuracy of GPS, the wide area coverage of digital photogrammetry and the all-weather change detection capabilities of InSAR, synergy is derived to form a faster and more efficient monitoring system, with a higher spatio-temporal resolution than has previously been available. Although GPS and photogrammetry form the core of this monitoring solution, the technique is designed so that different surface measuring technologies could be integrated to form a coastal model. The use of least squares surface matching is an elegant method of fusing data, and could be applied to lidar data in preference over photogrammetry, or for detecting differences between the two techniques. Where underwater measurements may be required, the use of surface matching to integrate water-penetrating lidar data into the coastal model would be a further application of this research.

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