SYNERGY OF GPS, PHOTOGRAMMETRY AND INSAR FOR COASTAL ZONE MONITORING

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ABSTRACT:

This paper reports on research that aims to develop a technique for rapidly monitoring coastal erosion over wide areas, by deriving synergy from three integrated measurement technologies. These technologies are the global positioning system (GPS), automated digital photogrammetry using imagery acquired with a small format digital camera, and synthetic aperture radar interferometry (InSAR). The technology for all three of these techniques has been available for the last few years but only recently has it become potentially accessible for multiple use by coastal managers. Through integration, it is anticipated that the optimum monitoring solution in terms of spatio-temporal coverage, precision, accuracy, time and expense will be achieved.

1. INTRODUCTION

1.1 Background

The issue of coastal zone management is increasingly important to government authorities that are confronted with problems of erosion, marine flooding, landslides and other phenomena that affect the existence of coastal assets within their administrative boundaries. The displacement of property and population can be a costly business for local government, especially in built-up areas. Faced with legal consequences of not predicting land movements, it is imperative that monitoring systems are deployed to regularly record changes to the coastline, so that prediction can be attempted. Areas of Britain's coastline are very susceptible to coastal erosion, high profile examples being Gunner Point at the western tip of Hayling Island in Hampshire, Beachy Head in East Sussex and the Hythe coast in Kent.

In areas of erosion or deformation, it is not uncommon to make use of field survey techniques to monitor discrete points in the areas of interest. The standard survey tool for this has traditionally been the total station, but more recent research has concentrated on the use of the global positioning system (GPS). For wider area surveys, photogrammetry, with imagery taken using large format metric film cameras and measurements performed manually on analytical instrumentation, is an accepted method of data production for coastal management purposes. The efficiency of photogrammetric processing in coastal management has been improved in recent years following the introduction of digital photogrammetric workstations that have provided the ability to automate measurements when using scanned photography (Smith and Waldram, 1996). Nevertheless, the inherent problems of slow image acquisition due to film processing and the need to perform extensive ground survey remain (Mills and Newton, 1996). Indeed the processing chain is further complicated by the need for analogue to digital conversion of the imagery by scanning the film. In addition to these factors, deteriorating atmospheric conditions in Europe mean that the number of days suitable for acquiring imagery using large format film cameras is in decline (Reed, 1999). For organisations involved in standard topographic map production this is a problem but it has a far greater impact when monitoring environments that can be subject to rapid change.

1.2 Motivation

The motivation behind this research is to develop a survey technique that is based on three mapping technologies for rapidly monitoring coastal zone erosion. The three technologies are GPS, digital photogrammetry (using imagery from a digital sensor rather than a film camera) and synthetic aperture radar interferometry (InSAR). The technology for all three of these techniques has been available for the last few years but only now has it become accessible for multiple use by the type of user targeted by this research. This research is not only developing each technique individually, but also integrating them to form the optimum monitoring solution in terms of spatio-temporal coverage, precision, accuracy, time and expense.

2. METHODOLOGY

2.1 GPS

The first stage of the monitoring technique involves a comprehensive ground survey of the area of interest by GPS. Early GPS research into coastal monitoring saw the technology used primarily to observe and monitor single points. However, with the development of on-the-fly kinematic post-processing algorithms, GPS can equally be used to record strings of points using a roving receiver and a static base station (Edwards et al., 1999). Dual frequency GPS receivers are used to acquire a coarse resolution, but cm accurate, wireframe digital elevation model (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 environmental concerns allow, the roving GPS receiver is mounted on an all-terrain vehicle (Figure 1) to speed up data collection and improve efficiency of the survey.

Figure 1. GPS roving receiver mounted on an all-terrain vehicle

2.2 Photogrammetry

The second 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 and inherently stable imagery. Use of a microlight camera platform (Figure 2) 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 flying window (Warner et al., 1996). Although the ground coverage of a small format camera is limited when compared with conventional large format photography, for narrow coastal strip surveys where only one single strip is needed, this problem is minimised.

Figure 2. Thruster microlight aircraft

The use of small format digital imagery results in a large number of images covering the coastal strip, having implications on the number of photo control points required to transform the stereomodels into the ground coordinate system. Because of automated 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 in recent years. 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.

Conventional photogrammetric processing follows a set workflow: interior orientation, where image space and camera parameters are defined; relative orientation, where stereomodels are formed by identifying conjugate points in the Von Gruber positions of 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, the absolute orientation phase comprises a least squares adjustment transforming the coordinates of a set of points in the model space to known control in the object space using a three dimensional conformal transformation (comprising a scale factor, three translations and three rotations).

Instead of using ground control points to give absolute orientation to the strips of digital imagery, this research uses independently collected DEMs to scale, translate 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 minimised.

To remove the need for costly ground control, the floating photogrammetric surface produced from the relative orientation stage of processing is fused with the DEM collected using GPS. 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 due to the data collection, and may be recognised as vegetation, buildings and vehicles. The photogrammetric survey is repeated episodically to develop a temporal model of the coastline. By matching the new DEM on to the old DEM, true surface differences can be identified, indicating where change may have occurred.

2.3 InSAR

The integrated GPS/photogrammetric 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 aerial photographic surveys. Although the spatial resolution of radar imagery is poor, interferometric processing allows a change detection sensitivity of mm 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

3.1 Test Site

The North Yorkshire coast is comprised mainly of unstable materials that are highly susceptible to erosion, as the Holbeck Hall landslide in Scarborough in June 1993 showed (Ordnance Survey, 1994). This much-publicised landslide caused considerable damage to property and involved Scarborough Borough Council, the local government authority, in a drawn-out legal battle. Scarborough Borough Council has identified many other potential problem areas, one such area being Filey Bay, the test site for this research study.

Filey is a small town of around 7000 inhabitants on the North Yorkshire coast of England, situated in a 12 km bay (Figure 3). The northern 8.6 km of the bay is mainly comprised of soft glacial till, a material susceptible 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 the test site. A report commissioned in 1991 estimated an average erosion rate of 0.25 m per year in the bay (Elliott et al., 1991). However, this information was based on only seven discrete erosion posts distributed along the bay, and conceals a more complex periodicity of cliff failures related to storm events and beach dynamics. The local shoreline management plan (one of a series of plans that have been set in place by the Department of Environment, Food and Rural Affairs, a government body, to manage each individual coastal system in Britain) identified the monitoring of cliff processes and beach levels as key issues for the management of Filey Bay.

During the development of this new 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.

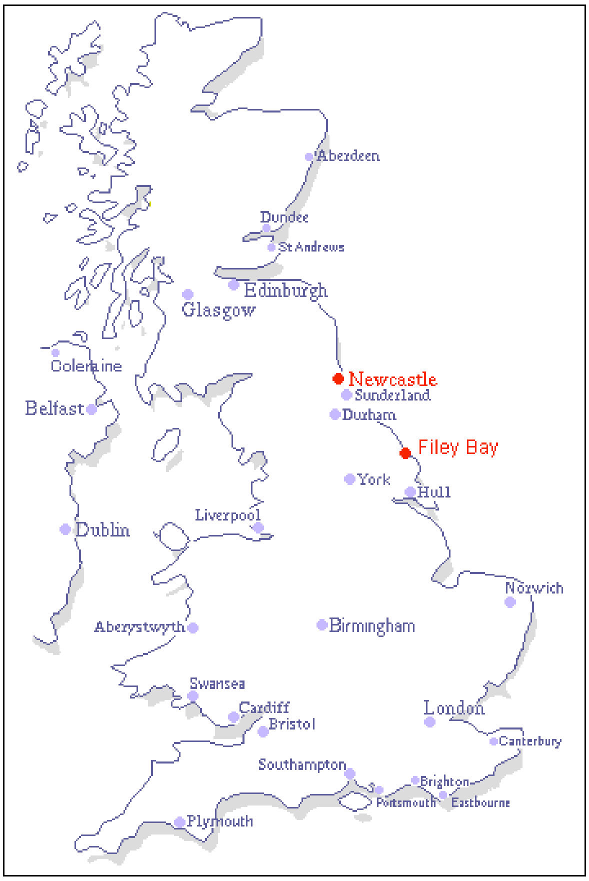

Figure 3. Location of Filey Bay, North Yorkshire, UK

3.2 GPS Survey

Leica System 500 dual frequency GPS receivers were used to traverse the breaks in slope, creating a wireframe DEM of the beaches and cliffs at each epoch of data collection. On the smooth and unobstructed beach an 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 (Figure 4).

Figure 4. The GPSycle

Multiple height repeatability studies of this GPS methodology were carried out along a known baseline, resulting in a standard deviation of 0.014 m. This figure is better than the precision expected of the photogrammetric measurements made at the second stage of the survey. A wireframe model from a GPS survey is shown in Figure 5.

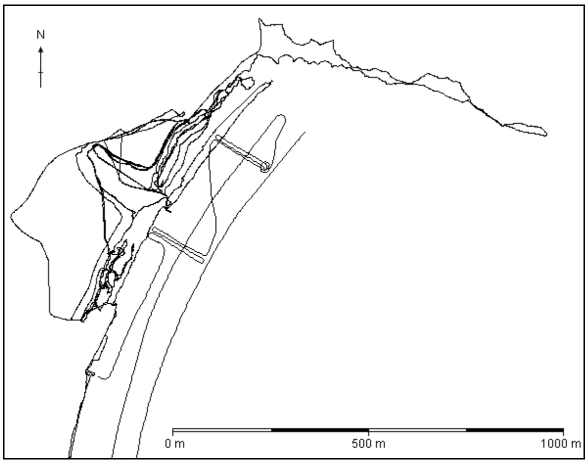

Figure 5. GPS wireframe model

Individual lines of GPS data were then concatenated into a single DEM for use in the later surface matching procedure. Figure 6 shows an example three dimensional DEM that results from several GPS survey strings.

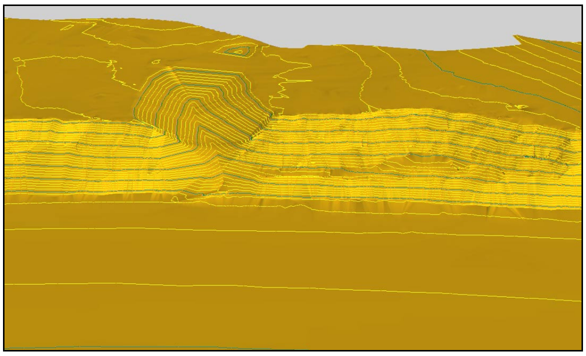

Figure 6. DEM created by GPS strings of points (1 m contours)

3.3 Aerial Survey and Photogrammetric Processing

Digital imagery was acquired from a Thruster Microlight platform (Graham, 1988) as shown in Figure 2, using a Kodak DCS 660 camera (Figure 7). 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 (600 m), the camera was set at ISO200 and f/4 with an exposure time of 1/400 s. A 28 mm Nikkor lens was used, giving an approximate photoscale of 1:22 000. A fore/aft overlap of 60% was achieved, this configuration providing a ground pixel size of 0.20 m and an expected heighting precision of 0.35 m (Light, 2001).

Figure 7. Kodak DCS 660 digital camera mounted in the Thruster microlight

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 (a typical image can be seen in Figure 8). From this it can be seen that even with sophisticated aerial triangulation algorithms, following conventional photogrammetric workflow would mean a correspondingly large amount of ground control would be needed, increasing the time and expense of the solution.

Figure 8. Near-vertical aerial image taken with the Kodak DCS 660 digital camera

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 (Figure 9). The resolution of the DEMs created varied according to the nature of the monitored features. Coarser DEMs were measured over large stretches of coastline, and then smaller, finer models added in areas of more detailed processes, such as landslides or embayments.

Figure 9. DEM generated in LH Systems SOCET Set from the Kodak DCS 660 aerial imagery (3 m contours)

3.4 GPS and Photogrammetric Data Fusion

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 60 m below the 'true' surface level (Figure 10); hence surface matching was crucial in removing this transformation error and merging the two data collection techniques.

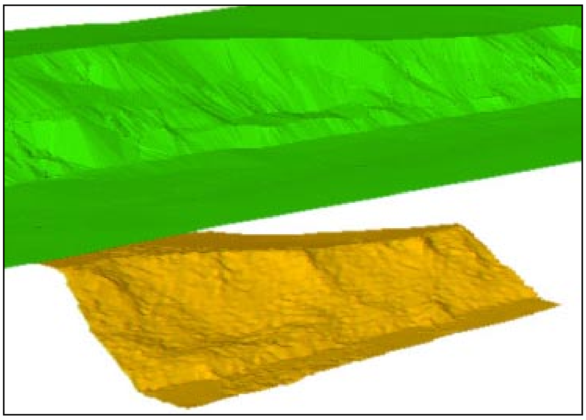

Figure 10. Photogrammetric DEM (bottom) in relation to the GPS derived DEM (top) at the end of the strip

Photogrammetric DEMs were matched to the corresponding GPS areas using the least squares surface matching algorithm, resulting in integrated surfaces (Figure 11), more accurate than when using a single technique alone. Total station cliff profiles were measured at six 'control areas' along the 8.6 km coastal strip; these were used in match verification, showing correlation values of up to 0.98 between the merged GPS and photogrammetric surfaces.

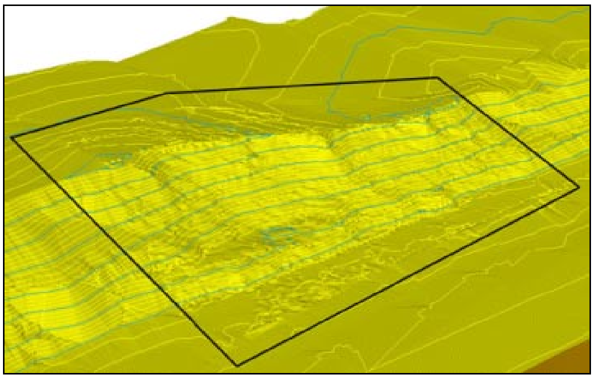

Figure 11. Merged GPS and photogrammetric derived DEMs (1 m contours)

3.5 InSAR Image Acquisition and Processing

The merged GPS and photogrammetric DEMs provide a high resolution surface to be used in InSAR processing. Interferometric processing was performed using the JPL/Caltech repeat orbit interferometry package, ROI_PAC, version 1.0 beta. Unfortunately, since this programme of research began, the European Space Agency's ERS-2 satellite suffered a loss of gyro stabilisation meaning that the repeat orbits required for interferometry have not been possible. In addition the launch of ENVISAT, the replacement to the ERS-2 satellite, was delayed until March 2002, making the proposed temporal update to the coastal model impossible.

Nevertheless, in order 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. Current work is being carried out to process these images (Figure 12) which, if successful, will give an historical insight into the erosion processes active in Filey Bay. Areas of coherence between image pairs will highlight small coastal changes, whereas it is expected that incoherent areas may be indicative of larger changes having occurred, requiring field inspection or further survey to be carried out.

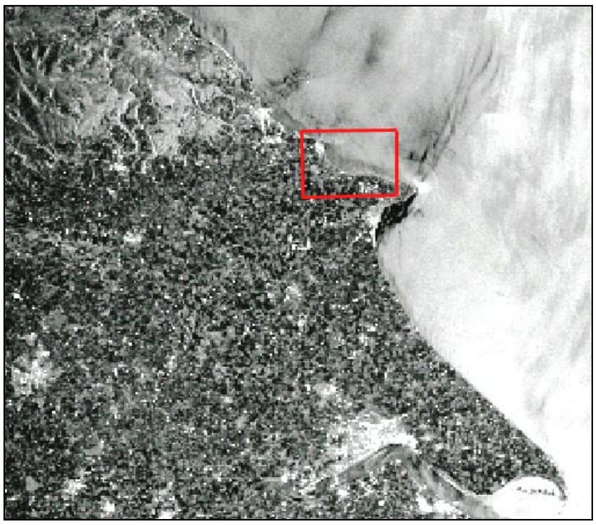

Figure 12. 100 km^2 ERS-2 SAR Scene of North Yorkshire, UK. Image acquired on 15th May, 2000. Filey Bay is Boxed. © ESA

4. 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 new monitoring solution, the technique is generic 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 (both terrestrial or airborne) in preference over, or in addition to, GPS or photogrammetry. Further, the application of this methodology is not restricted to coastal zone monitoring and modelling. Environmental and engineering applications that could adopt this type of monitoring methodology are plentiful, with the technique now being utilised, for example, in an investigation into the reactivation of post-mining ground subsidence in the UK.

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