ELEVATION MODELS FOR GEOSCIENCE

“Monitoring coastal change using terrestrial LiDAR”

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ABSTRACT

The paper describes recent applications by the British Geological Survey (BGS) of the technique of mobile terrestrial LiDAR surveying to monitor various geomorphological changes on English coasts and estuaries. These include cliff recession, landslides and flood defences, and are usually sited at remote locations undergoing dynamic processes with no fixed reference points. Advantages, disadvantages and some practical problems are discussed. The role of GPS in laser scanning is described.

INTRODUCTION

The use and application of terrestrial-based **Li**ght **D**etection **A**nd **R**anging (LiDAR), using a method popularly known as *laser scanning*, has greatly increased over the past five years. The perception of the technique has changed, from that of a novel, but complex surveying tool to a relatively simple, almost routine method for precision measurement. The method was first widely used within the quarry industry where the results of repeat surveys were used to manage and plan material extraction. The technique has subsequently found architectural, civil engineering and industrial applications and, more recently has been adopted by the computer games industry to capture street scenery. Within geoscience, terrestrial LiDAR has been applied to the monitoring of volcanoes (Hunter *et al.*, 2003), earthquake and mining subsidence, quarrying, buildings, heritage and conservation, forensics (Paul & Iwan, 2001; Hiatt, 2002), landslides (Rowlands *et al.*, 2003) and coastal erosion (Hobbs *et al.*, 2002; Miller et al., 2006; Poulton et al., 2006). The method has developed in parallel with airborne LiDAR, and to some extent terrestrial photogrammetry (Adams et al., 2003) and other airborne/ spaceborne techniques (Balson et al., 1998; Webster & Dias, 2006). This paper describes the different techniques and applications to which the British Geological Survey (BGS) has used terrestrial LiDAR over the past six years, and the successes and difficulties that have been encountered over that time.

TERRESTRIAL LiDAR – APPLICATIONS AT BGS

Since 2000, the BGS has used various terrestrial LiDAR and GPS systems in combination to measure, record and monitor a variety of geological exposures and geomorphological subjects, initially in collaboration with 3DLaserMapping Ltd. Most of the work has centred on the monitoring of active landslides on eroding coastlines, where the target surface is visible from a number of locations and is generally free of vegetation. Good reflections are returned from natural rock and soil materials at these sites, with rare exceptions where water seepage dramatically reduces the reflectance of dark mudrocks.

The platform for the scanner is usually a tripod (Figure 1). This provides the versatility and mobility essential when scanning in a dynamic environment, where any kind of permanent installation is ruled out. The instrument can either be positioned over a known point or a differential global positioning system (dGPS) antenna substituted for the scanner to obtain the position, provided that the height is accurately measured, and the discrepancy between antenna and scanner heights is accounted for. Care must be taken to ensure tripod stability, particularly in sand. Most cliffs can be laser-scanned from the beach or rock platform using this method, but with certain caveats described later.

Figure 1 Laser scanner mounted on tripod – mobile set-up

Perhaps surprisingly, the method is also suited to low-lying features, normally only considered for airborne LiDAR, with the proviso that elevated vantage points are necessary. These may be provided by a vehicle roof in a temporary configuration (Figure 2) or, increasingly commonly, a dedicated vehicle mounting. Most vehicle mounting arrangements suffers in strong winds, although jacks were used at the four corners of the vehicle to eliminate suspension movement and provide stability. A modular gantry (Figure 3) or hydraulic platform may also be used. However, there are important issues of stability particularly where the instrument cannot be remotely operated. In the case of critical monitoring, e.g. for a large extremely hazardous landslide or volcano, a permanent solid monument is preferred, and if possible the instrument mounted on a long-term basis. The latter situation minimises errors due to instability and setting up associated with temporary tripod-mounting, but of course ties up the instrument for long periods and may expose it to damage. In a coastal situation the installation of a solid monument is usually not feasible. The set-up shown in Figure 4, whilst providing a solid platform, can only be temporary as the tide covers the block, as evidenced by the mussels attached to it.

Figure 2 Laser scanning from vehicle roof – mobile set-up

Figure 3 Laser scanning from a 6m high modular gantry – temporary set-up

In most cases it is not possible to erect permanent monuments on the coast or estuary from which to laser-scan. Where monitoring is required using temporary mobile platforms (e.g. tripods), laser scans must be oriented to a fixed grid reference system. In areas of coastal erosion lacking fixed reference points, the current solution is geodetic-quality dGPS. The raw output data from a scan consist of vertical and horizontal angles, distances, and reflective intensities, plus calibrated digital images where available. The angles and distances are subsequently ‘oriented’ into *xyz* grid co-ordinate positions (local or global) on the computer using dGPS (or other) location information. This format allows ‘oriented’ scans taken from other positions to be combined, as well as roving GPS data sets, to form a single model. Recently, the additional feature of calibrated digital photography has enhanced the method, allowing both the raw data and the final 3D model to be coloured accurately, the outcome resembling a 3D photo. This is very useful for the geoscientist who wishes to visualise, record, and measure terrain, structures, volumes, and processes.

Figure 4 Laser scanner mounted to rock-bolt on WW2 concrete block – temporary set-up

COASTAL RECESSION

Coastal recession is of worldwide concern, particularly in the light of current global climate change predictions, associated sea level changes and increased storm occurrence (Lee & Clark, 2002; Clayton, 1989). Monitoring of recession is considered a key factor in successful coastal management and hazard mitigation (Hall et al., 2002). The coastal environment is one in which high precision surveying can be made difficult by the dynamic nature of the environment. Typically, away from the built environment there are no lasting reference points with which to 'fix' each survey. Each element of the eroding coastline, i.e. cliff, platform, and beach, such as those in many parts of eastern and southern England, is in an almost continuous state of flux. Tides, unstable slopes, and the routine destruction of any fixed reference points therefore create an immediate problem for the surveyor using terrestrial LiDAR in these environments. Hence the need to accurately fix scans based on mobile or temporary set-ups such as those shown in Figures 1 and 2. The use of dGPS to locate laser scans can itself be compromised close to high cliffs, particularly where the satellite configuration is unfavourable.

Methods other than terrestrial LiDAR have been used to monitor unstable cliffs. These may be subdivided into direct and other remote techniques. Examples of the former include instrumented rock-bolts and cable tensiometers. Examples of the latter, Time Domain Reflectometry (Pasuto et al., 2000), and Digital Image Processing (Allersma, 2000).

As with other sciences, sophisticated computer models are increasingly being used to characterise and predict coastal cliff recession (Walkden & Hall, 2005), particularly where the element of climate change is introduced. These require quantitative input data, such as those obtainable by terrestrial and aerial LiDAR and by other remote techniques. Direct slope stability monitoring methods tend to be targeted at specific features where movement is expected. They therefore provide only local information, and crucially may miss unforeseen movements or events. Quantitative information about mass behaviour usually requires a remote method.

SLOPE DYNAMICS PROJECT

The British Geological Survey has been carrying out coastal monitoring in England using terrestrial LiDAR since 1999 (Hobbs et al., 2002). The Slope Dynamics Project has 12 coastal locations where ‘soft’ rock cliffs are subject to marine erosion and/or landslide activity. These sites are scanned annually or bi-annually (depending on the rate of change) to assess the influence of geology, geomorphology, and geotechnics on the process of cliff recession. Recently, active inland landslides have been included (Rowlands et al., 2003), though these tend to be more unusual and less dynamic than their coastal counterparts. As part of the project, platforms and beaches are included in the scans so that the relationships between wave attack and cliff degradation can be examined. The role of landslides on cliff recession is a topic of some interest in Britain, particularly along the east and south coasts of England where the rocks making up cliffs and platforms are comparatively weak, susceptible to erosion and instability, and marine attack is powerful. Huge quantities of sediment liberated from the cliffs are moved along the coast or offshore, and re-deposited by the sea. Modelling this action in response to time and environmental conditions is key to understanding the likely effects of climate change. Such models require quantitative information about cycles of sediment supply and the relationship with platform erosion and beach thickness in order to calibrate their predictions. Terrestrial LiDAR is one way of doing this, albeit on a local scale.

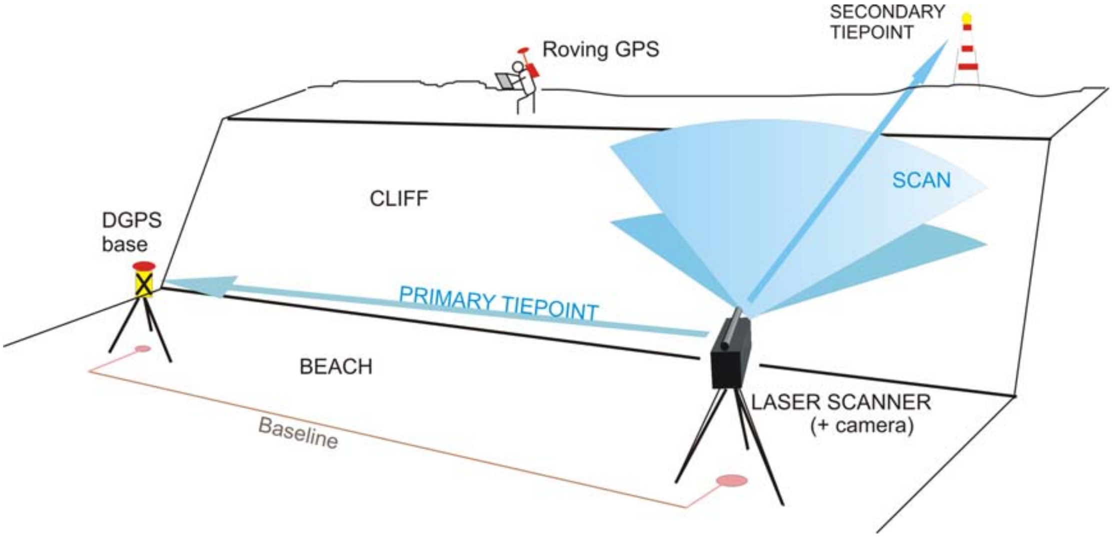

Figure 5 Coastal mobile terrestrial LiDAR method

The method used by the project in the coastal environment involves setting up a baseline on the foreshore, parallel to the cliff with a tripod at each end (Figure 5). The tripods are alternately occupied by a laser scanner and a dGPS antenna. The scanner fixes the position of the other tripod using either a single-shot (or an automated micro-scan) to a reflective target in place of the dGPS antenna, and then scans the cliff and platform. This may be repeated along the foreshore, or in some cases on the cliff top in order to get the fullest possible coverage. Where large-scale rotational landslides and large embayments are present, this task may be difficult, particularly where access to the cliff is impossible or unsafe. Coverage of ‘shadow’ areas may be improved by infilling with a roving GPS where access is possible. The scan data consist of *xyz* position and reflective intensity, with the possible addition of a digital image mosaic provided by a built-in calibrated camera. The final output can be in the form of a ‘point cloud’ (Figure 6), a 2D intensity plot (Figure 7), a 3D point-cloud coloured from the photo-mosaic (Figure 8), or a 3D triangulated ‘solid’ surface model (Figure 9) over which the photo-mosaic has been draped (Figure 10). The coloured point-cloud output (Figure 8) is visually effective where the density of points is high, but the solid model allows greater manipulation and the calculation of areas, volumes, and cross-sections. False-colour models can be utilised to show height (Figure 11) and range (Figure 12). The various uses of these models by the geoscientist are summarised in Table 1.

Table 1 Uses for each model type

Model: *Uses:*	2D intensity	3D point-cloud	3D colour point-cloud	3D solid	False-colour
Lithology recognition	✓		✓	✓	
Geomorphology		✓	✓	✓	✓
Structural geology			✓	✓	
Volumes, areas				✓	✓
Cross-sections				✓	

The ‘Scan A’ example shown in Figures 6 to 13 is a 20 m high cliff formed in matrix-dominant Late Devensian tills (Withernsea Till and Skipsea Till Members of the Holderness Formation), from part of the 50 km long Holderness coast of East Yorkshire. Historical erosion rates are between 1 and 2 m per year (Balson et al., 1998). Landslides on this coastline typically consist of single rotational failures and smaller toppling failures. The rotational features tend to develop en-echelon, a factor possibly related to sub-vertical joint patterns in the tills.

It is clear from the figures depicting Scan A that each model contains gaps or ‘shadow’ areas, which represent areas that the laser was unable to ‘see’. For instance, in Figure 13 a boulder close to the scanner has cast a long laser ‘shadow’ across the beach thus preventing any points being captured behind it. This can be rectified to some extent by carrying out multiple scans from several positions each having a different viewpoint on the same object. Then with the application of the dGPS, or other, 3D model orientation method, these ‘shadows’ can be significantly reduced or eliminated. Of course, this adds considerably to the amount of post-processing required. New dGPS systems are reducing the amount of post-processing by improved real-time processing, for example by mobile telephone communication with a GPS network. However, this may introduce a fresh problem associated with mobile network coverage in remote locations.

PROBLEMS TO CONSIDER

One problem with the triangulated ‘solid’ surface is that uneven coverage of points in the original point cloud results in either gaps in the model (Figure 9) or oversized polygons (Figure 14) depending on the threshold parameters selected. This is particularly the case where the cliff is receding unevenly from crest to toe, i.e. it has a ‘stepped’ profile, or where landslides are of a rotational type, featuring back-tilted slip masses, and hence are in the laser ‘shadow’ when scanned from the beach. As the laser scanner sweeps the subject from its fixed position it has the attribute of a shotgun; that is, nearby features are densely covered with points compared with distant features. In the case of a largely planar subject such as a building, this may not be a problem. However, for natural features such as cliffs, the result may be wide variation in the surface detail captured, and hence the integrity of the 3D solid model.

In the case of large coastal landslide complexes, the range of the instrument becomes an issue. Many high-speed laser scanners, having a maximum range of typically less than 500 m, might struggle with such features, particularly where access to the cliff to carry out multiple scans is impossible. A common problem encountered during the project has been the inadequacy of PC / software combinations to deal with the millions of points produced by modern scanners, notwithstanding that the scanners used were not classed as ‘high-speed’. This is particularly the case where ‘solid’ models are required. The repeated scanning of the same cliff enables changes in elevation to be displayed and quantified, provided that a solid grid-oriented model for each epoch has been produced.

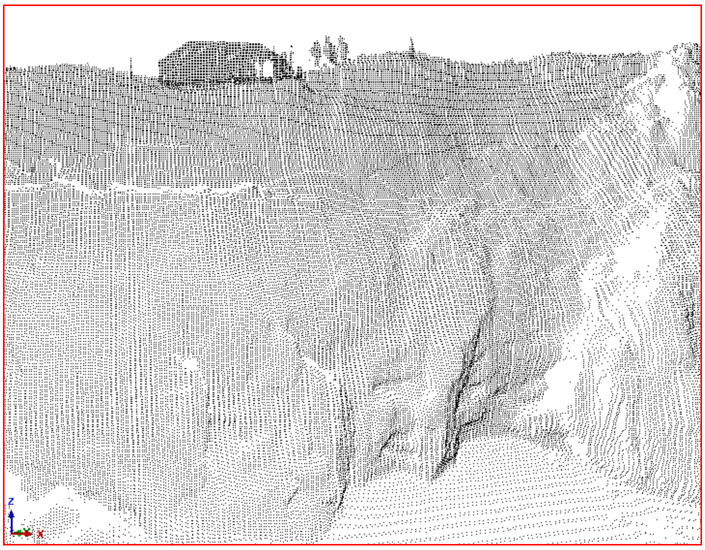

Figure 6 Part of Scan A showing raw point cloud

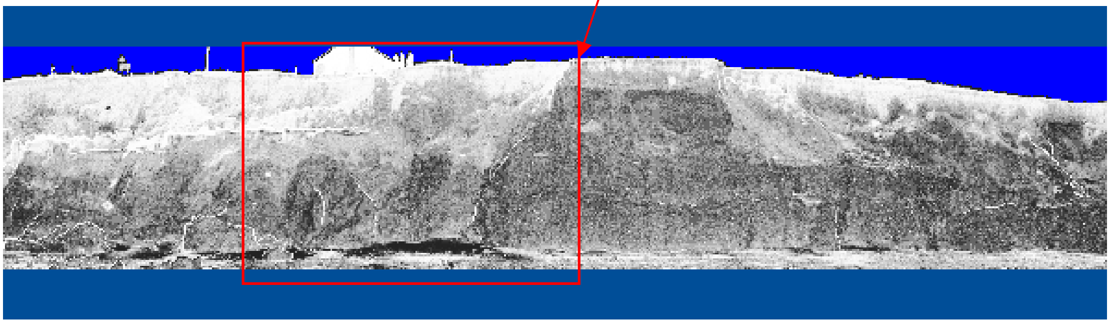

Figure 7 Full Scan A – 2D intensity plot

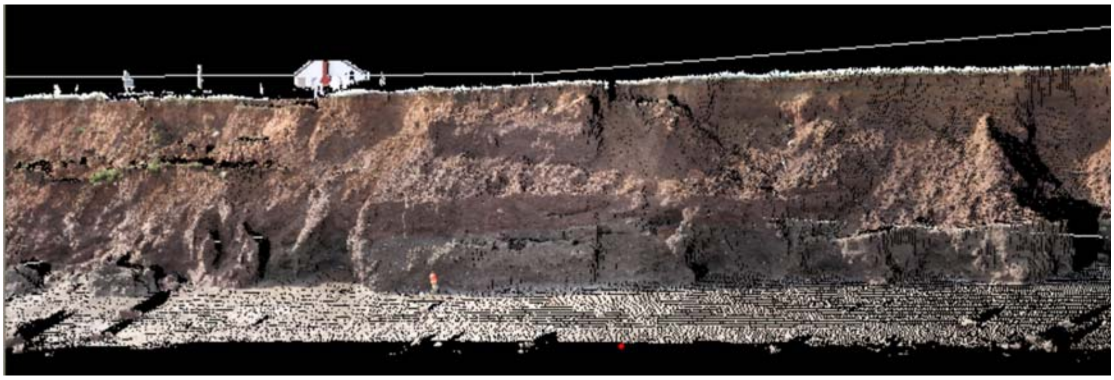

Figure 8 Full Scan A – 3D coloured point-cloud

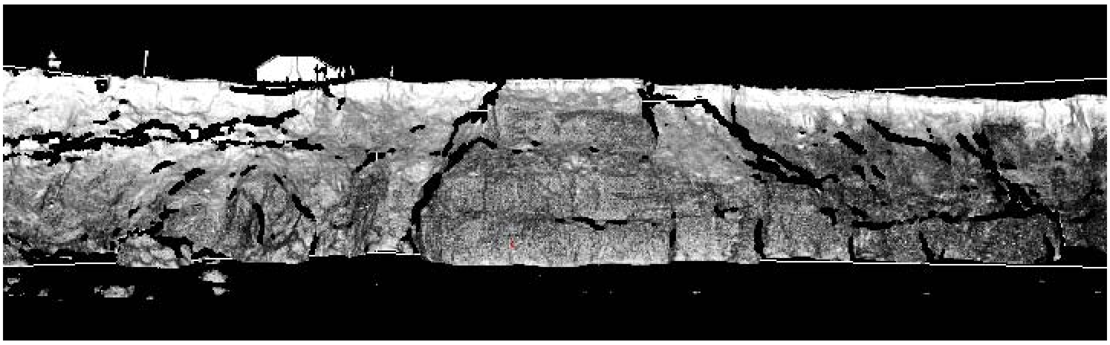

Figure 9 Full Scan A – 3D triangulated ‘solid’ surface model

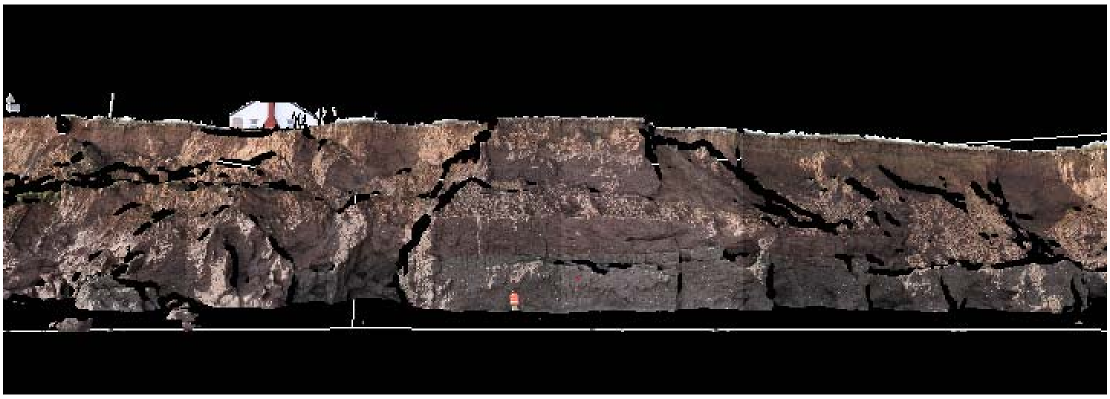

Figure 10 Full Scan A – 3D triangulated surface model with digital colour photo overlay

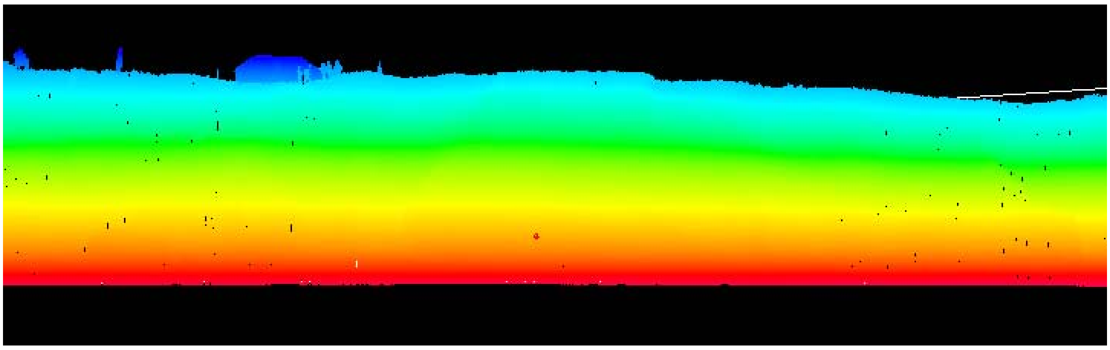

Figure 11 False-colour 2D height model for Scan A (red=low, blue=high)

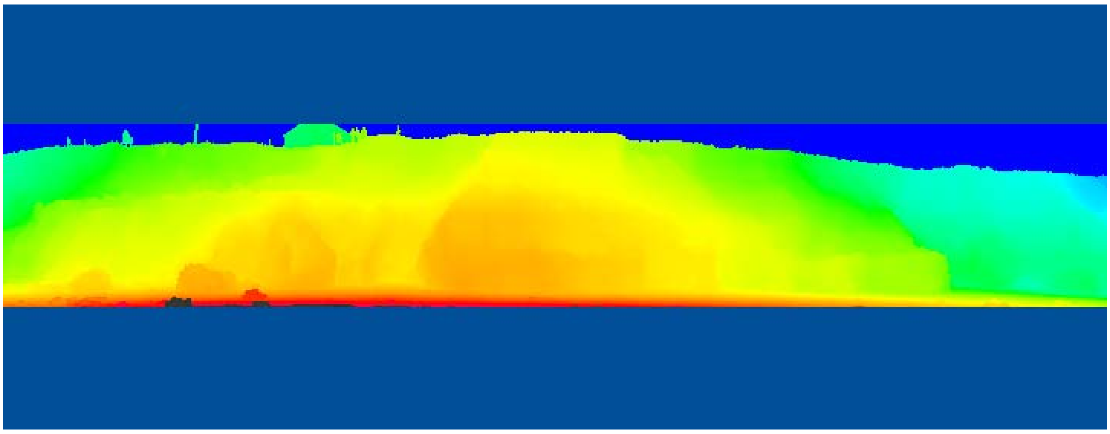

Figure 12 False-colour 2D range model for Scan A (red=near, blue=far)

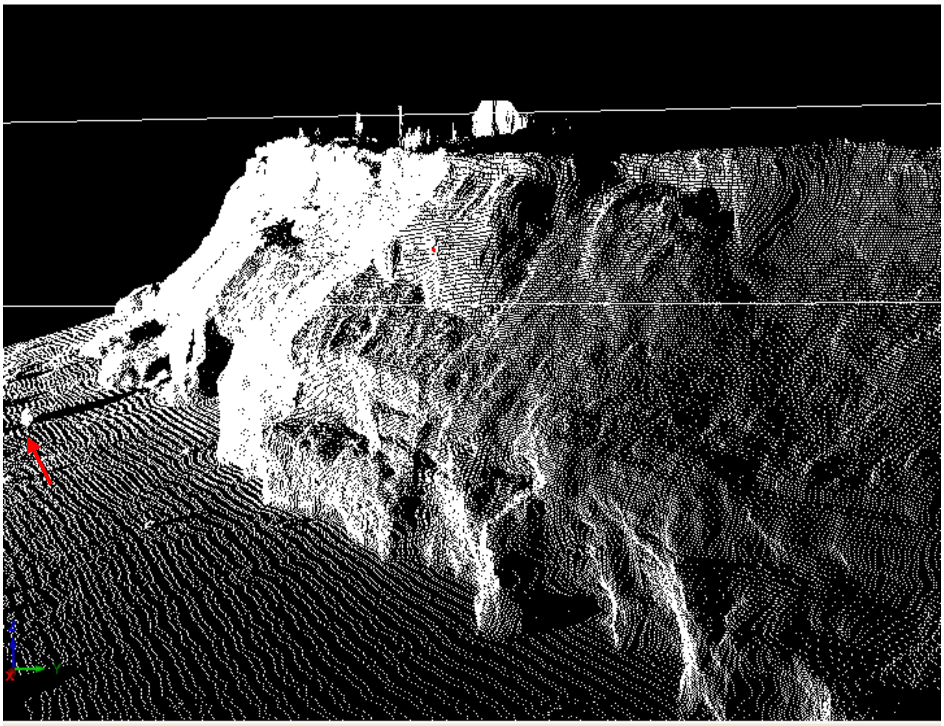

Figure 13 Side view of part of Scan A – 3D raw point-cloud (red arrow: boulder casting shadow)

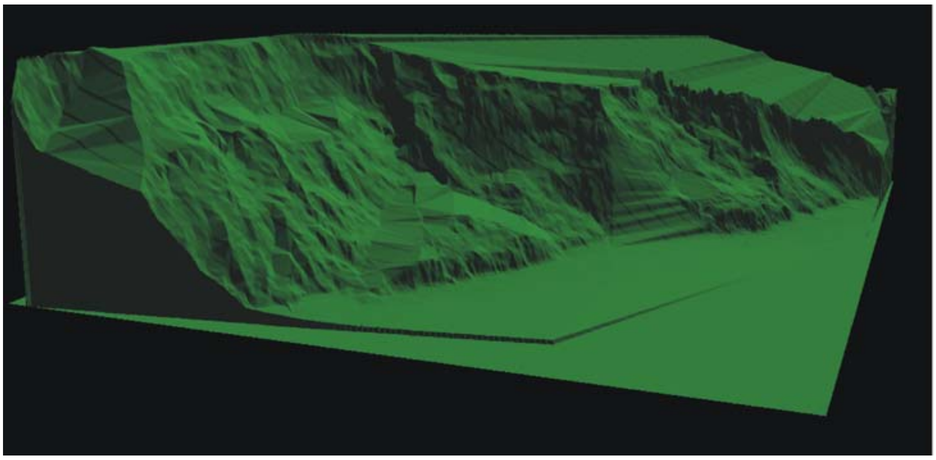

Figure 14 Scan B: triangulated surface model

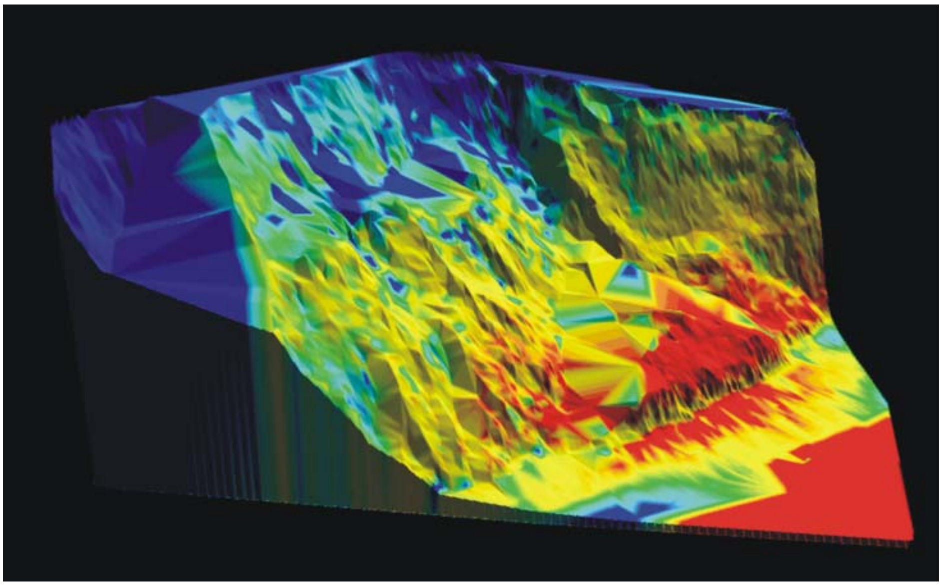

Figure 15 Scan B: elevation 'change' model for part of Scan B (refer to Figure 14) (red=height increase, blue=height decrease)

CHANGE MODELS

The 'Scan B' example shown in Figures 14 and 15 is of a cliff up to 50 m high on the North Yorkshire coast consisting of complex superficial deposits of till and other interlayered glacial deposits overlying folded and weak Speeton Clay Formation mudrocks. The 'change' model in Figure 15 shows the elevation difference between two solid 3D models, derived from scans taken one year apart. The resulting annual vertical displacement is coloured proportionately so that red is maximum ground level rise and blue is maximum ground level fall, though the two are not of equal magnitude. In terms of slope morphology the change model shows us that a debris flow at the toe of the cliff has accumulated material, the backscarp has lost material, and changes have occurred to the beach levels. Information in the area of the oversized polygons to the rear of the debris flow is probably unreliable. Again, the density and reliability of data are important factors when interpreting these change models (Miller et al., 2006).

When considering change models of coastal cliffs it is important to include the foreshore (platform and beach) as part of the same model as the cliff itself. This is for two reasons: firstly, the beach is a transient feature which may consist of both transported material and debris derived locally from the landslide. As such, support of the cliff toe and restriction of seepage are also transient features affecting the cliff itself. Secondly, a deep-seated landslide may have its slip surface extending below the level of the foreshore and hence the foreshore becomes directly involved in the movement. In the long-term, the erosion of the platform itself must be considered as part of the model (Walkden & Hall, 2005).

The methodology for producing 'change' models is very much dependent on the software packages available to the user, and can be achieved in a variety of ways and with variable effectiveness depending on the geometry of the subject. These usually involve more than one package, and possibly as many as four. Issues relating to the robustness of such models have been addressed by Miller et al. (2008).

CONCLUSIONS

In order to correctly interpret the terrestrial LiDAR change models described, a combination of models should be considered. These could include the elevation and range models (Figures 11 & 12), which can have their own change models derived so that the vertical and horizontal components of movement can be resolved. In its simplest form, a rock fall from a vertical cliff face represents a loss of material from the cliff face and an accretion of debris on the beach. However, a similar fall from the crest of an inclined cliff will result in accretion at mid-cliff. This might appear from an elevation change model alone as if caused by an uplift of strata, as for example at the toe of a rotational landslide, rather than a deposition of fallen debris. Subtle pre-cursor processes such as the opening of joints may produce apparent 'accretion' of the cliff face prior to failure and ultimate recession. Such small movements may or may not be resolved by the scan depending on the method and equipment used.

The basic 2D intensity model (Figure 7) is useful in distinguishing textures. This has a greater applicability to man-made structures and materials (e.g. concrete, metal, brick), but can still be useful for distinguishing the lithologies of strongly contrasting geomaterials. Laser scan models enhanced by calibrated digital photography (Figures 8 & 10) are a useful resource for the geoscientist, as the textures and colours greatly enhance the interpretation of lithology, structure, and geomorphology. This is of course further enhanced by the 3D capability, whereby the true geometry of coastal landslide and erosion features can be appreciated. Solid 3D models allow volumes and areas to be calculated either in relation to a planar datum or to a previous model. Thus, displaced volumes may be calculated and displaced masses estimated.

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