# VEHICLE BASED WAVEFORM LASER SCANNING IN A COASTAL ENVIRONMENT

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**ABSTRACT**

This paper presents the results of an investigation into the use of a waveform lidar system from a ground based vehicle. Data was collected using a Riegl LMS Q560 laser scanner mounted on the roof of a Landrover driven along a 7 km stretch of coastline at Filey Bay, North Yorkshire, UK. An IMU and differential GPS unit, part of IGI's AeroControl system, were used to provide measurement of sensor orientation and position. Data with an average spatial resolution of 20 cm was collected.

The coastline and intertidal zone are notoriously difficult to monitor given the limitations on activity imposed by the tide, extent of coastline, and the limited availability of reliable permanent control. Despite this, the coastal environment is an important asset, the condition of which often needs to be carefully monitored so as to improve the understanding of coastal processes and mechanisms which ultimately leads to improved management decisions and policies. Importantly, not only does the changing topography of coastal cliffs need to be monitored, but so does the profile of the beach and extent and type of vegetation. In many cases, the use of scattered, periodic measurements of coastal change has, therefore, been replaced with airborne survey using photography and/or airborne lidar which provide higher density geometric data. However, despite this, access to data with a high spatial and temporal resolution is still limited. A ground based rapid mapping survey solution may provide a more responsive solution and given the highly dynamic nature of the coastal environment, help to improve the understanding of coastal zone dynamics.

Data collection took around 15 minutes, emphasising the appropriateness of the technique to the survey of the coastal zone. This is substantially quicker than the time that would be required to collect comparable data from multiple scans using a conventional static terrestrial laser scanner. The acquired data was quantifiably compared against ground truth data collected within one day of the lidar survey, and also against existing airborne lidar and photogrammetric datasets from previous survey campaigns. The project also considered the potential advantages of using the full laser waveform to improve analysis, in particular in dealing with vegetation along the soft rock cliffs.

While the Filey Bay coastline was relatively well suited to the application of such a mobile mapping system, it is recognised that not all coastal sites would be the same. However, there are many other applications where the use of a ground based waveform lidar may be more useful than regular lidar alone, such as in the survey of vegetation along transport routes. This paper, therefore, contributes to the discussion on new methodologies for the rapid survey of linear features, helping to provide managers and engineers with a clearer view of dynamic environments in which it has previously been very difficult to survey using ground based surveying technology.

## 1. INTRODUCTION

Terrestrial laser scanning is becoming common in the survey of natural landforms (Rosser et al., 2005). Static ground-based laser scanners are, however, limited in the speed at which data capture can take place. This problem is exacerbated in the surveying of coastal areas where data collection might be required between tides or over long stretches of coastline. While airborne lidar systems (ALS) allow more rapid collection of terrain information over much larger areas, it can be difficult to deploy a system quickly as they are heavily reliant on favourable weather conditions and logistical constraints. When it is necessary to quantify change that might occur between short periods of time (for example between successive tides) or immediately after significant events (such as a major storm) neither technique provides a wholly satisfactory solution. To overcome some of these shortcomings, especially in corridor environments where data capture is required along a narrow strip (such as coastlines, rail or road networks), ground based laser scanners have been mounted on vehicles to increase the mobility of the sensor. When combined with GPS to provide position information so called 'rapid-static' laser scanning has been performed, increasing the speed at which a scanning survey can be undertaken (Rixon et al., 2003).

Other solutions, possibly with greater potential for rapid, responsive survey, have seen the combination of ground and airborne survey instrumentation to create ground based mobile mapping systems (MMS). These systems utilise the same navigation devices (inertial measurement units and GPS) and mapping sensors (digital camera, video systems, laser range finders or radar) as airborne platforms. Ellum and El-Sheimy (2002) identify 13 examples of MMS based on land vehicles dating back to 1991, which mainly rely on photogrammetric techniques for data capture. More recent examples have begun to utilise laser scanning sensors, also known as lidar, these include the GEOMOBIL system (Talaya et al., 2004), and the StreetMapper System offered by 3D Laser Mapping of Nottingham, UK (Streetmapper, 2006).

### 1.1 Aims and objectives

To investigate the utility of ground based MMS for the collection of high quality terrain information in the coastal zone a test dataset was collected in partnership with a commercial contractor. This study aimed to assess the accuracy, completeness and consistency of this dataset and derived DTMs against an independent control dataset and against an airborne lidar dataset of the same area. (For the purpose of demonstration the lidar system used included full waveform digitisation capability.)

This paper will describe the system deployed and briefly cover the nature of the test site. It will then outline the survey process and data processing stages (for both the ground based and airborne lidar surveys) before presenting the results of the comparison between surveyed check points and the airborne lidar. It will then discuss the issues surrounding the use of waveform data before providing a more general discussion on the use of mobile mapping in the coastal zone.

### 1.2 System description

In this study a Reigl LMS Q560 airborne lidar system with full waveform digitising capabilities was mounted on the roof of a 4x4 vehicle (Figure 1). This lidar sensor was used with a AEROcontrol GPS/IMU system from the German Company IGI mbh. This incorporates a dual frequency GPS system and a high grade 256 Hz IMU, which is quoted as providing 0.01 ° in heading and 0.004 ° in roll and pitch (Hug et al., 2004). A GPS receiver was sited at a local control station to provide the data required for the differential post-processing required to determine the vehicle trajectory. GPS processing was performed with GrafNav, while GPS and INS integration utilised IGI's AEROoffice software. The lidar system was supplied and operated by 3D Laser Mapping, Nottingham. Mounting of the system on the vehicle and the initial runs necessary to collect the data to calibrate and verify its operation took less than two hours and was completed on-site. The system was mounted looking to the right and behind the vehicle.


Figure 1. The lidar system mounted on the 4x4 vehicle.

### 1.3 System calibration

The entire system was mounted on a frame so the relationship between the GPS, IMU and laser profiler was fixed. Offsets between the sensors were measured by tape, while the orientation of the lidar system was determined by a calibration process. TerraSolid's TerraMatch was used to align overlapping lidar flight-lines to check points located on the cliff and beach. This process provided heading, roll and pitch corrections relating to the mounting angles of the laser profiler. These were used in subsequent data processing.

### 1.4 Test site

The coastal site chosen to test the system was Filey Bay, located 5 km to the south of the town of Scarborough, North Yorkshire, on the Eastern coast of the UK. 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. 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' (Elliot et al., 1991). It has been previously been subject to studies on the use of integrated geomatics techniques for coastal monitoring (Buckley et al., 2002; Mills et al., 2005) and recent survey data, including airborne lidar was available against which the MMS data could be compared.

## 2. METHODOLOGY

### 2.1 Survey description

Data collection with the MMS took place at low tide on the 26$^{th}$ June 2006. In order to initialise the inertial navigation system (INS) an initial speed of 25 mph was maintained along a 200 m stretch of flat beach. After this speed had been achieved the rest of the data collection was performed at 20 mph or less. The vehicle was driven along the beach keeping the toe of the soft cliffs at a distance of around 50 m. This provided a scan angle sufficient to survey the entire height of the cliff, although in some areas it was necessary to navigate around obstacles which required tight manoeuvring, shortening or lengthening this distance. Data collection along a 6.7 km stretch of the bay took around 15 minutes for a single pass. The collected waveform data was 4 GB in size, although the size of the processed point cloud, as delivered by the contactor in the ASPRS LAS format (Graham, 2005), was 550 MB and contained over 20 million data points. Table 1 outlines the typical point densities found in the LAS dataset.

| | Point density (points per m$^2$) |
|---|---|
| Beach | 70 |
| Cliff toe | 25 |
| Mid cliff | 15 |
| Top of cliff | 10 |

Table 1. Typical point densities within the dataset.

At each of two test sites (named CPK and HUN respectively) around 100 GPS survey points were collected on the cliff face and along the top and bottom of the cliff area. This provided an independent dataset against which the MMS data could be compared. The two test sites were located at opposite ends of the collected dataset. Test site CPK is located in the north of the bay with cliff heights of approximately 30 m. The soft cliff slopes are relatively shallow and, over stable areas, the cliff is covered by areas of small trees and bushes. Less stable areas of the cliff have no vegetation cover leaving only exposed earth. The base of the cliff has a 2 m high sub cliff made of exposed earth. Test site HUN is located 6 km to the south of CPK. It also has soft cliffs of up to 30 m in height, although the depth of the sloping cliff (the distance from the toe to the cliff-top edge) is larger than that at the CPK site. However, a small plateau is responsible for much of that depth, resulting in the HUN site actually having steeper cliffs than the CPK site. Vegetation cover is also less extensive and, where found, restricted to short grass only. Check points at both sites were selected on areas of exposed earth so they could be compared to the bare earth ground surface generated from the MMS dataset.

### 2.2 Data pre-processing

Initial pre-processing was undertaken by the commercial contractor, 3D Laser Mapping Ltd. Vehicle trajectory was determined using the locally operated base station at the CPK site (resulting in baseline lengths of no more than 6 km). On delivery, datasets covering the two test sites were extracted from the point clouds. Figure 2 shows a perspective view of the CPK dataset, while Figure 3 shows a close view of the remains of a small landslide (highlighted in Figure 2).

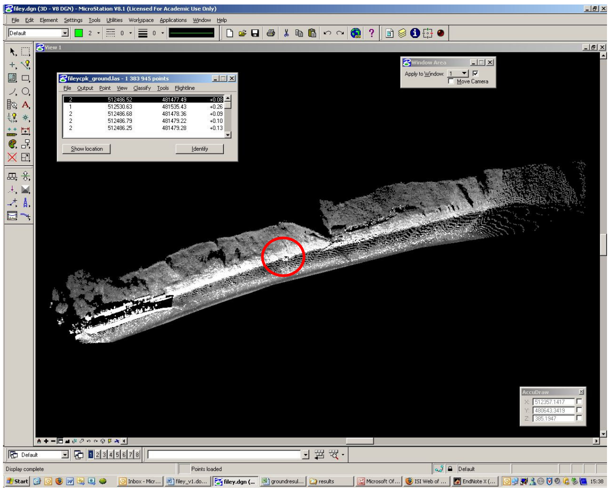

Figure 2. Data collected by the MMS for the CPK site (shaded by intensity).

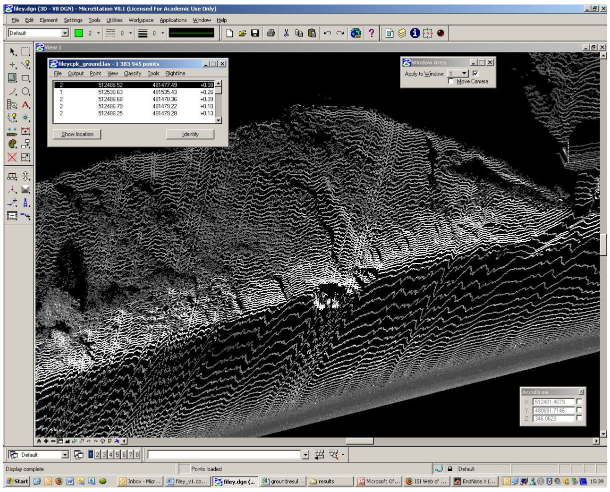

Figure 3. Data collected by the MMS for the CPK site (shaded by intensity).

Classification of the collected point data for each test site was required to determine a ground surface free from vegetation cover (Axelsson, 1999). This was carried using Terrasolid's lidar processing suite: TerraScan and TerraModel.

During pre-processing each point in the laser dataset is provided with a flag indicating it as:

- the only echo for a particular laser measurement;
- the first echo of many;
- the last echo of many;
- an intermediate return.

See Section 4 for how these flags were determined. Figure 4 shows data at the HUN site shaded by echo class. First, last or intermediate echoes (blue, green and yellow points respectively) are generally seen around areas of known vegetation. Point echo class was used in the classification procedure: first and intermediate echoes were classified as vegetation; last echoes and only echoes were classified as default; low points were then excluded from the default class; finally a ground surface was determined from the default class (TerraScan, 2005). The results of applying this procedure to the HUN test site are shown in Figure 5. To inspect the results of the classification, Terrascan's TerraModeler software was used to generate a surface model based on the determined ground points for each of the two test sites (Figure 6).

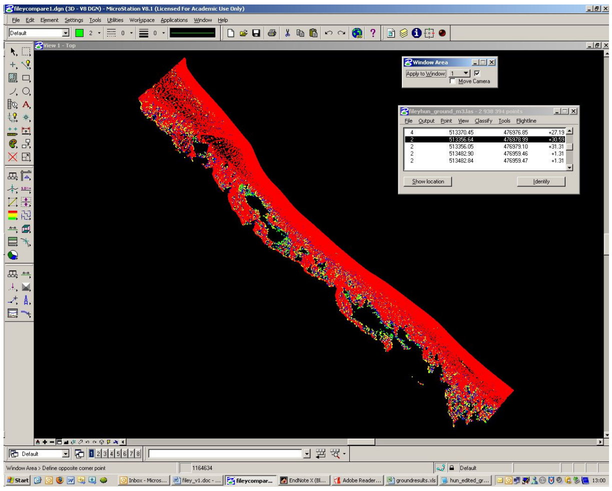

Figure 4. HUN test site shaded by point echo (red: only echo; blue: first echo; green: intermediate echo; yellow: last echo).

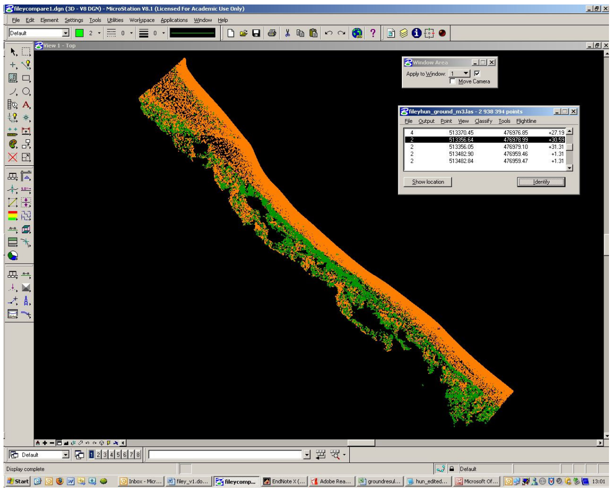

Figure 5. HUN test site shaded by point class after classification (orange: ground; green: vegetation).

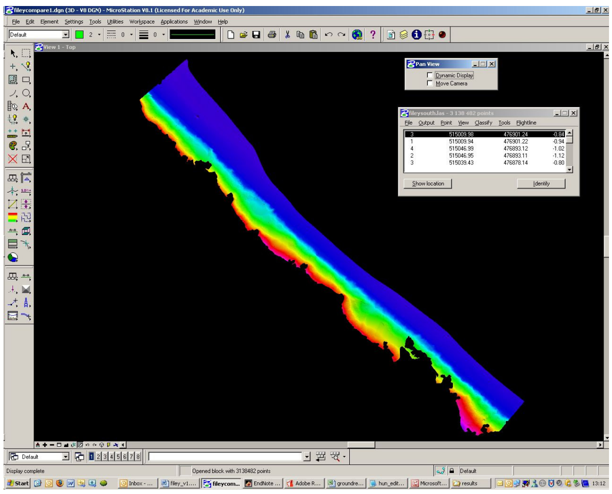

Figure 6. Surface model generated for the HUN test site shaded by elevation (blue: low; purple: high).

### 2.3 Airborne lidar

An airborne lidar dataset of around 15 million points, collected by the NERC Airborne Remote Sensing Facility approximately eight weeks prior to the ground based survey, was also available for the bay area. The data was collected with an Optech ALTM-3033, using an Ordnance Survey active GPS station located approximately 15 km away for differential processing. This dataset had an average point density of around 2 points per $m^2$ over the two test sites.

Prior to use, the airborne lidar data was classified in Terrasolid's Terrscan software in the same manner used to process the MMS data. The surface model generated from this data is shown in Figure 7. The ground points generated from this classification procedure were then validated against 803 pre-collected ground points collected on a road circuit located in the CPK test site. These check points were taken from an existing archive of survey data.

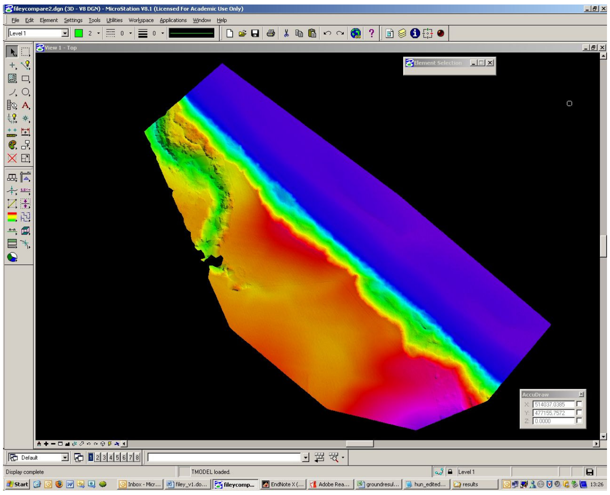

Figure 7. Surface model generate for the HUN test site from airborne lidar data coloured by elevation (blue: low; red: high).

The results of this comparison are provided in Table 2. With a root mean square (RMS) error of 0.103 m for elevation the airborne dataset was considered to be within the expected specification of the system and, therefore, suitable as a second validation dataset. Notably, such a dataset provides a continuous coverage, rather than the discrete points provided by the GPS survey.

| | |
|---|---|
| Std deviation (m) | 0.029 |
| Root mean square (m) | 0.103 |
| Minimum dz (m) | 0.020 |
| Maximum dz (m) | 0.200 |
| Mean dz (m) | 0.099 |

Table 2. Control point testing against 803 check points in the CPK area.

### 2.4 Validation methodology

Validation of the collected mobile mapping data was performed against the surveyed check points collected in the field using RTK GPS (estimated to have a 0.03 m in plan and 0.06 m in elevation). RTK GPS is increasingly used in the survey of natural landforms so knowing how a new data capture technique compares against it is of interest. The mobile data was also validated against surfaces generated from the airborne lidar survey.

Check point evaluation was performed in TerraScan, while comparison of the mobile mapping and airborne datasets was performed using the Land Survey System (LSS) from the McCarthy Taylor Partnership. Results were visualised and summarised in Matlab. Cross sections were also generated to compare the surfaces derived from the airborne datasets with the surfaces generated from data collected by the mobile mapping system.

## 3. RESULTS

### 3.1 Validation against collected survey check points

Table 3 provides summary statistics for the comparison of the ground based data against the collected checkpoints at each site.

| | CPK | HUN |
|---|---|---|
| Standard deviation (m) | 0.209 | 0.200 |
| Root mean square (m) | 0.222 | 0.267 |
| Minimum dz (m) | -0.423 | -0.595 |
| Maximum dz (m) | 0.511 | 0.644 |
| Mean dz (m) | 0.080 | 0.181 |
| Number of points | 37 | 26 |

Table 3 Mobile data compared against surveyed check points

Check points found to be at the edge of the dataset or the edge of data voids had to be excluded from this assessment as the quality of the triangulation at these locations was poor due to lack of data. Data voids resulted from occluded areas (caused perhaps by hollows in the cliff) or from obstacles such as thick vegetation obscuring the view of the cliff face.

Surveyed check points were collected in areas of bare earth only. While it would have been preferable to adopt a systematic approach to check point distribution, this was not possible. Both sites were, in places, too steep for access or vegetation would have prevented check points from being collected. Instead, check points were collected in a regular grid where terrain and surface cover allowed, in addition to significant breaklines.

### 3.2 Validation against airborne lidar

To provide a more complete assessment of the collected datasets the two test sites were compared with the recently collected airborne lidar available for the site (see Section 2.3). Table 4 provides a summary for the comparison made between the lidar data and the collected mobile mapping data.

| | CPK | HUN |
|---|---|---|
| Standard deviation (m) | 0.256 | 0.296 |
| Root mean square (m) | 0.261 | 0.298 |
| Minimum dz (m) | -2.622 | -2.881 |
| Maximum dz (m) | 1.157 | 1.706 |
| Mean dz (m) | -0.046 | 0.296 |

Table 4 Mobile data compared against airborne lidar data

These figures broadly agree with the assessment made against the surveyed check points with similar RMSE errors. Although, as might be expected given the increased number of samples, the minimum and maximum values are larger.

## 4. WAVEFORM DATA

Waveform laser scanning has received a lot of attention in recent years. Whereas previously the electronics of the lidar system have determined first and last pulse returns improvements to hardware and storage now allow for the digitisation of the entire returning waveform. This gives users the opportunity to better control the way in which significant pulses are determined during post-processing.

The motivation for using waveform data stems from a number of applications. Mainly those using relatively large footprints such as those collected by the Laser Vegetation Imaging System, dubbed LVIS (Blair et al., 1999), which provides footprints of between 10-100 m. In these cases the returning beam will, most likely, contain returns from a number of different targets including vegetation, buildings and water. Methods to detect significant pulses within the returns have been the subject of research to provide vegetation models, improved terrain modelling (for example for studies of hydrology) and near shore bathymetry.

The choice of waveform processing strategy has been shown to have an affect on the resulting DTM quality. Methods for peak detection include thresholding, centre of gravity, maximum, zero crossing of the second derivative, and constant fraction and are described in Wagner et al. (2004).

For the data collected in Filey the range values of each pulse on the waveform were determined using Riegl’s RiAnalyze software based on a Gauss Pulse Estimation technique. This aims to combine the execution time of a simple centre of gravity approach with the accuracy of Gaussian pulse fitting and provides the multiple returns described in Section 2.2.

In addition to improving the selection of points for mapping applications other uses for waveform data include determining the slope of the target surface, and surface parameters such as reflectivity and roughness, by considering the characteristics of the returning waveform (for example determining if any pulse widening was evident). Such features may be significant for geotechnical studies, for example in the coastal zone.

However, waveform laser scanning is not widely used and, at present, software for processing this type of data is largely developmental in nature. Also, in practice, operational issues have an impact on the usefulness of the data. In this case study two considerations are relevant. Firstly, the beam divergence of the Q560 laser scanner is 0.5 mrad, providing a footprint of 50 mm at 100 m range. This very small footprint will mean far fewer objects are within the measurement beam reducing the need to identify individual targets within the beam. Although, it is possible that vegetation could be present in this measurement footprint. However, the minimum target separation is around 0.5 m (Hug et al., 2004), meaning that individual targets within a footprint would need to be separated by at last this amount in order that they be detected. Based on this assessment, and considering the likely make up of the cliffs in the test site (largely covered by short vegetation) it is unlikely that significant improvements would be expected from the use of waveform digitising. However, from inspection of the collected data there are examples where significant targets can be identified. In this example the use of the Q560 system has allowed additional points to be determined, helping to define vegetation more fully and provide additional ground points in areas occluded by vegetation (see Figure 8 and Figure 9).

Use of waveform systems in the future will need to consider other issues, including archiving strategies: waveform data formats are proprietary in nature and very large in size.

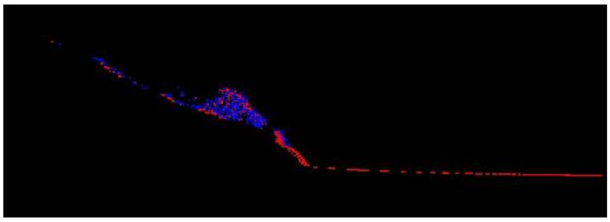

Figure 8. Only/first pulse data in an area of vegetation.

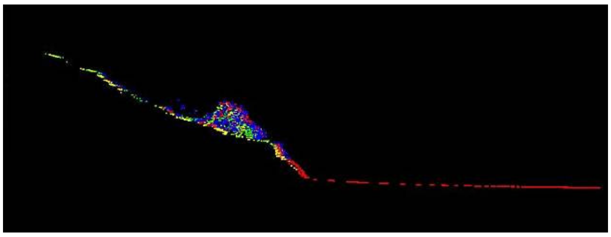

Figure 9. All data determined from the full waveform.

## 5. DISCUSSION

Clearly one of the biggest limitations to using a ground based system to collect detailed models of coastal cliffs is the limitations imposed on coverage and access. Not all areas on the cliff, especially at the HUN site where the cliff angle is quite shallow, are visible from a vehicle driving along the beach. Also, while coverage of the toe of the cliff face is likely to be very good, delineation of the cliff-top may not be straightforward using MMS data alone.

This is also the case where man made structures (such as structures on the seafront of Filey town) occlude the measurement beam. While it may be possible to provide additional data in some areas (for example by driving the vehicle along the promenade) it will not be possible to drive the vehicle along the length of the cliff top. Although the coverage is likely to improve for steeper cliffs, in general, to be able to generate a complete model, fill-in data from other techniques is likely to be required.

However, coverage of the beach itself and of the toe of the cliff is generally unobstructed given the height of the vehicle and the relative height of any beach undulations. In coastal morphology applications requiring a number of accurate beach profiles within a single tide such a system may be invaluable.

The second limitation to the generic use of such a system is the access restrictions to a site. While access to the beach at Filey is straightforward and the beach surface is firm enough to allow easy driving, other beaches may have costal defences or coastal management which obstruct a vehicle, or have a surface unsuitable for driving such as loose rocks. This may be solved by use of another type of vehicle, but it is unlikely that the delicate laser scanner would react well to rough terrain.

The data collected for this study was limited to a single pass of the survey vehicle. As the system was mounted to observe to the right of the vehicle, features orientated towards the oncoming vehicle were not recorded. A second pass in the opposite direction would have been required to fully scan the cliff face. This was not possible during the data collection period as the sensor would have to have been remounted. In practical terms the need for a second pass could only be avoided by mounting a second profile to simultaneously collect data in front of the vehicle or a second scanner mounted to the left and behind.

Finally, the success of the point classification is likely to have a significant affect on the parity between the collected datasets and the actual cliff face. Further work to validate the classification of point data, in particular in heavily vegetated areas is required. The methodologies employed for determining multiple echoes from individual ranging measurements is also an important factor. While the use of a waveform digitising system has allowed additional points to be measured in areas of vegetation, further work is required to establish the usefulness of the waveform data in this application and the practical differences between processing strategies.

## 6. CONCLUSIONS

The study has demonstrated the collection of laser scanning from a moving platform in the coastal zone. It has compared this data with control data and an airborne lidar dataset. After removing an offset between the datasets the ground based data was shown to have an RMS error of around 0.26 m in elevation. While further work is required to investigate this error further, the study has shown the potential for mobile systems in coastal areas, especially for the collection of detailed beach surface information and profiles of lower cliffs most vulnerable to the action of the waves. The system clearly complements the airborne data which may be collected at a lower spatial resolution and less often. The ease of deployment of such as system is one of its greatest benefits and may be of particular use in scientific studies where data with a high temporal resolution is required.

If coastal engineers, developers and planners can be given a more detailed view of coastal changes it will lead to an improved understanding of the mechanisms and processes involved. This will help to prioritise coastal defence schemes and improve decision making, improving the certainty for land/property owners living along the coastline. While a MMS is unable to provide a complete picture of coastal change it complements existing methods, especially ALS.

Further work arising from this study can be summarised as:

- Investigation and validation of point cloud classification routines, in particular those used for vegetation extraction.
- Consideration of interpolation errors on the data.
- Examination of the collected waveform data.
- Systems for the independent validation of captured data should be used (such as a photogrammetric measurements) for simultaneous data validation.

## 7. ACKNOWLEDGEMENTS

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