

## Letters to ESEX

# Ultra-rapid topographic surveying for complex environments: the hand-held mobile laser scanner (HMLS)

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# ESPL

Earth Surface Processes and Landforms

**ABSTRACT:** Terrestrial laser scanning is the current technique of choice for acquiring high resolution topographic data at the site scale (i.e. over tens to hundreds of metres), for accurate volume measurements or process modelling. However, in regions of complex topography with multiple local horizons, restricted lines of sight significantly hinder use of such tripod-based instruments by requiring multiple setups to achieve full coverage of the area. We demonstrate a novel hand-held mobile laser scanning technique that offers particular promise for site-scale topographic surveys of complex environments. To carry out a survey, the hand-held mobile laser scanner (HMLS) is walked across a site, mapping around the surveyor continuously *en route*. We assess the accuracy of HMLS data by comparing survey results from an eroding coastal cliff site with those acquired by a state-of-the-art terrestrial laser scanner (TLS) and also with the results of a photo-survey, processed by structure from motion and multi-view stereo (SfM-MVS) algorithms. HMLS data are shown to have a root mean square (RMS) difference to the benchmark TLS data of 20 mm, not dissimilar to that of the SfM-MVS survey (18 mm). The efficiency of the HMLS system in complex terrain is demonstrated by acquiring topographic data covering ~780 m<sup>2</sup> of salt-marsh gullies, with a mean point spacing of 4.4 cm, in approximately six minutes. We estimate that HMLS surveying of gullies is approximately 40 times faster than using a TLS and six times faster than using SfM-MVS. © 2013 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

**KEYWORDS:** HMLS; topographic survey; DEM, gullies; laser scanning

## Introduction

Many geomorphological studies have some form of topographic measurement at their heart. When kilometres of coverage are required, airborne instruments are usually used, resulting in data with metre-scale spatial resolutions and vertical accuracies generally of a few tens of centimetres. However, over the more limited distances of the site scale (e.g. tens to hundreds of metres), surveys have historically been carried out on the ground, initially with levels and theodolites, and now with total stations. Satellite navigation systems [e.g. Global Positioning System (GPS), Global Navigation Satellite System (GLONASS)] have also added to the geomorphologist's armory, allowing survey work to be easily positioned within a global coordinate system. Although such methods provide good accuracy and precision for the measurement of individual points, significant time is required to collect a sufficient density of data for useful digital elevation models (DEMs) of the landscape to be produced.

Site-scale high resolution DEMs are now routinely produced using ground-based terrestrial laser scanners (TLSs) to provide dense data sets, often with millions of individual measurements at millimetre-to-centimetre accuracies (e.g. Heritage and

Hetherington, 2007). However, laser-based measurements require line of sight and, with TLS systems being tripod-mounted, this can significantly increase survey times in complex topographic environments. In such scenarios, with few vantage points from which large proportions of the project site are observable, multiple scan positions must be used to cover the full area required. Consequently, time-consuming instrument repositioning must be repeatedly carried out and the complexity of the subsequent data processing is also increased.

Advances in the mobile collection of topographic data have been made through the use of ground-based (James *et al.*, 2007; Bird *et al.*, 2010; Gessesse *et al.*, 2010) or aerial consumer cameras [e.g. on kites or unmanned aerial vehicles (UAVs), Marzolf and Poesen, 2009; d'Oleire-Oltmanns *et al.*, 2012; Niethammer *et al.*, 2012; Hugenholtz *et al.*, 2013]. Airborne systems provide synoptic views that facilitate coverage of difficult terrain, but factors such as the required piloting skill have hindered early mass adoption of UAV technology. Nevertheless, successful trials are now being also carried out with UAV-mounted laser scanners and even range cameras (Kohoutek and Eisenbeiss, 2012). Most recently, DEM-generation from both ground and aerial photographs has been

facilitated through the application of structure from motion (SfM) and multi-view stereo (MVS) three-dimensional (3D) processing algorithms (Niethammer *et al.*, 2010; Castillo *et al.*, 2012; Harwin and Lucieer, 2012; James and Robson, 2012; James and Varley, 2012; Fonstad *et al.*, 2013). SfM-MVS surveys have been demonstrated to be capable of precisions  $\sim 1/1000$  of the observation distance (James and Robson, 2012) so, over metres to tens of metres, they can deliver data of comparable accuracy (millimetres to centimetres) to TLS systems. In complex terrain such as gullies, the rapid photograph collection required for SfM-MVS has shown it to be a highly cost effective technique with respect to TLS use (Castillo *et al.*, 2012). However, SfM-MVS approaches do require effort to scale and georeference the resulting models, and difficult illumination conditions can be a challenge for all photo-based techniques (Gimenez *et al.*, 2009).

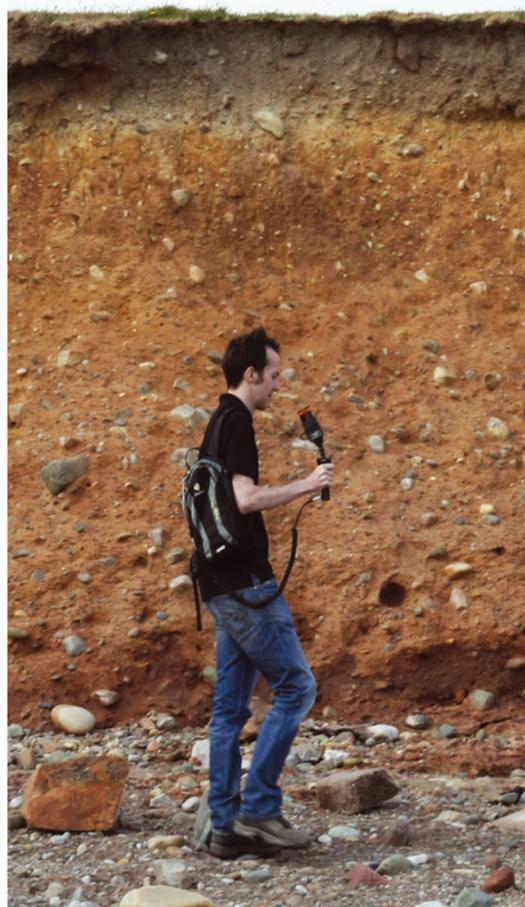
Here we evaluate a new ground-based approach using a hand-held mobile laser scanner (HMLS) that represents a significant advance in our ability to collect topographic data in complex terrains by combining the inherent scale and reliability of laser techniques with the flexibility of on-foot surveying and a delivered data density typical of scanning systems. With a maximum laser range of 30 m, the HMLS is designed as an area scanner and can be distinguished from hand-held 'object' scanners [which typically use a structured light measurement approach and have ranges of up to 1–5 m, e.g. Mantis Vision's MVC-F5, or see Mankoff and Russo (2013) for similar application of the Kinect].

To carry out a survey, the HMLS is walked around the site, capturing a swath of data up to  $\sim 30$  m wide, *en route*. In this way, convoluted topography can be effectively surveyed at walking speed, with the surveyor simply following a path which allows all required areas to be observed from some point along it. Automated 3D scene reconstruction from the resulting data is carried out using sophisticated simultaneous localization and mapping (SLAM) algorithms which simultaneously compute the full instrument path and a point cloud of surface measurements. The HMLS system works best in enclosed environments where static surface features fully surround the sensor and provide well distributed, consistent laser returns to facilitate convergence in the processing algorithms (e.g. indoors, surrounded by walls, floor and ceiling). In contrast, outdoor environments are characterized by surfaces that can be highly irregular, covered with vegetation and seldom 'surround' an observer, and thus represent much more challenging applications for reconstruction. For technical details on the novel SLAM algorithms developed, as well as mobile mapping test results from early versions of the system, the interested reader is referred to the robotics literature (Bosse *et al.*, 2012; Bosse and Zlot, 2013). With an instrument cost of  $\sim$  £14k, the HMLS is affordable for a laser-based system, but its use is associated with additional charges for the required online SLAM processing, which represent of the order of £200 per kilometre of surveyor path.

In this article we validate the accuracy of a HMLS for outdoor topographic surveying suitable for geomorphological applications, and demonstrate its utility in complex terrain. Using a coastal cliff site, we compare a HMLS survey with benchmark data from a state-of-the-art TLS. A simultaneous SfM-MVS survey was also carried out, allowing the relative performance of two new techniques to be directly assessed. We then demonstrate HMLS use in more complex topography by surveying a region of multiple salt-marsh gullies, where tripod-based scanning would be laborious.

## Method and Data Collection

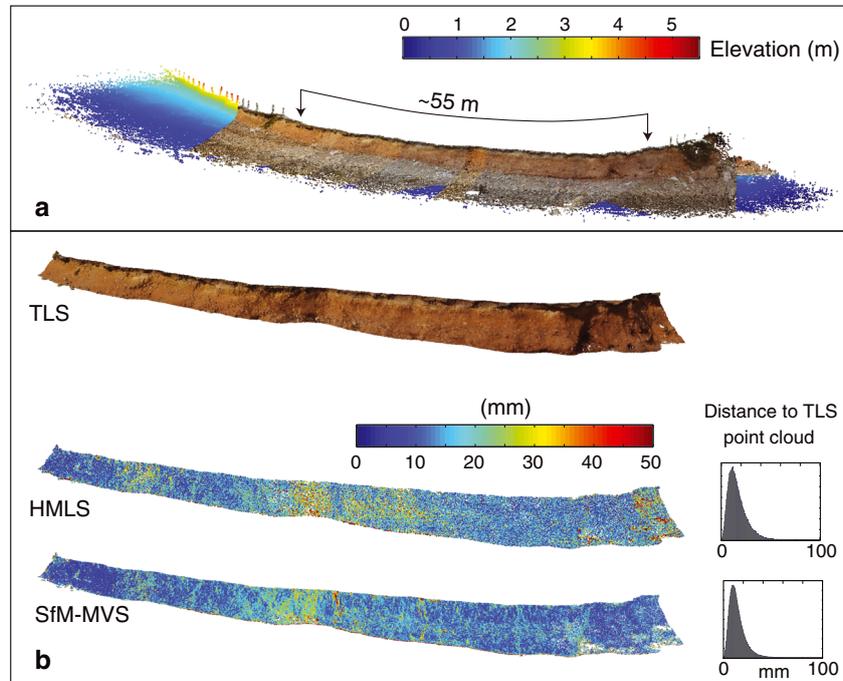
The HMLS instrument, the Zeb1, is a hand-held scanner (0.7 kg) linked to a netbook computer or, on the most recent version, just a data logger (see Figure 1 for the entire system



**Figure 1.** The Zeb1 hand-held mobile laser scanner (HMLS) in use at the coastal cliff site Sunderland Point, UK.

in use). There are no significant power requirements and, with typical usage represented by repeated  $\sim 20$ -minute surveys, a full day of work can be carried out prior to recharging. The scanner comprises a scan head (with an inertial navigation system and an eye-safe laser giving 43 200 measurements per second), spring-mounted on a hand grip (Bosse *et al.*, 2012). To carry out a survey, the system is initialized and logging is started with the scanner initially lying stationary. After a calibration period of  $\sim 15$  seconds, the survey is executed by moving at walking speed whilst gently oscillating the Zeb1 scan head backward and forward to capture data from the full 3D environment. The laser specifications cite a 30-m measurement range, but this is unlikely to be achieved outdoors (due to ambient solar radiation), and a survey swath of up to  $\sim 15$  m around the instrument is more realistic. To facilitate accurate reconstruction and avoid problems associated with drift, the survey path should form a closed loop, so that the same region is covered at the beginning and the end of the path. When collection is complete, the data are uploaded for automatic processing by a remote server, which integrates the laser and inertial navigation data and normally delivers the results in a similar time to that taken for the initial walking survey. The processed data are returned as a 3D point cloud model, with a manufacturer-cited accuracy of 30 mm, that can be viewed and analysed in any generic point cloud processing software.

The site used to verify Zeb1 performance under outdoor conditions was a 2–3 m high,  $\sim 55$ -m long coastal cliff at Sunderland Point, UK (Figure 2), with easy low tide access around the cliff base. The HMLS survey was carried out by the surveyor walking along the foot of the cliff, and back again to close the survey loop. The TLS data were acquired



**Figure 2.** Topographic measurement of the cliff face. (a) The full 3D point cloud from the HMLS survey; for visualization purposes, some points have been shaded from the photographs acquired for the simultaneous Sfm-MVS survey. The remaining data are shaded by their elevation (above an arbitrary datum). The arrows highlight the cliff section selected for comparison of the HMLS and Sfm-MVS surveys with the benchmark TLS data (b). Differences are determined by calculating point-to-point distances, and are shown by the shading in the point clouds and by the histograms (see Table I for statistical values).

from two locations, 20–40 m from the curved cliff face, using a Riegl VZ-1000 (with range measurement accuracy and precision specifications of 8 and 5 mm, respectively). The TLS data were combined within Riegl's RiScan Pro software (v 1.7.7) to form the benchmark point cloud dataset. Finally, the Sfm-MVS photo-survey comprised taking 87 photographs of the cliff section from distances of ~20–30 m, and using automated processing to derive a point cloud model. Protocols for photograph acquisition at this site, and the associated processing procedures, are described in James and Robson (2012), where the same Sfm-MVS approach was used to derive erosion rates.

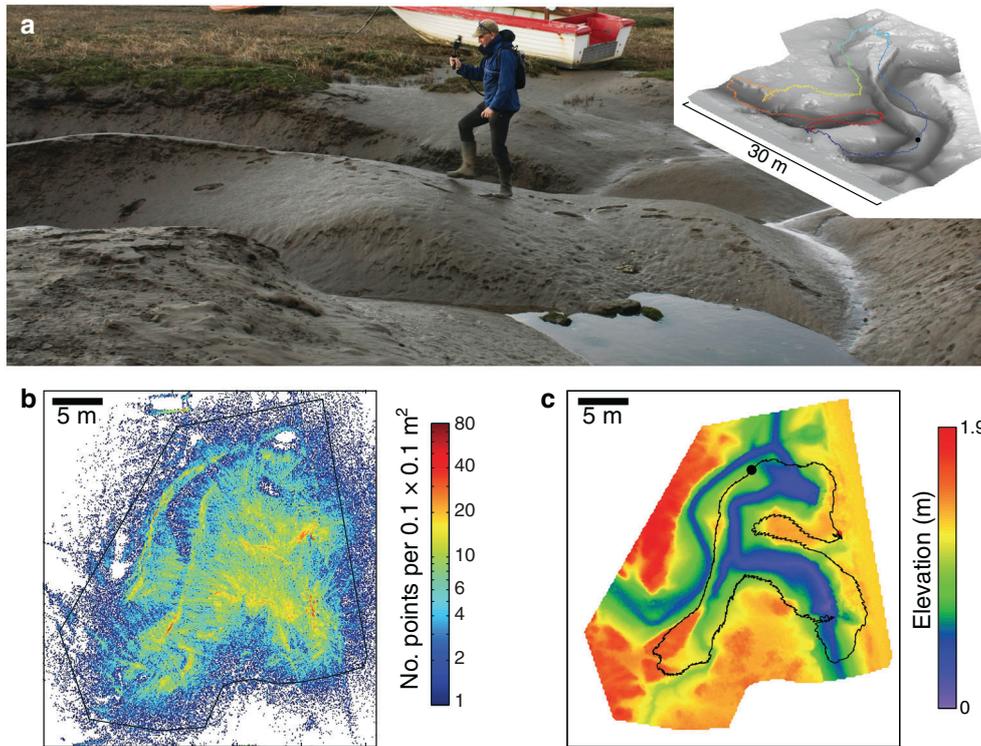
The HMLS and Sfm-MVS data sets were then registered to the TLS model. For the HMLS data, this was initially carried out in RiScan Pro software by refining a manual alignment of the HMLS model to the TLS data with RiScan Pro's automated multi-station adjustment. Sfm-MVS data required both scaling and georeferencing, which was carried out with *sfm\_georef* software (James and Robson, 2012), using coordinates of fence and groyne posts identified in the TLS survey as control points, and deriving the equivalent locations from the image set. All point clouds were then cropped to the cliff face region of interest (Figure 2b) and alignment to the TLS data was optimized by using an iterative closest point procedure in Cloud Compare (<http://www.danielgm.net/cc/>). Differences between the surveys were then determined by calculating nearest neighbour point-to-point distances (for each point in a survey, the 3D distance between it and the closest point in the TLS cloud).

Although the cliff site provided the opportunity for a detailed assessment of Zeb1 accuracy in an outdoor environment, it does not represent a site with particularly complex topography (e.g. it could be surveyed completely by the TLS from two scan positions). Thus, to demonstrate HMLS use in a more difficult environment, a nearby region of sinuous salt-marsh gullies (Figure 3a) was also surveyed with the Zeb1. At this site, the surveyor travelled an irregular looped path along the crests between gullies (Figure 3), covering an area of approximately 25 m × 30 m.

## Results and Discussion

The characteristics of the cliff surveys are given in Table I. As anticipated, the TLS survey took longest to carry out, with both the HMLS and Sfm-MVS data collection taking less than 10 minutes each. The HMLS survey was the most rapid (despite the surveyor covering a longer path than was actually required) because a steady walking pace was maintained, in contrast to the stop-start nature required for the Sfm-MVS photograph acquisition. For all techniques, the point densities acquired could be varied by changing acquisition (e.g. walking speed for HMLS use) or processing parameters, but nominal or default values were selected to give overall representative results (Table I). The point-to-point differences calculated between the surveys and the TLS data show that the HMLS data are similar in accuracy to those from Sfm-MVS (Figure 2b), with root mean square (RMS) differences of 20 and 18 mm, respectively. With such values being close to the accuracy (8 mm) and precision (5 mm) of VZ-1000 range measurements, it is difficult to extract significantly more detail from the comparisons. However, the HMLS results appear slightly more noisy, which is reflected in the broader tail of the error distributions (Table I, Figure 2b), with 98.0% of data lying within 5 mm of the TLS results, compared to 99.0% for Sfm-MVS.

For both Sfm-MVS and mobile scanning, instrument position is initially determined incrementally, so error accumulation can potentially cause drift along surveys. For the Zeb1, survey design (with start and end at the same location) minimizes the potential for drift, with the processing algorithms automatically closing the loop through matching the initial and final 3D scenes together. At the cliff site, the out-and-back survey would allow any problems to be identified by the apparent appearance of twinned, parallel surfaces in the resulting data, which were not observed. Some areas of systematic offset from the TLS data are observable midway along the cliff, but these differences are similar for both HMLS and Sfm-MVS surveys, suggesting a cause other than drift (which would have little



**Figure 3.** HMLS survey of complex tidal salt-marsh region. The surveyor (a) walked an irregular looped path along crests between gullies and the resulting point cloud data were used to derive a 0.1-m-resolution DEM (illustrated by the inset oblique hill-shaded relief map). In (b), the variation in x–y measurement point density across the region is shown, with the black line giving the region of the DEM (c). The path of the Zeb1 scan head is shown by the irregular line overlays in (c) and (a, inset), with the position of the surveyor in (a) indicated by the filled black circle. The linear region of flat topography [next to the length scale in (a, inset)] is a road that abuts the gullies.

**Table I.** Survey characteristics for the analysed region of cliff face (Figure 2) at Sunderland Point

	Technique		
	TLS	HMLS	SfM-MVS
Instrument	Riegl VZ-1000	3D Laser Mapping Zeb1	Canon EOS 450D, 28 mm lens
Survey time (minutes)	~30–40 <sup>a</sup>	6.3	8
Number data points (k)	797	120	449
Approximate point spacing (mm)	13	34	17
Point-to-point distances to TLS (mm):			
RMS		20.2	17.8
Mean		16.9	14.4
Median		14.4	12.2
Interquartile range		11.5	9.3

<sup>a</sup>The longer time includes that taken to collect photographs with the scanner. These enable the point cloud to be coloured but are not an absolute requirement for topographic measurement.

reason to be expressed similarly in both datasets). It is thus possible that these differences actually reflect an issue in the TLS data (e.g. some bias effect on inclined surfaces).

At the gully site (Figure 3), the ~110 m survey path was traversed with the HMLS (over slippery mud) in just over six minutes, generating 433 k data points and a ~780 m<sup>2</sup> core region of dense data coverage (399 k points, an average point spacing of 44 mm), allowing a 0.1-m-resolution DEM to be constructed (Figures 3b and 3c). When using laser systems, the presence of water surfaces can provide problems with reflections, but the Zeb1 results appear remarkably clean – only a minor amount of post-processing was carried out to remove returns from spectators on the periphery of the survey. Data from the region of water seen in Figure 3a are at a lower density than those from solid terrain, but suggest that the Zeb1 was successfully receiving some returns from the water surface. Other notable areas of low data density are from

vegetated regions, which are known to present complexities when using either laser-based systems (Coveney and Fotheringham, 2011) or photo-based techniques (Gessesse *et al.*, 2010; Castillo *et al.*, 2012; Fonstad *et al.*, 2013). It is emphasized that surface relief and the consistency of laser returns (e.g. from non-vegetated areas) are integral to the performance of the SLAM algorithms that derive the 3D geometry. Thus, although surveys in flat or heavily vegetated areas are possible (Bosse *et al.*, 2012), they are likely to be significantly reduced in accuracy, and other measurement techniques may be more appropriate.

The efficiency of the HMLS data collection compares favourably with those previously determined for TLS and SfM-MVS surveying of erosion gullies. Based on a sinuous gully near Cordoba, Spain, Castillo *et al.* (2012) estimated that, for a 100-m long gully reach, practical field data collection with a TLS requires ~8.3 minutes per metre of gully (i.e. including

instrument setup times etc.). SfM-MVS data collection was approximately six times faster, at 1.3 minutes per metre (Castillo *et al.*, 2012). In comparison, and using an estimate of a 400 m return path required to cover a 100-m-long sinuous gully reach, along with the average rate of approximately five minutes per 100 m of survey path that we achieved on the salt marsh, data collection with an HMLS would take 20 minutes, or 0.2 minutes per metre. We anticipate this to be somewhat conservative but, nevertheless, it suggests that gully surveys with a HMLS could be 40 times faster than with a TLS and six times faster than using SfM-MVS. This efficiency implies that, even with the associated online data processing charges, HMLS would represent a cost effective survey technique.

## Conclusions

New HMLS technology offers significant advance over currently available techniques for rapid survey of complex topography that exhibits poor line-of-sight coverage, and is commonly the subject of geomorphological study. Although the HMLS does not yet quite deliver the data density or accuracy of modern TLS instruments, its convenience will make it a highly practical surveying solution for difficult environments. When centimetre-level topographic data are required over distances of the order of hundreds of metres (or less), HMLS should join SfM-MVS as a technique to consider when planning future surveys. For complex linear features such as gullies, field data collection with a HMLS is expected to be approximately 40 times quicker than with a TLS, and six times quicker than using SfM-MVS. With good viewing conditions, SfM-MVS can deliver greater data densities and slightly greater accuracies, but HMLS may be favoured for delivering scaled models independent of lighting conditions, faster, and with minimal data processing requirements for the user.

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