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# The use of high-resolution field laser scanning for mapping surface topography in fluvial systems

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**Abstract** Advances in spatial analytical software allow digital elevation models (DEMs) to be produced which accurately represent landform surface variability and offer an important opportunity to measure and monitor morphological change and sediment transfer across a variety of spatial scales. Many of the techniques presently employed (aerial LIDAR, EDM theodolites, GPS, photogrammetry) suffer coverage or resolution limitations resulting in a trade off between spatial coverage and morphologic detail captured. This issue is particularly important when rates of spatial and temporal change are considered for fluvial systems. This paper describes the field and processing techniques required for oblique laser scanning to acquire 0.01-m resolution digital elevation data of an upland reach of the River Wharfe in the UK. The study site is variable with rapidly changing morphology, diverse vegetation and the presence of water, and these are evaluated with respect to DEM accuracy. Issues regarding location, frequency and distance are discussed with reference to survey accuracy and efficiency for the scanner, and a field protocol is proposed. Data cloud merging was achieved with a high degree of accuracy (sub-centimetre) and scanner accuracy is shown to be very good for exposed surfaces. Vegetation and water decrease the accuracy, as the laser pulse is often prevented from reaching the ground surface or is not returned.

**Key words** field survey; lidar; oblique laser scanning; reach scale mapping; River Wharfe, UK

## INTRODUCTION

Recent advances in spatial analytical software now allow the construction of digital elevation models (DEMs) which accurately represent landform surface variability and offer an excellent opportunity to measure and monitor morphological change across a variety of spatial scales (Brasington *et al.*, 2000; Fuller *et al.*, 2005). The development of increasingly sophisticated field survey equipment (aerial LIDAR, EDM theodolites, GPS, photogrammetry) has enabled an attendant increase in the volume of data collected in the field, allowing production of interpolated DEMs of the fluvial environment (e.g. Lane *et al.*, 1994; Milne & Sear, 1997; Heritage *et al.*, 1998; Brasington *et al.*, 2000; Fuller *et al.*, 2005). Many of these techniques suffer coverage or resolution limitations resulting in a trade off between area surveyed and morphologic detail captured. This issue is particularly important when viewed alongside the high spatial variability and often rapid temporal rate of morphologic change occurring in fluvial systems.

At a reach scale the acquisition of high-resolution topographic information is central to the effective construction of a DEM (Westaway *et al.*, 2000). Oblique field-based laser scanning (LIDAR) now offers a significant improvement in the speed accuracy resolution and areal coverage of topographic data acquisition. Nagihara *et al.* (2004) have demonstrated the utility of the new technique in acquiring a high resolution (0.1 m average point spacing) topographic data set of a 400 $m^2$ area of a barchan dune, achieving an accuracy of 6 mm. The acquisition of similar fluvial data sets opens up major new opportunities to investigate morphology and processes acting over a range of scales, since issues concerning operator bias and interpolation error would be significantly reduced. The resolution and accuracy requirements of Westaway *et al.* (2000) are a step closer to reality using the new technique.

This paper describes the field and processing techniques used to acquire 0.01-m resolution digital elevation data of an upland reach of the River Wharfe, UK. The study site is highly variable, allowing issues of rapidly changing morphology, diverse vegetation and the presence of water to be evaluated. Issues regarding scan location, frequency and distance are discussed with reference to survey accuracy and efficiency and a field protocol is proposed. Issues around the merging of large data clouds are addressed and suggestions are made concerning the value of the raw and processed data sets in relation to roughness characterization, channel change and fluvial processes.

## FIELD SITE

The study site at Highhouses on the River Wharfe, North Yorkshire, England, comprises a 150 m straight reach flowing over limestone that may be divided into an upstream gravel-cobble bed grading into cobbles and boulders before flowing over smooth bedrock downstream (Fig. 1). The channel width is fairly uniform at around 12 m ± 1 m and has a natural boundary along most of its length. Flow in the river at the study site is not permanently gauged; however, a rated section of the bedrock sub-reach indicates that "bankfull flow" occurs at around 25 $m^3 s^{-1}$. Flow in the channel may cease during dryer periods in the summer, leaving only a few small pools of water and exposing much of the bed.

## DATA COLLECTION

The channel and the surrounding confined floodplain were surveyed over a period of two days in August 2003 when the river had stopped flowing. The Riegl LMS Z210 scanning laser was used to collect a series of independent data sets recording range distance, relative height, surface colour and reflectivity. The instrument works on the principle of "time of flight" measurement using a pulsed eye-safe infrared laser source (0.9 μm wavelength) emitted in precisely defined angular directions controlled by a spinning mirror arrangement. A sensor records the time taken for light to be reflected from the incident surface. The scanner unit is mounted on a tripod and is then capable of scanning through 80° in the vertical and 330° in the horizontal, stepping 0.072° to 0.36° depending on the resolution required and the time available for scanning. Vertical scanning rates vary between 5 and 32 scans $s^{-1}$. Angular measurements are recorded to an accuracy of 0.036° in the vertical and 0.018° in the horizontal. Range error is up to 0.025 m to a radial distance of 350 m.

A series of high resolution scans were carried out in the centre of the study channel upstream and along the right and left bank ensuring substantial scan overlap. The effect of this approach is to increase the point resolution across the surface and reduce the possibility of unscanned areas due to the shadowing effect of roughness elements along the line of each scan. Mounting the scanner as high as possible above the surface being scanned also reduces the problem of shadowed areas.

## EXTRACTION OF 3-D TERRAIN DATA

Data from individual scans must be merged to a single project co-ordinate system to generate the primary digital elevation model (DEM) data. This was achieved using fixed points with known project co-ordinates as defined by theodolite survey. The RiScan software allowed visualization of each scan data cloud permitting identification of the tie points. The scanner co-ordinate system was then re-registered to the project co-ordinates. Generally reorientation accuracy was less than 0.01 m (Table 1).

The resultant meshed set of laser scans were clipped to remove unwanted peripheral information. The final data set of some 22 million points covers a channel and overbank area of roughly 150 m × 15 m surveyed at an average 1-cm resolution (Fig. 1(a)). Such a data set is able to capture detail of the riverbed gravels ($D_{50}$ = 0.16 m, $D_{84}$ = 0.27 m), bedrock surface and vegetation character (Fig. 1(b) and (c)) and represents the most detailed reach scale topographic survey of a river channel conducted to date.

**Table 1** Error in scan cloud merging using visually identified tiepoints for the River Wharfe at Highhouses.

| | Average tiepoint error: | | |
|---|---|---|---|
| | *x* | *y* | *z* |
| Mean | –0.0176 | –0.00011 | 0.001078 |
| Standard error | 0.002014 | 0.004054 | 0.001856 |
| Median | –0.013 | 0 | 0.001 |
| Standard deviation | 0.015983 | 0.032429 | 0.014846 |
| Sample variance | 0.000255 | 0.001052 | 0.00022 |
| Kurtosis | 1.526561 | 3.014815 | 3.87862 |
| Skewness | –1.42257 | 0.549687 | 1.116431 |
| Sample number | 64 | 64 | 64 |

## DATA ACCURACY

The ability to record grain scale characteristics across reach scale surveys requires both high point resolution and good range accuracy. Point densities of 10 000 $m^{-2}$ have been achieved using 12 meshed scans along the 150 m study reach. Laser scan data accuracy was evaluated through the collection of approximately 150 independent prominent surface point co-ordinates using an EDM theodolite (Table 2), obtained at the same time as the laser scan survey. The POLYWORKS polygon processing software was used to generate a triangular irregular network DEM of the surface of the meshed data (Fig. 1(a)). Residual errors between the theodolite and laser DEM elevations were computed (Fig. 2(a)), revealing a very good agreement between the laser data surface and the independent theodolite points.

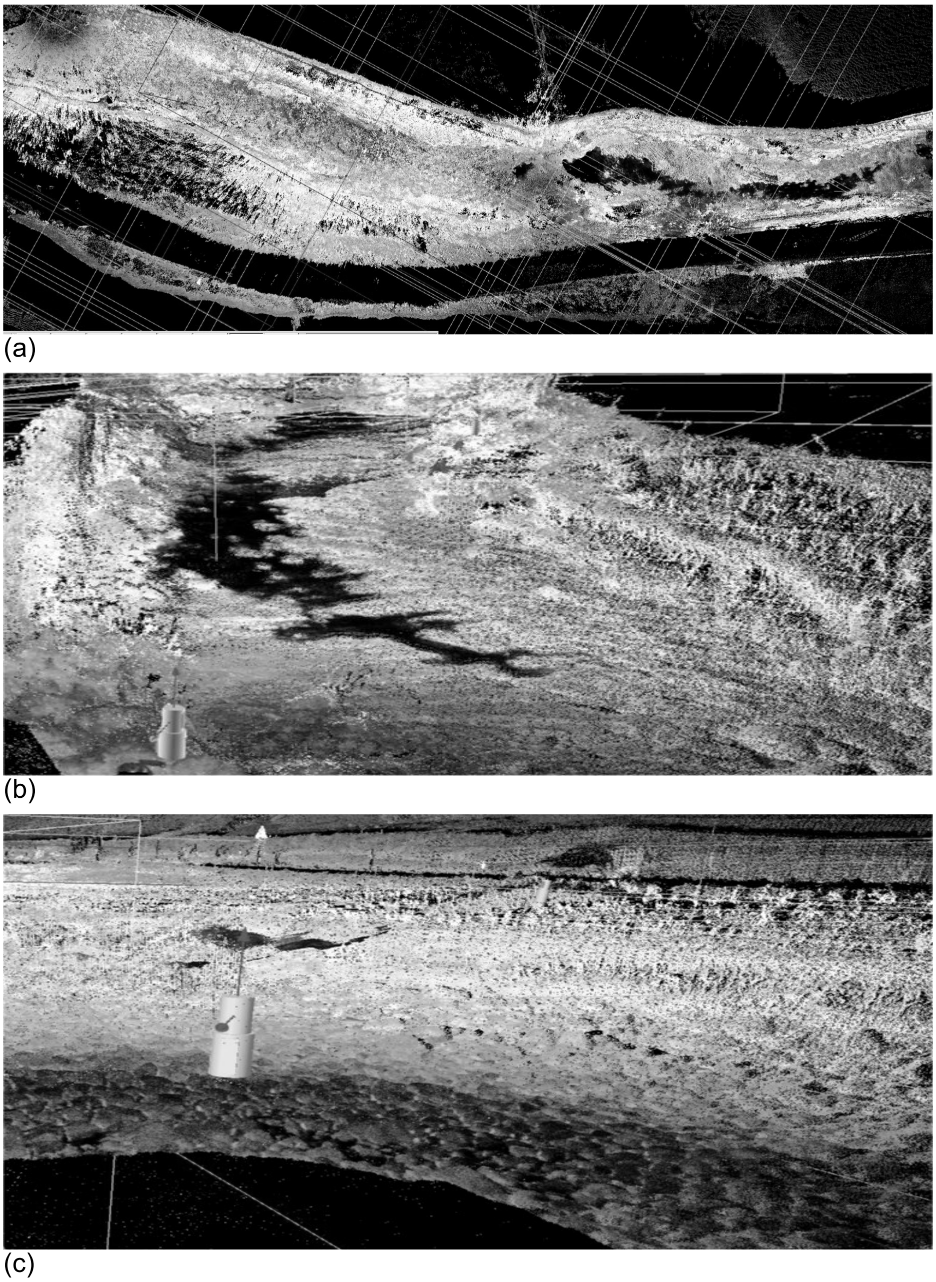

**Fig. 1** DEM surfaces of: (a) the final triangular irregular network of the River Wharfe at Highhouses, (b) bedrock step detail and (c) cobble bed and bankside vegetation character.

**Table 2** Laser scan error across differing surfaces on the River Wharfe study reach at Highhouses.

| | Alignment | Bedrock | Rock gaps | Broad leaved vegetation | Grass | Water | Water edge |
|---|---|---|---|---|---|---|---|
| Mean | 0.003804 | –0.0065 | 0.254738 | 0.074912 | 0.068672 | –0.25552 | –0.23597 |
| Variance | 0.027997 | 0.021146 | 0.017128 | 0.016816 | 0.007778 | 0.019568 | 0.006654 |
| Standard deviation | 0.167322 | 0.145417 | 0.130875 | 0.129675 | 0.088193 | 0.139886 | 0.081571 |
| Sample number | 157 | 93 | 44 | 33 | 19 | 47 | 23 |

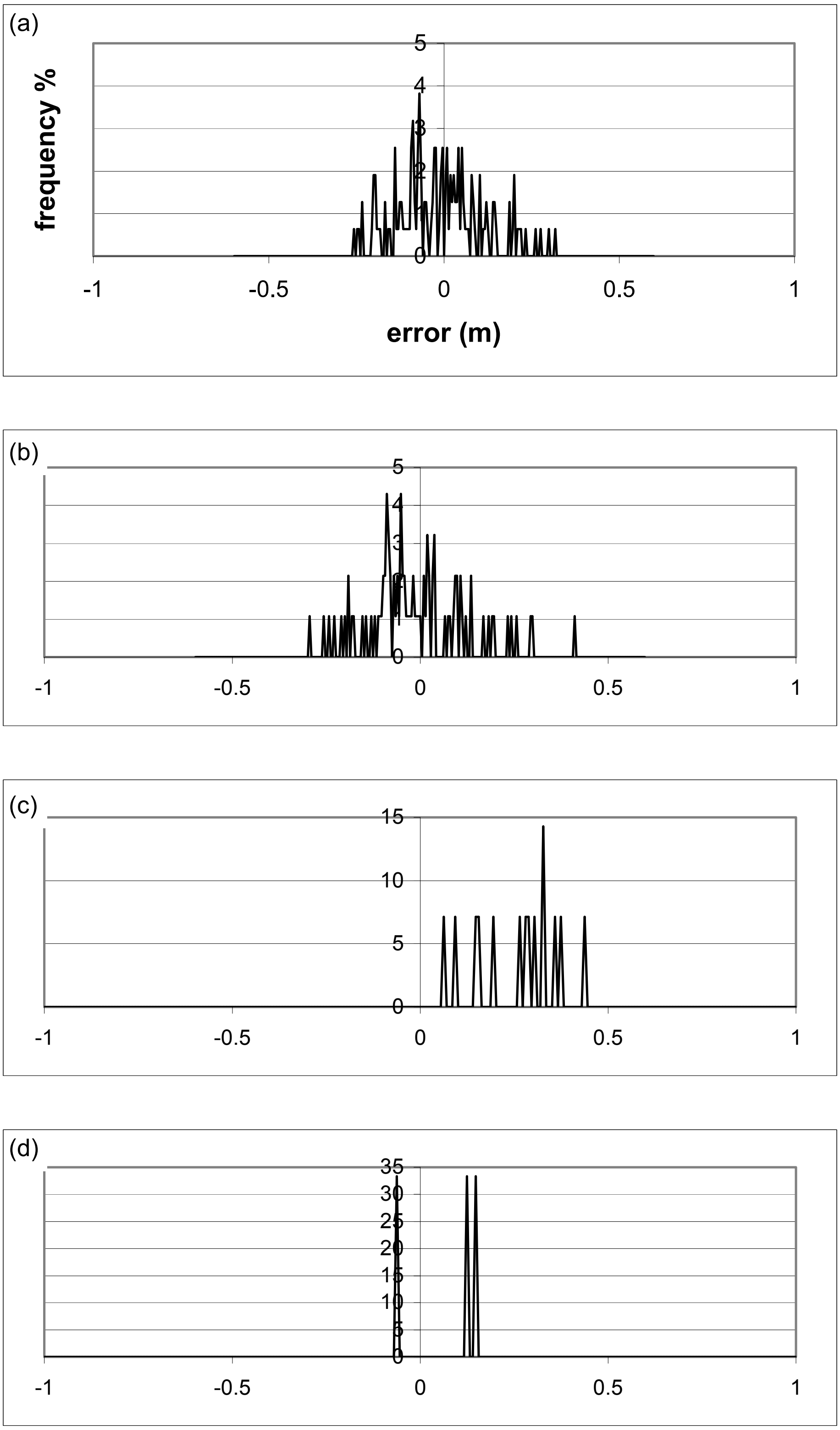

**Fig. 2** Laser scan DEM error frequency (%) for the River Wharfe at Highhouses: (a) assessed against independent theodolite points and across varying terrain, (b) bedrock, (c) rock gaps, (d) broad leaved vegetation, (e) grass, (f) water, (g) waters edge; (e), (f) and (g) are shown overleaf.

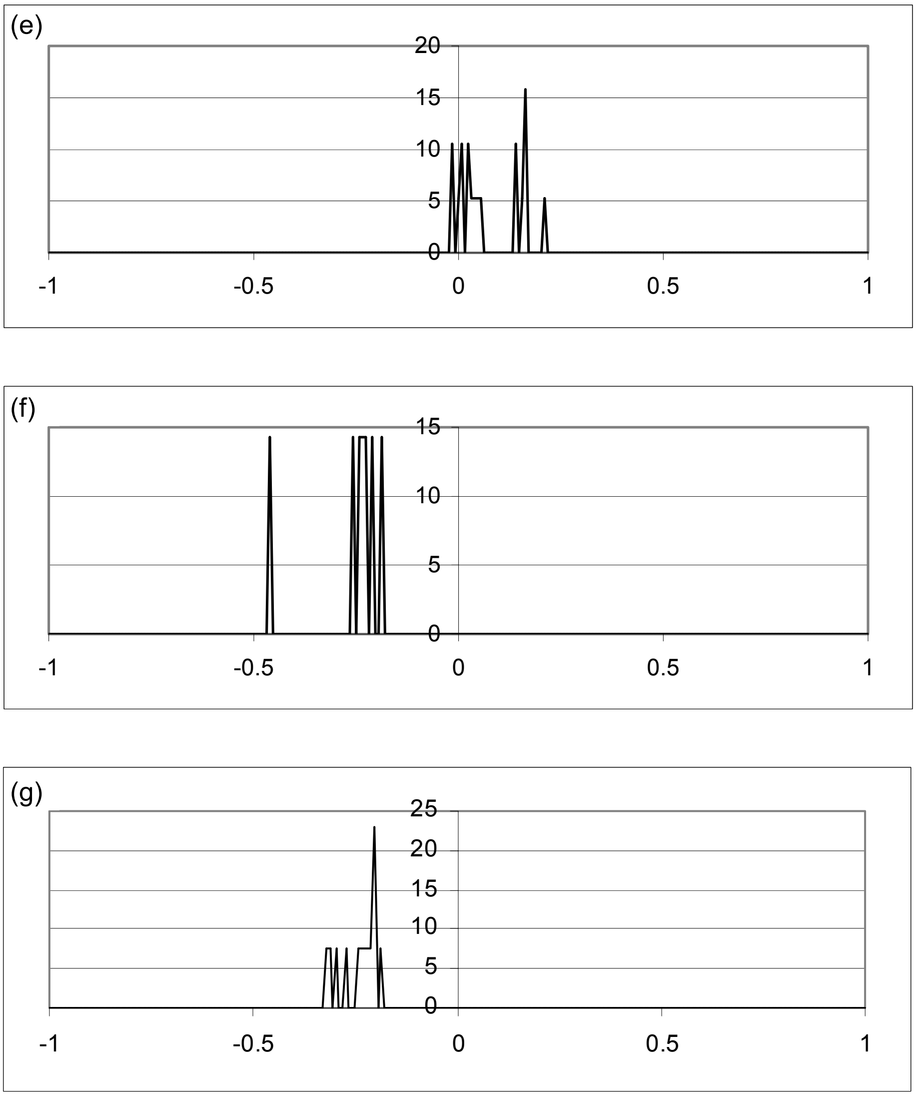

**Fig. 2 Continued**. Laser scan DEM error frequency (%) for the River Wharfe at Highhouses: (e) grass, (f) water, and (g) waters edge.

The terrain across the study reach was variable, including bedrock, a range of sediment sizes, vegetation and water. The accuracy of the laser scan DEM was assessed across each of these surface types (Table 2, Fig. 2). It is clear that across smooth bedrock surfaces visible from many scan locations (Fig. 2(b)), the laser scan accuracy was as good as for the exposed cobble and rock surfaces used as scan tie points, with a mean error of 0.004 m. The data are slightly negatively skewed indicating that the laser based DEM surface is below the theodolite survey points, however the error is minimal. Larger errors of ±0.3 m are occasionally recorded. DEM data for the gaps between cobbles and boulders were less accurate (Fig. 2(c)) displaying a consistently positive discrepancy relative to the theodolite points, with average errors of 0.025 m. This error is caused by the shadowing effect of adjacent clasts preventing penetration of the pulsed laser light into the interstitial spaces and leading to an overestimate of the true surface. Such errors are greatest where the surrounding material is large and the gaps narrow, and where the angle of incidence of the laser pulse is low. Vegetation also leads to apparent error in the determination of the study surface. The average error in identifying the ground surface in areas covered in broad-leaved vegetation is apparently quite low (0.07 m), with the laser survey overestimating the true height due to the laser pulse being reflected off the leaf surface before reaching the ground. A conventional theodolite survey ignores the vegetation. The error appears bimodal (Fig. 2(d)) with a positive discrepancy of 0.2 m reflecting the average leaf height. Occasional underestimates of surface height are more difficult to explain and require further study. Grasses show a different response, with a more variable accuracy around a mean error of 0.07 m (Fig. 2(e)), this is due to the lower leaf density and more diffuse leaf structure of the grasses allowing some of the laser pulses to reach the ground thus returning a coordinate value equivalent to that recorded by theodolite survey. The greater spread of errors across this vegetation type is due to the pulses penetrating the vegetation to varying degrees before being reflected off a grass stem or the ground surface. The effect of water on scan data accuracy is apparent from Fig. 2(f). Often the laser pulse is scattered over water and no return is recorded. However, where the water is clear, calm and shallow and the angle of incidence of the laser pulse is high, some penetration does occur. In the case of the Wharfe pools, where the water was clear and calm with an average depth of around 0.1 m, the error in elevation returns from the laser survey was of the order of 0.23 m. Further work is required to determine whether a correction factor may be applied to these data to provide more accurate elevation data in this environment. A similar effect is noticeable from waters edge data (Fig. 2(g)). The inaccuracy here raises issues concerning the use of laser data in defining water boundaries and in deriving water surface slope information. Data may also be returned when the water is turbid and where the water surface is disrupted due to high bed roughness, although the accuracy is highly variable (see Heritage *et al.*, 2005).

## DISCUSSION

The use of oblique laser scanners to generate detailed accurate DEMs of landforms represents a major improvement on previous methods, both in areal coverage and DEM accuracy. The density of data points acquired using the new technique precludes the need for major DEM interpolation, a process known to introduce errors (Lane, 1998). Data may now be acquired at a density sufficient to represent the surface at the grain scale estimated at between 4000 and 10 000 points $m^{-2}$ by Lane *et al.* (1994). The issue of point distribution and potential operator bias (Lane *et al.*, 2003) is also rendered obsolete as a dense cloud of meshed radial data points ensures that a surface is sampled many times. Data point quality may still potentially prove to be an issue for some studies aimed at the sub-grain scale as the range error on current instruments may lead to inaccuracies in the DEM surface. Studies at the sub-bar scale, identified as a significantly under researched area by Charlton *et al.* (2003), would suffer much less from such small errors, and the rapidity with which the laser data may be acquired enables change at this scale to be monitored frequently (see Heritage *et al.*, 2005).

Laser data accuracy has been shown to be a function of the instrument range error (something that is being improved upon with each new generation of scanner), object visibility, vegetation and the presence of water. Issues relating to atmospheric moisture may also be important. Heritage *et al.* (2005) report significant spurious data points above the survey landform surface following laser scanner operation in rain, high winds and fog. Object visibility has also been reported as an issue with photogrammetric studies (Bailey *et al.*, 2001), where deeply shadowed areas return inaccurate elevation data. Vegetation has also been reported as obscuring the ground surface in airborne lidar (Charlton *et al.*, 2003) and photogrammetric studies (Bailey *et al.*, 2001), and also affects the ability of GPS equipment to detect satellite presence leading to data collection problems (Heritage *et al.*, 2003). This study has noted the ability of some laser pulses to penetrate the vegetation and return a signal from the ground surface. A similar effect has been observed for airborne lidar (Optech, 2001).

The ability of the scanner to rapidly acquire detailed 3-dimensional (3-D) data also addresses the issue of recording rapid temporal change. Nagihara *et al.* (2004) surveyed 400 $m^2$ in half a day, and the 150 m study reach used here was surveyed in a day and a half. Hetherington *et al.* (2005, this volume) also report successfully recording diurnal braidplain changes at the sub-bar scale at the snout of the Mont Miné and Ferpècle glaciers, Switzerland.

## CONCLUSIONS

This paper reports on a new rapid oblique laser survey technique for the natural environment, it has potentially wide application across a variety of disciplines. However, the accuracy of the data obtained is determined by field operation, terrain character and instrument specifications. It is suggested that the following operations are conducted in the field:

(a) Minimize the scan distance to ensure greater scan point density.
(b) Ensure that scan locations are chosen to minimize scan shadow effects.
(c) Optimize the scan angle by setting the instrument well above the scanned surface to ensure greater visibility between topographic highs.
(e) Utilize a reflector system where possible to reduce post-processing time.
(f) Collect independent tiepoint/error check data as this can also be used to minimize systematic bias in the DEM caused by poor reflector/tiepoint merging.
(g) Ensure that some reflectors/tiepoints are placed at the edges of the scanned area to minimize propagation of meshing errors.

Laser DEM accuracy is shown to be very good for exposed surfaces such as cobble tops and bedrock. Data point resolution allows features at the grain scale to be recognized in the DEM and the overall survey accuracy would allow for changes at the sub-bar scale to be reliably recorded and quantified. Errors are apparent across vegetated surfaces with only limited penetration of the pulsed laser signal through to the ground, however, manual analysis of the laser data could identify these points. It is also suggested that the distribution reflects stem/leaf density and further research is underway to link this with surface roughness.

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