

Comparing LiDAR-Generated to Ground-Surveyed Channel Cross-Sectional Profiles in a Forested Mountain Stream

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Abstract

Airborne Light Detection and Ranging (LiDAR) holds promise to provide an alternative to traditional ground-based survey methods for stream channel characterization and some change detection purposes, even under challenging landscape conditions. This study compared channel characteristics measured at 53 ground-surveyed and LiDAR-derived cross-sectional profiles located in six study reaches of Little Creek, a forested headwater stream on Cal Poly's Swanton Pacific Ranch, near Santa Cruz, CA. Three LiDAR datasets were compared in this study, with flights in 2002, 2008, and 2010, a period of rapid improvement in LiDAR technology. Visual and statistical agreement between field-surveyed and LiDAR-derived channel characteristics (bankfull depth, bankfull width, bankfull area, and thalweg elevation) show improvement as LiDAR technology has matured. Improvements are explained, in part, by the decrease in point spacing along the cross-sectional profiles (averaging 3.0 m in 2002, 1.0 m in 2008, and 0.49 m in 2010). Bankfull width was more accurately measured than bankfull depth or cross-sectional area. In 2010, two thirds of the LiDAR-derived cross-sections provided bankfull width within 10 percent (0.46 m) of the field-surveyed width. These initial findings show the improvements in LiDAR capabilities over time, though also point to difficulties that remain for remotely measuring channel geometry on small, headwater mountain streams.

Key words: bankfull, change detection, channel, LiDAR

Introduction

Channel features are currently measured using a variety of ground survey techniques (e.g., Harrelson et al. 1994). Field surveys often require significant personnel commitments and funding to complete, and may lack the sample density (longitudinally along the channel) necessary to describe change throughout the system. The prospect of utilizing airborne Light Detection and Ranging (LiDAR) to map channel features and detect change over time, has generated considerable interest for applications in environmental assessment and monitoring. LiDAR technology has become well-established for producing detailed bare-earth Digital Elevation Models (DEM). Results from several studies show that LiDAR accuracy ranging from ± 0.02 m to 0.30 m root mean square error (RMSE) vertically and 0.15 to 0.30 m horizontally can be achieved in optimal survey conditions of flat even terrain, free from obstructions such as vegetation (Csanyi et al. 2005, Frenc 2003, McKean et al. 2005, Reutebuch et al. 2003). In mountainous and forested terrain,

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additional sources of error are attributed to terrain slope (Kraus and Pfeifer 1998), aspect and topographic ruggedness (McKean et al. 2005), and density of forest overstory and understory vegetation (Reutebuch et al. 2003). Other factors pertain to flight and sensor parameters of the survey including flying height, aircraft speed, pulse rate, scan angle, and positional error imparted from the GPS and IMU (Hyypä et al. 2005). Software processing of LiDAR data can also introduce error through mis-classification of bare-earth terrain points, and in the interpolation of the final digital elevation model. Despite the additional challenges encountered in mountainous terrain, wide consensus has formed supporting the use of LiDAR for high-resolution terrain mapping (McKean et al. 2005).

Agreement between ground-surveyed and LiDAR-derived channel features has been demonstrated with promising results in the semi-arid grassland and shrub-steppe environment of southeast Arizona (Miller et al. 2004) and in the more mountainous terrain of northeastern Oregon (Faux et al. 2009). Measuring channel morphology in densely forested environments can be more problematic, due to the lower ground-point densities achieved under dense cover (James et al. 2007). However, given sufficient flight and sensor specifications, detailed feature extraction and measurement is possible, even in dense forest settings (White et al. 2010). It now appears that airborne laser mapping technology is becoming capable of providing an alternative to traditional survey methods for at least some measurements of channel geometry.

Approach

Conventional ground survey data are compared to LiDAR-derived measurements of channel shape, ultimately necessary for channel characterization and change detection purposes. The primary objective of this study was to evaluate and compare the accuracy of channel cross-sectional profiles derived from three separate LiDAR flights. It was hypothesized that LiDAR-derived channel characteristics are visually and statistically similar to ground-surveyed channel characteristics. Further goals included an evaluation of LiDAR technology to aid the monitoring of geomorphic change.

Study area

The study site is located within the Little Creek watershed, 22 km north of Santa Cruz in the central part of California's Coast Ranges (*fig. 1*). The Little Creek watershed is a 526 ha tributary watershed to Scotts Creek and is partially located within Swanton Pacific Ranch. Swanton Pacific Ranch is an education and research facility of the California Polytechnic State University promoting informed land stewardship. Terrain within the study area is steep and rugged, with elevations ranging from 12 m to 488 m and inner gorge ground surface slopes that exceed 80 percent. The watershed contains approximately 6.5 km of stream length, for a drainage density of 1.2 km/km². Streams include first-, second-, and third-order channels as defined by Strahler (1964), based on the USGS 10 m DEM, topographic mapping, and field verification. Average channel gradient ranges from 1.8 percent to 5.0 percent and the channel type can be characterized as step-pool (Montgomery and Buffington 1997). Mean bankfull channel width is approximately 5 m. The mostly

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forested watershed is dominated by second-growth coast redwood (*Sequoia sempervirens*), and includes components of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) and tanoak (*Notholithocarpus densiflora*). knobcone pine (*Pinus attenuata*) and brittle-leaf manzanita (*Arcostaphylos crustacea*) are also found along portions of the watershed ridgelines. Mature red alder (*Alnus rubra*) dominates the riparian community and is among the few deciduous overstory species present. The percentage of riparian overstory canopy cover ranges from approximately 40 percent to 95 percent, with an average of 80 percent.

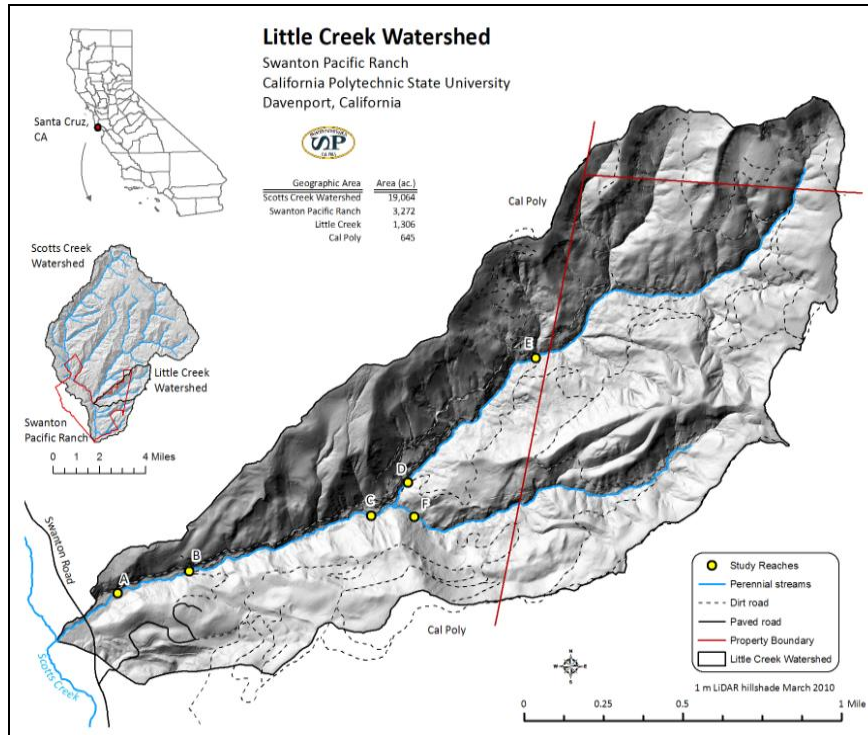


Figure 1—Little Creek watershed and locations of study reaches.

Field survey methods

As part of the Little Creek Study, a long-term watershed monitoring project being conducted at Swanton Pacific Ranch, channel features were surveyed annually (2000 to 2011) at six study reaches (A through F) (fig. 1) for the purpose of observing channel change over time. The study reaches differ in channel size and shape, valley confinement, and overstory canopy cover. More complete descriptions of the study reaches are found in Hilburn (2010). Annual surveys using traditional ground-based surveying methods ensue at the six reaches, each with 10 monumented cross-sectional profiles spaced approximately 4.6 m apart over 50 m of stream channel. As part of the field survey, characteristics describing geomorphic features, including bankfull elevation, thalweg elevation, and edge-of-water are identified. This information is used to calculate bankfull depth (bfd), bankfull width (bfw), and bankfull area (bfa) for each cross-sectional profile.

LiDAR data collection

Airborne LiDAR surveys of the study area were conducted in March and April 2002, February 2008, and March 2010 for the purposes of evaluating watershed features, evaluating the ability to detect change, and to document improvements in LiDAR capabilities over time. Comparisons of ground-surveyed and LiDAR-derived measurements of forest roads and stream channel characteristics began in 2002 and are ongoing (Hilburn 2010, White 2010, White et al. 2010). Data from 2002 were collected by Spencer B. Gross Inc., Portland, Oregon, while the 2008 and 2010 datasets were collected by Airborne 1, El Segundo, California.

LiDAR flight and sensor parameters represent “high-resolution” survey specifications provided by vendors at the time of the surveys. The LiDAR data collected in 2002 were evaluated at 21 open and flat checkpoints, with a vertical RMSE of 0.08 m. Data from 2008 and 2010 were evaluated at over 1000 RTK-GPS checkpoints and a show similar precision of 0.09 m and 0.06 m RMSE, respectively. These values are useful to ensure proper system calibration and performance, but are not indicative of vertical accuracy in areas of steep slopes and dense vegetation. Parameters of each flight and specifications of the LiDAR sensors differed across flights, but are not addressed extensively here. One noteworthy difference was sensor pulse rate, which increased from 20,000 pulses per second in 2002 to 100,000 pulses per second in 2008 and 150,000 pulses per second in 2010. Bare-earth filtering was provided by the vendor to classify points as either ground or non-ground and this classification was used for the remainder of the analysis.

LiDAR feature extraction

Each LiDAR dataset was used to create a Triangular Irregular Network (TIN) surface, from which the cross-sectional profiles were extracted. Horizontal coordinates for the left and right endpoints of each cross-section were established in the field survey using a total station and local control network. A 0.5 m buffer was constructed around each profile line and ground returns located within this buffer were used to construct a TIN for that profile. Bankfull elevation as identified in the field was used to calculate bankfull depth (bfd), bankfull width (bfw), and bankfull area (bfa). Ground survey data from 2010 are used in this study and assumed to represent ground conditions across all flights. Survey data from 2008 was also plotted to show the small magnitude of change experienced over the study period. Similarly, while the LiDAR flights occurred in early spring and the ground surveys were conducted during summer months, no channel-changing flow events occurred during those intervening months.

Results and discussion

Results are presented with a discussion focusing on ground return point spacing along profiles, qualitative observations showing visual agreement, and finally, a quantitative evaluation describing agreement for each channel feature. Further emphasis is placed on describing improvement over the three LiDAR datasets.

LiDAR ground return points

One measure of LiDAR performance and suitability is found by examining the density of ground points. In 2002, the average spacing between ground returns in the Little Creek watershed was 2.05 m; this number dropped to 1.1 m in 2008, and ultimately to 0.53 m in 2010. Given that the channel cross-sections are located under dense riparian canopy, ground point density is expected to be less than the overall watershed average. In this study, the average spacing between ground points along the profile lines is 3.03 m in 2002, 1.00 m in 2008, and 0.49 m in 2010. That is, on average, the number of LiDAR points along the profile lines increased from 3, to 16, to 28 observations across the three flights. It should be noted that the average number of LiDAR observations per transect is approaching the average number of field-surveyed points. In many cases individual cross-sectional profiles had more LiDAR points than surveyed observations. Questions still remain, however, regarding how well the ground-return points reflect actual channel elevations, and how many observations are necessary to accurately characterize the channel and aid channel change detection.

Visual and measured comparisons

Observing the graphical representations of the LiDAR-derived and ground-surveyed cross-sectional profiles is an important first step in understanding the agreement between the derived and surveyed profiles. *Figure 2* provides examples using the B10 cross-section. *Figure 2a* shows the agreement between the 2008 and 2010 field surveys. The error associated with field surveys is also important to understand in relation to the derived profiles. The B10 field surveys show good agreement for the 2008 and 2010 surveys. However, other profile locations are more problematic due to large obstructions in the channel and difficulties associated with the vertical positioning of the Philadelphia rod. There is also human error introduced by having different field personnel perform the surveying. Preliminary error estimates performed for the 2002 field survey found bed elevations to vary by ± 0.05 m and profile areas to vary by ± 1.22 m².

There are substantial visual differences between the LiDAR-derived profiles for B10 in 2002, 2008, and 2010 (*fig. 2b*). Most notable is the 2002 survey which had only four ground points within the 0.5 m buffer around the profile line, versus 27 in 2008 and 84 in 2010. Field surveyors collected 35 and 41 points for B19 in 2008 and 2010, respectively. A question to be answered is how many LiDAR returns are necessary to describe the profile for characterization and aid in change detection? Visually comparing the 2010 field survey to 2010 LiDAR-derived profile (*fig. 2c*) provides further evidence that, at least for the B10 cross section, superior agreement can be achieved with the 2010 LiDAR. One challenge is to determine how to assess the agreement between LiDAR-derived and measured cross-sectional profiles for the purposes of channel characterization and change detection? One way is to compare measures of channel geometry that are typically made from field surveys of stream channels.

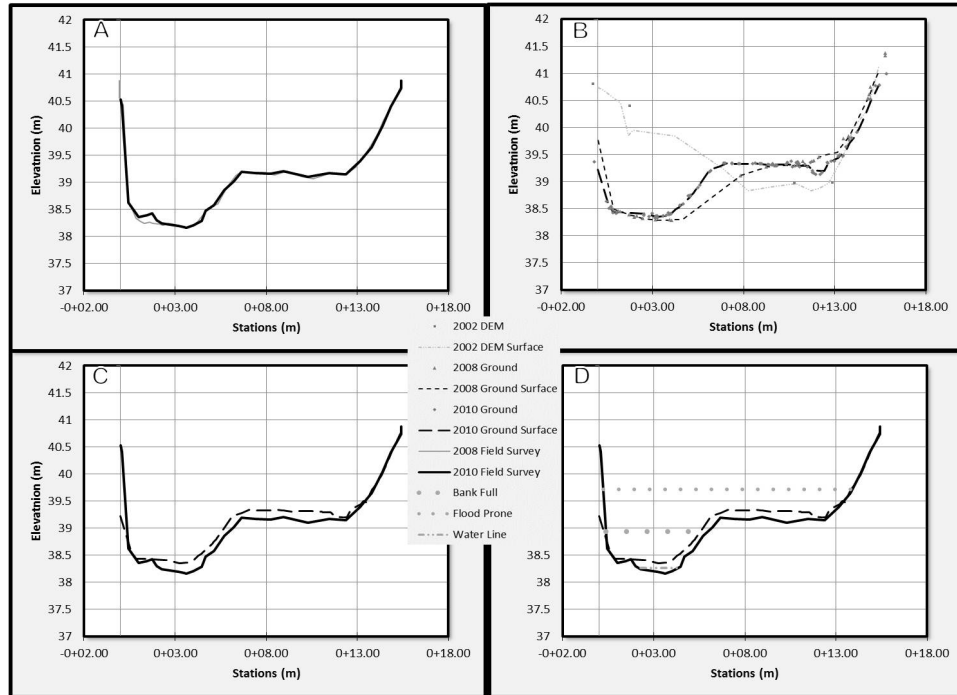


Figure 2a-d—B10 cross-sectional profile agreement for a) 2008 and 2010 ground- survey profiles, b) 2002, 2008, and 2010 LiDAR-generated profiles, c) 2010 LiDAR-generated and 2010 ground-survey profiles, and d) 2010 LiDAR-generated and 2010 ground-survey profiles showing water surface, bankfull, and flood-prone elevations.

Channel geometry measures often include bankfull dimensions. Indicators of bankfull stage are identified in the field during the surveys. Although a subjective determination based on field indicators, the importance of the bankfull relationships in fluvial processes and channel restoration is widely recognized in the literature (Leopold et al. 1964, Rosgen 1994). The B10 cross section shows good visual agreement for bankfull width (*fig. 2d*), and arguably, decent agreement for estimating bankfull depth and area. A more quantitative assessment of agreement follows.

Scatterplots and linear regression are used to summarize and compare field-surveyed versus LiDAR-derived dimensions (after Miller et al. 2004) across all cross sections (*fig. 3*). Results from the 2002 LiDAR are generally poor. Profiles from 2002 tended to overestimate bankfull dimensions; channels appeared to be deeper, wider and larger than when compared to those using field survey data. Both 2008 and 2010 LiDAR data show substantial improvements over the 2002 data. Bankfull depth and area are underestimated in the 2008 data, although bankfull width estimates are nearly unbiased. The 2010 cross sections showed the best overall correspondence to field survey measurements. These cross-sections have the highest R-squared values and are the most consistent across the range of surveyed channel dimensions. Still, both the 2008 and 2010 LiDAR estimates routinely underestimate bankfull depth. It is possible that the shallow water depth present during the LiDAR flights inhibited accurate measurement of the channel bed (Faux et al 2009).

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The average error of the LiDAR-derived feature measurements is presented in *figure 4*. In this figure, error is presented as a percentage of the field-surveyed bankfull

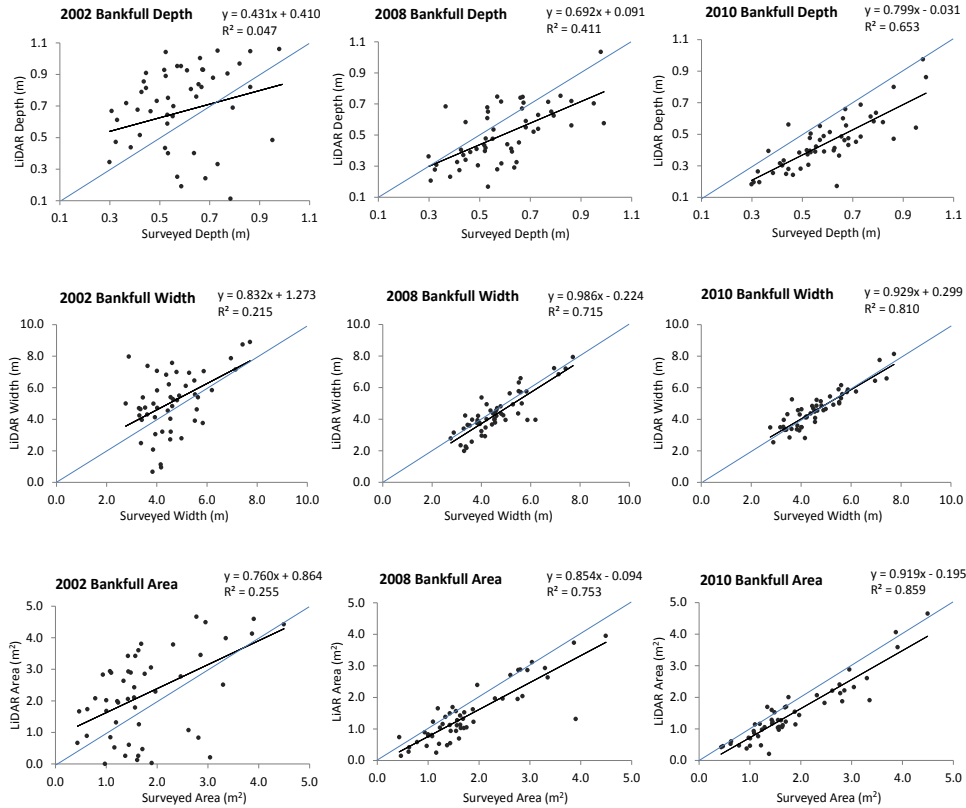


Figure 3—Scatterplots showing LiDAR- and field-surveyed channel features (bankfull depth, width, and area) from 2002, 2008, and 2010 data. A 1:1 line is drawn for reference.

dimension. While the absolute error for bankfull width, depth and area measurements were relatively small, taken as a percentage of bankfull channel dimensions, these errors appear more substantial. In the 2010 survey, two thirds of the LiDAR-derived cross-sections provided bankfull width within 10 percent (0.46 m) of the field values. Over 90 percent of cross-sections provided width measurements within 20 percent (0.91 m) of the field-surveyed value.

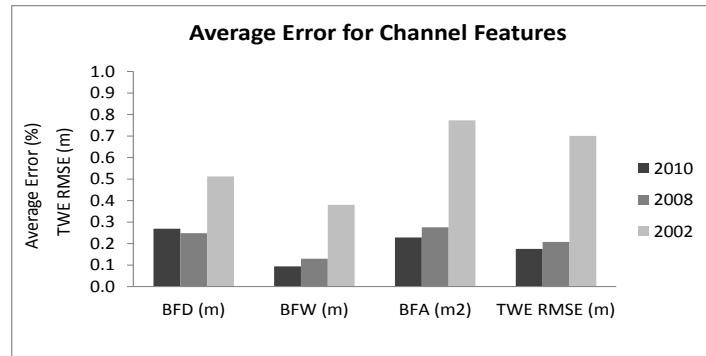


Figure 4—Average error between surveyed and LiDAR-derived channel features.

Comparing the LiDAR-derived thalweg elevations to field-surveyed elevations provides a measure of vertical accuracy. Scatterplots (*fig. 5*) show the reduction in vertical error in successive flights. Elevation differences are summarized with RMSE values of 0.7 m, 0.2 m, and 0.175 m for 2002, 2008, and 2010, respectively. One concern is the apparent positive bias (0.13 m) in the 2010 LiDAR elevation data. At this point it is unclear whether this is a characteristic of LiDAR returns reflecting from the water surface, or if there is a bias in the field survey control network. Additional survey work is planned to evaluate this anomaly further. If this bias were subtracted from the RMSE, the resulting RMSE would be 0.05 m, similar to the 0.06 m reported from the vendor accuracy report.

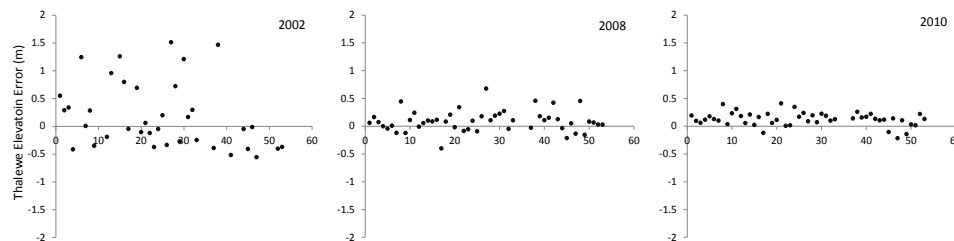


Figure 5—Error between surveyed and LiDAR-derived thalweg elevations.

Summary

Improvements in LiDAR technology translate to an increased ability of LiDAR to describe the physical characteristics of stream channels under challenging landscape conditions. The 2010 LiDAR survey was conducted during leaf-off conditions with a pulse repetition frequency of 150,000 laser pulses per second in order to maximize ground return density in this forested environment. While point density improved in 2010 versus 2008, improvements in overall accuracy were only marginal. This may result as point spacing approaches laser footprint size on the ground and the horizontal accuracy of pulse positioning (~ 0.3-0.5 m). Overall, many of the LiDAR-derived profiles agree quite well with the ground-surveyed profiles, yet many are considered inadequate for fine-scale characterization or geomorphic change detection. Limitations still exist due to water depth at the time of the LiDAR survey, obstruction from near-ground vegetation, dense overstory canopy coverage, and steep channel side slopes. Depending on the accuracy that is required, airborne LiDAR can provide useful measurement and characterization of small mountain

streams. As this technology continues to advance, the suitability of LiDAR and its performance for various applications should continue to be evaluated.

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