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Validation of Vegetation Canopy Lidar sub-canopy topography measurements for a dense tropical forest

M.A. Hofton[a,*], L.E. Rocchio[a,1], J.B. Blair[b], R. Dubayah[a]

[a]*Department of Geography, University of Maryland, College Park, MD 20742, USA*
[b]*NASA Goddard Space Flight Center, Code 924, Greenbelt, MD 20771, USA*

Abstract

Large footprint (greater than 10 m wide) laser altimetry is a useful technique for mapping topography (including sub-canopy), canopy height and vertical structure in densely vegetated areas. In March 1998, the Laser Vegetation Imaging Sensor (LVIS), an airborne laser altimeter, mapped a ~800 km^2 area of Costa Rica including the La Selva Biological Station using 25 m-diameter footprints as part of the pre-launch activities of the Vegetation Canopy Lidar (VCL) Mission. To investigate the utility of the lidar technique for making sub-canopy topography measurements, the precision and accuracy of the LVIS elevation measurements from this mission are assessed. Crossover analysis using laser shots whose recorded waveforms contained more than 50% of the total returned energy within their lowest reflections show the elevations have a precision of better than 1 m. Comparison of the LVIS elevations with coincident in situ ground elevation data reveals that the measurements are within ~1.5 m of each other on less than 3° slopes. All measurements are within ~5 m of each other (on slopes of up to 30°). These are very encouraging results given that the forests of this region are some of the densest, most complex on Earth, and that mapping their sub-canopy topography are near-impossible using any other remote sensing technique. Given the similarity of the measurement processes of the LVIS and VCL systems, these results suggest that the topographic measurements made by the VCL will meet stated accuracy goals under the majority of measurement conditions. Published by Elsevier Science Ltd.

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1. Introduction

Accurate topographic information of the Earth's surface is increasingly important for a variety of geophysical and biophysical applications. Existing digital topographic data sets such as GTOPO30 (USGS, 2001), GLOBE (Hastings and Dunbar, 1998) and DTED (NIMA, 2001)

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* Corresponding author. Tel.: +1-301-405-8543; fax: +1-301-405-8662.
E-mail address: mhofton@geog.umd.edu (M.A. Hofton).

[1] Present address: NASA Goddard Space Flight Center, Code 923, Greenbelt, MD 20771, USA.

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products have been generated from a variety of sources, but are often globally inconsistent, lack sufficient spatial resolution and suffer from substantial errors (e.g., Wolf and Wingham, 1992) such as noise and vertical discontinuities, limiting their usefulness at local, regional and global scales. Recent technological advances in airborne and spaceborne sensors have led to a new era of global topographic observation. Foremost among these technologies are interferometric synthetic aperture radar (IfSAR), and laser altimetry (or lidar) (e.g., Zebker and Goldstein, 1986; Garvin et al., 1998). The recent Shuttle Radar Topography Mission (SRTM), utilizing IfSAR techniques, mapped topography between 56° north and south during shuttle deployment in February 2000 (van Zyl, 2000) and will provide surface topography information at 90 m grid spacing with a vertical accuracy of $\sim$16 m (1σ). One of the disadvantages of IfSAR, however, is that for vegetated surfaces the technique provides neither true ground (sub-canopy) elevation, nor canopy height, but rather a height somewhere between the two (depending on the SAR wavelength, canopy closure and other factors that are not completely understood). In contrast, laser altimetry can provide both the sub-canopy topography as well as canopy topography.

The first global laser altimetry missions, the Vegetation Canopy Lidar (VCL) and the Ice, Cloud and Land Elevation Satellite (ICESat) are under development (Dubayah et al., 1997; Schutz et al., 2000). Using large-footprint laser altimetry, VCL will characterize the three-dimensional structure of the Earth's surface, measuring vegetation height, vertical vegetation structure, and ground topography, including sub-canopy topography (i.e., the elevation of Earth's surface below any overlying vegetation) to 1 m vertical accuracy over the majority of the Earth. These measurements will be acquired using an instrument with three laser ground tracks, each of which has 25 m-diameter laser footprints contiguous along track, with 4 km spacing between beams across track. Over its two-year lifetime, these three transecting beams will sample approximately 3% of the Earth's surface between 67° north and south producing about 5 billion observations of vertical structure (Dubayah et al., 1997).

Large-footprint (greater than 10 m-diameter) laser altimetry systems such as VCL have the ability to measure ground elevation, canopy height, and vegetation structure simultaneously over large areas because they digitally-record the shape of the return laser pulse, or waveform. The return waveform typically contains one or more distinct modes resulting from the interaction of the laser pulse with the vertical structure within the illuminated footprint.

Each mode represents a distinct reflecting surface within the footprint with higher modes usually representing vegetation and the lowest mode usually representing the ground surface. Subsequent analysis of the waveform enables both canopy top and sub-canopy topography estimates (assumed to be represented by the locations of the temporally-first return and centroid of the temporally-lowest reflection respectively), as well as the vertical distribution of intercepted surfaces, to be derived (e.g., Blair and Hofton, 1999; Hofton et al., 2000a).

Little validation of large-footprint measurements has been performed to date (e.g., Hofton et al., 2000b; Behn and Zuber, 2000), primarily because there are few large-footprint laser altimetry data sets. In anticipation of VCL, a series of calibration and validation experiments have been conducted in various locations around the world. In this paper we report on one such experiment where we test the ability of large-footprint (25-m) laser altimetry to measure sub-canopy topography in a structurally complex and dense broadleaf evergreen forest. Using an airborne laser altimetry system whose measurement process is similar to VCL, we examine the precision and accuracy of topographic retrievals in the forests of Costa Rica as compared to *in situ* elevation data. This region is representative of the tropical rainforest biome and thus presents one of the most difficult observational situations VCL will encounter because the amount of vegetation obscuring the ground within the laser footprint (i.e., canopy closure) is at or near its maximum.

2. Study area and available topographic data sets

2.1. The La Selva Biological Station, Costa Rica

The La Selva Biological Station (Fig. 1) is a 15-km^2 research station located in northeastern Costa Rica. The station has been extensively researched and a wealth of biological and physical data are available for the area (e.g., Bawa et al., 1994). The terrain of La Selva extends from about 30 m to 140 m above sea level, and is almost entirely covered by primary and secondary broadleaf evergreen tropical rainforest. The forest is structurally complex, consisting of upper canopy layers from 44 to 55 m high, small suppressed trees from 10 to 25 m high, and dense, low-level ground cover. The canopy closure is generally high, about 98–99% (Chazdon and Fletcher,

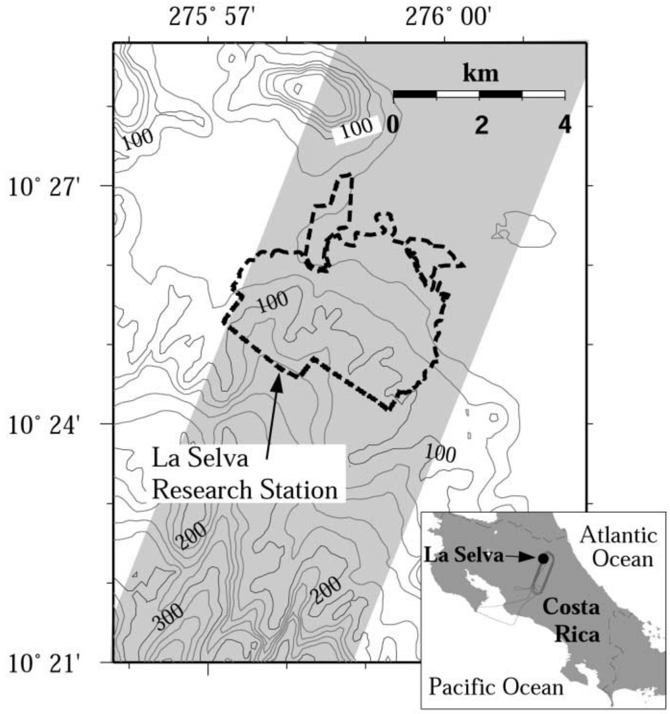

Fig. 1. Location map of La Selva Biological Station and available topographic data. The area mapped by the LVIS laser altimeter system is shaded light gray. The dashed line shows the outline of the La Selva Research Station. The area of La Selva was mapped using optical leveling. The topography of the region is shown contoured at 20 m intervals (obtained from the Digital Terrain Elevation Data (DTED) which is referenced to sea level). The series of lines in the inset lower right shows a typical flight pattern of the mission in 1998.

1984), and deriving the sub-canopy topography of the La Selva region presents a challenge using the majority of established surveying and remote sensing techniques.

2.2. Large-footprint laser altimetry data

In March 1998, large-footprint (25 m) laser altimetry data, including digitally-recorded return waveforms, were collected at La Selva and the surrounding environs. The data were collected using the Laser Vegetation Imaging Sensor (LVIS), an airborne scanning laser altimeter that can generate up to 1 km-wide data swaths (Blair et al., 1999). In VCL-emulator mode at La Selva, LVIS was flown ~6 km above the ground aboard the NASA C–130 aircraft to produce a swath of data approximately 650 m-wide. Footprint spacing was contiguous along-track and about 8 m (i.e., overlapping) in the across-track direction. Final coverage was much denser however, because repeated overflights were necessary to combat persistent cloud coverage. By the end of the mission two, 6 by 60 km areas including the La Selva Biological Station, had been densely mapped (Fig. 2). Data from this mission include the location of each laser footprint, the mean ground elevation and canopy top height within each footprint, and a vertically-located return waveform for each footprint representing the vertical distribution of intercepted surfaces. The footprint location, ground elevation and return waveform are referenced to the ITRF96 reference frame using the WGS-84 ellipsoid.

2.3. Validation data set

To assess the accuracy of the LVIS-derived ground topography, we compare the laser altimeter data with other elevation measurements available for the La Selva Research Station. These data include a set of about 9000 surveyed elevations collected by a ground crew using optical leveling techniques in 1991 (Fig. 1), including the positions of approximately 3000 survey points demarked by tubular metal monuments in the field (Sanford et al., 1994). The monuments are spaced 50 m apart from northwest to southeast and 100 m apart from northeast to southwest and nearly cover the whole of La Selva. The remaining survey positions are without physical monuments. All positions were transformed into the WGS-84 reference system from their original La Selva-specific coordinate system using a 6-parameter polynomial given by

$$UTM_{\text{Northing}} = A^{*}X_{\text{LaSelva}} + B^{*}Y_{\text{LaSelva}} + C, \tag{1}$$

$$UTM_{\text{Easting}} = D^{*}X_{\text{LaSelva}} + E^{*}Y_{\text{LaSelva}} + F, \tag{2}$$

$$Z_{\text{WGS-84}} = Z_{\text{LaSelva}} + 11.44\ \text{m}, \tag{3}$$

where $A = 0.826753$, $B = 0.564574$, $C = 813484.0$, $D = -0.564306$, $E = 0.826969$ and $F = 1152890.0$. This transformation was derived using the locations of five ground control points (GCPs) whose

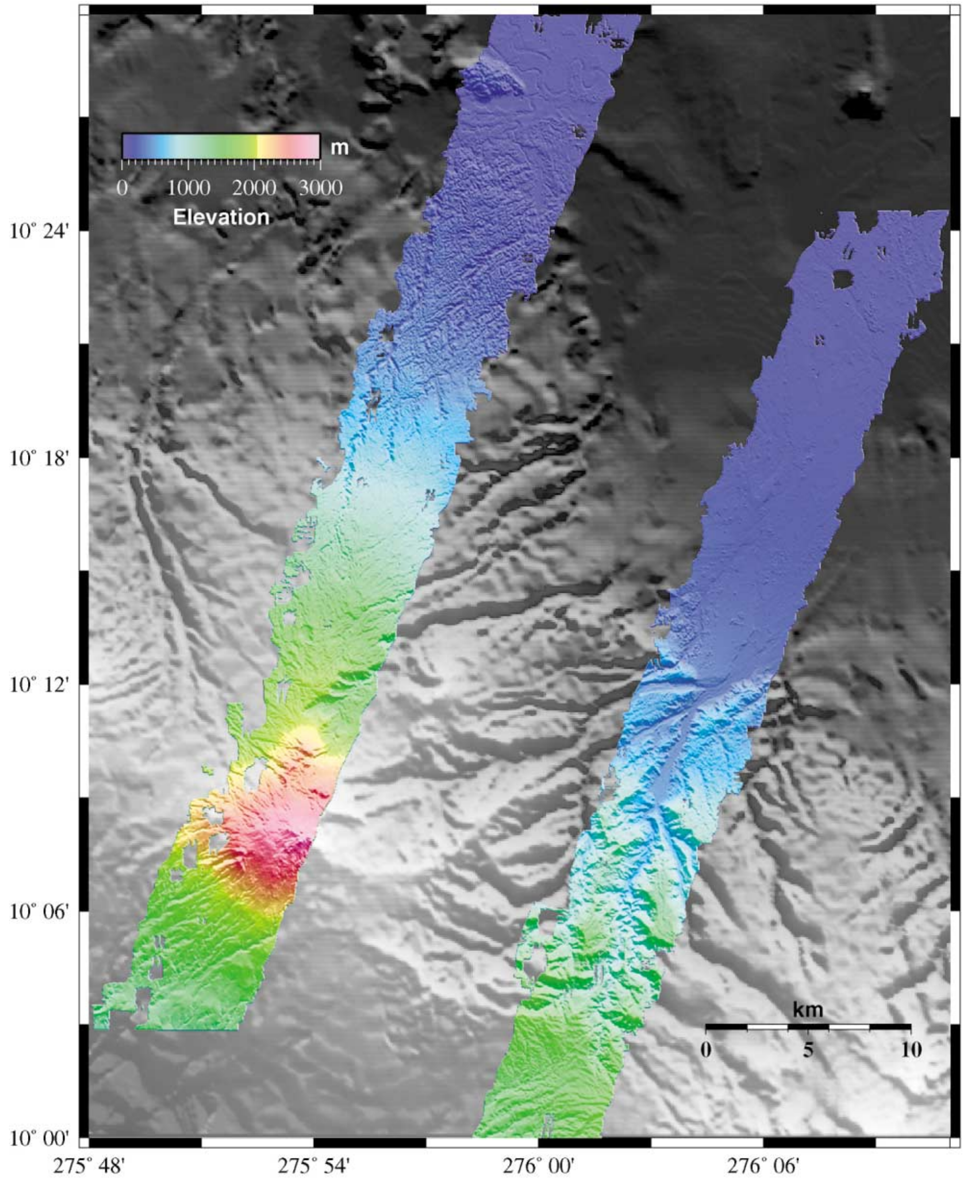

Fig. 2. Colored elevation and shaded relief image of sub-canopy topography mapped using the LVIS system in March 1998. The color bar top left gives the elevation relative to the WGS-84 ellipsoid. The La Selva Biological Station is located in the top of the westernmost swath. In the background is a shaded relief image of the topography obtained from the DTED Level 1 data (90 m spacing).

positions were measured using static, differential GPS techniques in 1997 and 1998. The transformation minimized the least squares difference between the original and GPS-surveyed positions of the GCPs. The vertical offset, 11.44 m, between the La Selva and WGS-84 reference systems corresponds to the average elevation difference between measurements in the original coordinate system and elevations determined using static, differential GPS surveying in 1998. Two points situated in the north of the area were used. All points occupied using GPS were situated in large clearings in order to have as wide a view of the horizon as possible and minimize possible multipath errors. Vertical differences resulting from local changes in the geoid relative to the WGS-84 ellipsoid are not accounted for in the transformation. These differences vary from north to south across La Selva (increasing in magnitude to the north), and have a maximum relative difference of 0.25 m, and may introduce vertical errors into the transformation.

3. Precision of lidar topography measurements

We assess the precision of the topography measurements derived by the LVIS system by comparing the elevations of numerous, repeatedly-sampled patches of ground (referred to as crossover analysis). A large number of such crossover points were generated by the overlapping nature of the along-track LVIS swaths over the duration of the mission. LVIS elevation measurements within 1 m of one another horizontally are compared, a total of 9003 footprint pairs. The use of such a small search radius is intended to minimize the influence of ground slope on the comparisons. For a large number of samples, the ideal distribution of elevation crossover differences is Gaussian, with a zero mean indicating no systematic errors remaining in the measurement. Fig. 3 shows the distribution of elevation differences for all LVIS footprints within 1 m of each other from the Costa Rica mission (i.e., not just within the confines of La Selva). The mean difference is 0.17 m, the standard deviation is 4.38 m, and the root mean square (rms) difference is 4.38 m. The distribution is non-Gaussian however; in particular, a high number of comparison points contribute to the histogram tails. Given the nature of the over flown terrain, in particular, the complex and dense nature of the canopy in the region, the primary cause of elevation differences

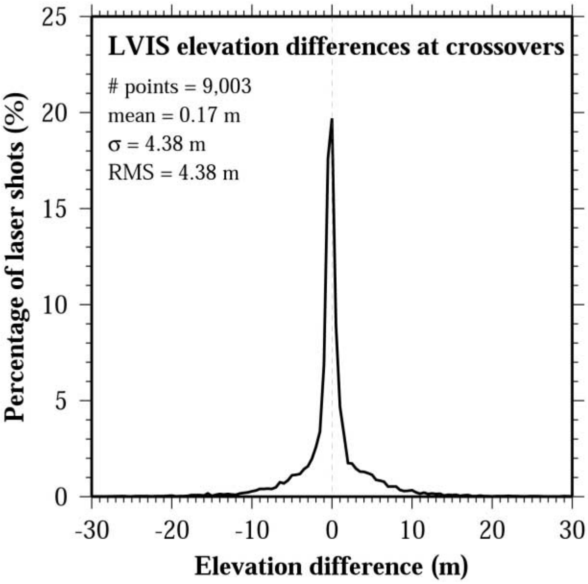

Fig. 3. Histogram of the elevation differences between near-coincident LVIS footprints from the Costa Rica mission. Measurements correspond to a 6×60 km area.

between coincident footprints seems likely to result from poor penetration of the laser through the canopy, for example, at the extreme ends of the LVIS swath under high airplane roll conditions. Vegetation and other reflecting surfaces above the ground decrease the amplitude of the lower ground reflection. If the amplitude of this lowest response or mode within the waveform is comparable to the amplitude of the waveform background noise (i.e., its return energy as a fraction of the total is low), then misselection of the location of the lowest reflection is possible during data processing, and the resultant elevation is not consistent with repeat measurements. The effects of waveform misinterpretation are potentially correctable by refined waveform analysis.

To assess the effect of the strength of the lowest return on the measurement precision, we investigate the elevation differences at the crossover points as a function of the return energy within the lowest reflection in the waveform. This return energy is calculated as a percentage of the total energy within each waveform. The elevation differences are shown in Fig. 4. As the energy of the lowest reflection within each waveform increases, the mean and rms differences, and standard deviation of the distribution decrease, and the elevation differences become more normally-distributed (Fig. 4). As expected, measurements made from waveforms containing less than 20% of the total return energy within their lowest reflection (i.e., the within-footprint canopy closure was greater than ~80%) cause the largest number of outliers in the distribution of elevation differences since these reflections are the hardest to precisely and consistently locate during processing (Fig. 4a). However, a large number of the crossover elevations are still within ~2 m of each other indicating even though the lowest reflection is relatively weak it has been precisely located. Measurements corresponding to waveforms with relatively strong lowest reflections have the highest elevation precision, better than 1 m (Fig. 4b and c).

4. Accuracy of lidar sub-canopy topography measurements

The assessment of the lidar measurement precision showed that the lidar elevation measurements are consistent to better than 1 m in some circumstances. Next we verify the accuracy of these observations by comparing them to near-coincident, independently measured ground elevations collected using ground-based surveying. Positions both with and without physical

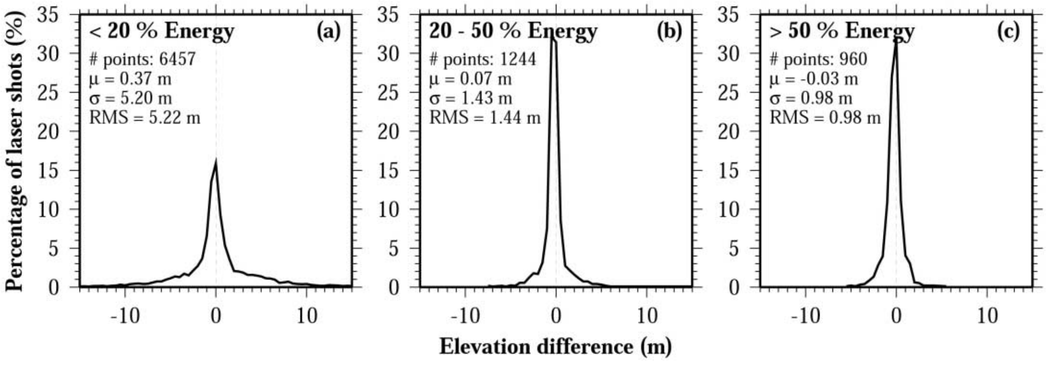

Fig. 4. Same as Fig. 3 except elevation differences are shown as a function of the percentage of return energy within the lowest reflection within the waveform; (a) less than 20%, (b) 20–50%, and (c) greater than 50%.

monuments are included. A histogram of the differences between the two elevation measurements is shown in Fig. 5a. The mean difference is 0.62 m, with standard deviation 1.27 m and rms difference 1.41 m. Only LVIS elevations corresponding to waveforms with greater than 20% of the total reflected energy within their lowest reflection are used. This reduces the possibility that waveform misinterpretation effects are included in the comparison. We also restrict the comparison to laser footprints situated on slopes of 3° or less (calculated from the DTED Level 1 elevation data at 90 m length scales) (Fig. 5) in order to minimize errors associated with the fundamental difference between the elevation measurements made using the lidar and ground-based techniques. The lidar elevation measurement represents the mean elevation within the lidar footprint, yet the ground-surveyed elevation is a measurement of a single point elevation on the ground. These measurements are only equivalent under low surface slope and roughness conditions. Under all other conditions, the elevation differences caused by the different measurement processes will be compounded by the horizontal offset between the laser footprint center and ground survey point location multiplied by the ground slope. Including all coincident measurements, that is, comparing the closest LVIS footprint within 12.5 m of each survey location (a total of 7414 points) yields a mean elevation difference of 2.54 m, with a standard deviation of 5.03 m and a rms difference of 5.64 m (Fig. 5a).

5. Discussion

Results show that using large (25 m) footprint laser altimetry, we are able to precisely and accurately measure sub-canopy topography in a densely-forested environment. Crossover analyses

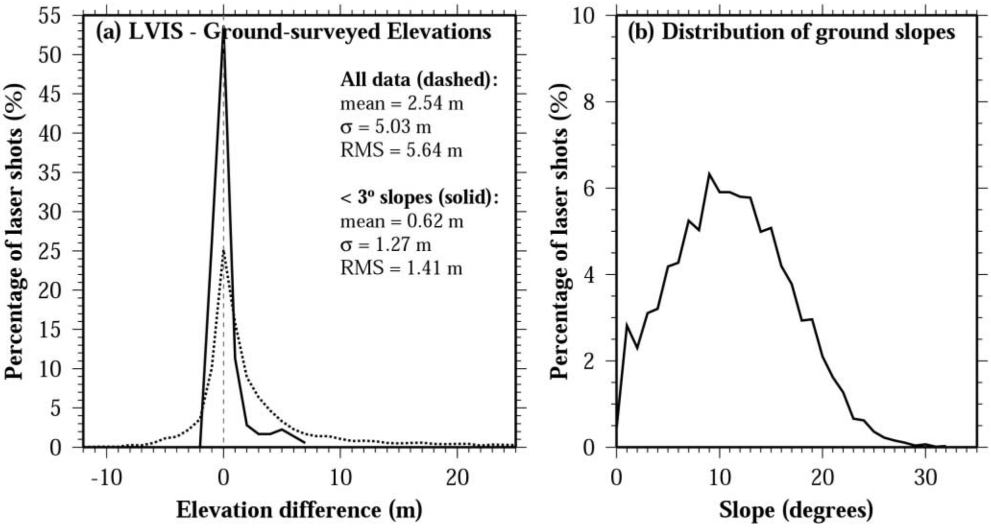

Fig. 5. (a) Histogram of the elevation differences between the LVIS ground elevation and the closest ground-surveyed measurement within a 12.5 m radius of the center of each LVIS footprint on slopes of less than 3° and for which the lowest reflection in the LVIS waveform contained more than 20% of the total return energy. The ground-surveyed elevations were subtracted from the LVIS measurements. 177 measurements were compared. The dashed line shows the histogram if all coincident measurements are included. (b) Distribution of slopes at each ground-based measurement location within La Selva (at 90 m lengthscales). The slopes were calculated using Level 1 Digital Terrain Elevation Data (DTED).

revealed the elevation measurements made by the LVIS system were within 1 m vertically of each other if the energy contained within the lowest reflection or mode within the return lidar waveform was high. These are very encouraging results given the complex and dense nature of the forest in this area, and the difficulties associated with consistently mapping ground topography in these conditions using remote sensing methods. Accuracy assessments were also encouraging. The comparison of the LVIS-derived topography with ground-surveyed elevation data indicated an overall difference of ~1.5 m. Only data collected on slopes of less than 3° were included in order to minimize effects resulting from fundamental differences in the measurement techniques; i.e., the two measurement techniques only produced equivalent elevation data under low surface slope and roughness conditions where the distinction between a point (the ground-surveyed measurement) and an area measurement (made by the lidar) is not important. Including all data points in the comparison showed that the data were within ~5 m vertically of each other.

The comparisons revealed, however, that the lowest lidar elevations within a footprint were biased relative to the ground-based measurements (the lidar data are above the ground-surveyed elevations). Possible causes of this bias include errors associated with the ground data, especially in regards to their reference frame, the failure of the laser to penetrate all the way through the canopy to the ground, as well as effects due to the misselection of the ground reflection during processing. If no ground reflection exists within the recorded waveform, it is impossible to directly measure ground elevation using the lidar waveform. Canopy penetration problems will be a factor on all air and spaceborne lidar missions. After accounting for the effects of time of day, cloud cover and the lifetime of the laser, the number of photons that reach the forest floor is primarily dependent on canopy closure, height of the canopy and structural stratification. At La Selva, the vegetation is characterized by a tall canopy, multiple layers of foliage and a well developed shrub and palm understory which greatly impede light penetration (Denslow and Hartshorn, 1994). The canopy closure is also generally high, about 98–99%, which is a common closure value for broadleaf evergreen forests (Chazdon and Fletcher, 1984). In terms of global topographic mapping with large-footprint laser altimetry, this signifies that the broadleaf evergreen biome (covering 9.7% of terrestrial land (DeFries et al., 1998)) is one of the most challenging environments in which to accurately capture sub-canopy topography.

We are able to broadly identify cases involving laser penetration problems by finding comparison points in which the minimum elevation within the recorded waveform is above the elevation of the corresponding ground-surveyed point. Approximately 4% of the comparison points are affected in this manner, suggesting that in only a small proportion of the shots did the lidar fail to penetrate the dense canopy to the ground, even in the very dense canopy cover conditions at La Selva. The mean elevation difference between these lidar and ground-surveyed measurements is +17.00 m, with standard deviation 6.73 m. Fig. 6a shows a recorded LVIS waveform which we believe does not contain a ground reflection, as well as the elevation of the ground-surveyed measurement. Also shown are the elevations of individual reflecting surfaces within the confines of the LVIS as footprint measured by a small footprint laser altimeter system, dubbed FLI-MAP (John E. Chance and Associates, Louisiana). These types of laser altimeter systems make high-resolution maps of small areas and derive the elevations of the highest (and sometimes lowest) reflecting surfaces only. The systems do not typically digitally record the return laser pulse shape, making only a real-time analog measurement of the travel time of the laser pulse. However, to measure sub-canopy ground elevation with laser altimetry, a portion of the beam must penetrate

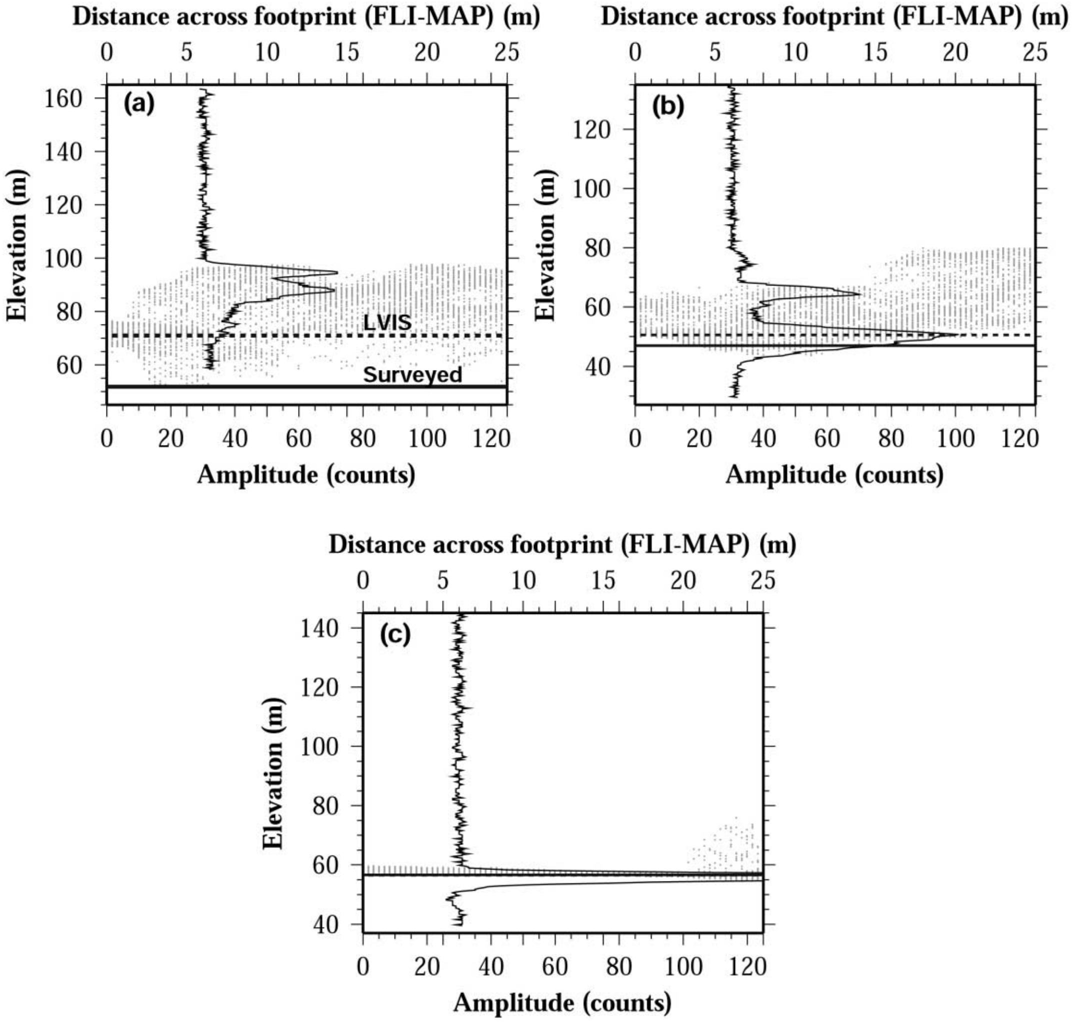

Fig. 6. Vertically-geolocated LVIS waveforms with the elevations of the ground-surveyed points shown by the solid horizontal lines. The elevations of the lowest surfaces determined during waveform processing are represented by the dashed lines. Examples in which the ground reflection appears (a) missing, or (b) mixed in with overlying vegetation returns are shown. (c) A waveform from bare ground. Corresponding elevation data measured by the FLI-MAP system within a 25 m square area centered on the LVIS footprint are shown as grey dots in each figure. The north end of the square corresponds to the distance of 0 m. In (c), vegetation was detected by the FLI-MAP system at the edge of the LVIS footprint.

through small gaps in the canopy to the forest floor. In structurally complex vegetation with high canopy closure (i.e., few gaps), laser ground interception can be difficult; thus in vegetated conditions, ground topography may be only rarely observed by these types of systems. The FLI-MAP system uses footprints with a nominal footprint diameter of ~0.1 m closely spaced across- and along-track to make vertical measurements with an accuracy of ~0.1 m (Huising and Gomes-Pereira, 1998). The majority of these measurements represent the elevation of the canopy, not the underlying ground (Fig. 6a). Note that without both ground-surveyed and FLI-MAP elevation data it is impossible to ascertain whether the ground response is contained within the vertical extent of the LVIS waveform.

An elevation bias can also be introduced into the lidar elevation measurement by the misselection during data processing of a mode from a higher reflecting layer within the canopy as the ground return. This misselection usually implies the ground reflection is "weak" (i.e., contains only a small proportion of the reflected energy from the footprint as a whole) and thus has been "overlooked" by the interpretation algorithm. However, since we have attempted to eliminate these laser shots by identifying waveforms containing weak ground returns it is more likely that the measurement bias is caused by the mixing of the ground return with reflections from low-lying vegetation. This results in an indistinct ground response, i.e., the lowest reflection has become convolved with reflections from higher surfaces (Fig. 6b), an effect which is compounded by within footprint slope and surface roughness. Improvements in our methods of waveform interpretation will enable better data accuracy. Digitally recording the shape of the return laser pulse means that these improvements can easily be applied. A return waveform from bare ground is shown for comparison in Fig. 6c.

These results build confidence in the ability of the VCL mission to accurately perceive and measure terrain elevation under vegetated conditions. Since the measurement processes of the LVIS and VCL systems are similar, we expect sub-canopy topography measurements made by the VCL in dense, complex forests to be similar to those presented here. In addition, the higher sensitivity of the VCL compared to that of the LVIS suggests that VCL data accuracy could be better in these forest types since higher sensitivity allows for more accurate detection of the lowest reflection. Furthermore, measurements made in less dense forests (that is, over the majority of the Earth) are expected to have a higher accuracy since less ground obscuration enables stronger ground reflection and facilitates accurate ground detection. Thus, it seems likely that the topographic measurements made by the VCL will meet stated accuracy goals under the majority of measurement conditions.

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