Validation of SRTM Elevations Over Vegetated and Non-vegetated Terrain Using Medium Footprint Lidar

Michelle Hofton, Ralph Dubayah, J. Bryan Blair, and David Rabine

Abstract

The Shuttle Radar Topography Mission (SRTM) generated one of the most-complete high-resolution digital topographic data sets of the world to date. The elevations generated by the on-board C-band sensor represent surface elevations in "bare earth" regions, and the elevations of various scatterers such as leaves and branches in other regions. Elevations generated by a medium-footprint (>10 m diameter) laser altimeter (lidar) system known as NASA's Laser Vegetation Imaging Sensor (LVIS) were used to assess the accuracy of SRTM elevations at study sites of variable relief, and landcover. Five study sites in Maine, Massachusetts, Maryland, New Hampshire, and Costa Rica were chosen where coincident LVIS and SRTM data occur. Both ground and canopy top lidar elevations were compared to the SRTM elevations. In "bare earth" regions, the mean vertical offset between the SRTM elevations and LVIS ground elevations varied with study site and was approximately 0.0 m, 0.5 m, 3.0 m, 4.0 m, and 4.5 m at the Maine, Maryland, Massachusetts, New Hampshire, and Costa Rica study sites, respectively. In vegetated regions, the mean vertical offset increased, implying the phase center fell above the ground, and the offset varied by region. The SRTM elevations fell on average approximately 14 m below the LVIS canopy top elevations, except in Costa Rica where they were approximately 8 m below the canopy top. At all five study sites, SRTM elevations increased with increasing vertical extent (i.e., the difference between the LVIS canopy top and ground elevations and analogous to canopy height in vegetated regions). A linear relationship was found sufficient to describe the relationship between the SRTM-LVIS elevation difference and canopy vertical extent.

Introduction

Interferometric Synthetic Aperture Radar (INSAR) and laser altimeter (also referred to as lidar) measurements of topography provide complementary approaches to characterize the Earth's surface. In February 2000, the Shuttle Radar Topography Mission (SRTM), on board NASA's Space Shuttle Endeavour, was used to generate the most complete high-resolution digital topographic database of Earth to date. Using an orbit inclination of 57°, 80 percent of the Earth's total landmass was imaged at least once during the 11-day mission. The SRTM consisted of a specially modified radar system, incorporating both X- and C-band sensors (e.g., Hensley *et al.*, 2000). The data were processed by NASA's Jet Propulsion Laboratory (JPL) (C-Band) and the German Aerospace Research Establishment (DLR) (X-Band), providing digital elevation models (DEM's) at 1 and 3 arcsecond resolutions. The SRTM data were expected to have a horizontal accuracy of less than 20 m, and 90 percent (1.6 standard deviations) absolute and relative height errors of less than 16 m and 10 m, respectively (e.g., Bamler, 1999). Validation efforts incorporating ground-based kinematic Global Positioning System (GPS) and other data such as DEMs indicated that the accuracies exceeded specifications (e.g., Rodriguez, 2005; Brown *et al.*, 2005; Kocak *et al.*, 2005). Rodriguez (2005) found horizontal accuracy was better than 12 m (90 percent), absolute vertical accuracy was better than 9 m, and relative vertical accuracy was better than 10 m. Accuracies also varied by continent and region (Rodriguez, 2005); for example, absolute errors of −4.0 m and −1.1 m were found for areas in Iowa and North Dakota, respectively (Kellndorfer *et al.*, 2004). However, given the relatively short operating wavelength of the C-Band sensor (5.6 cm), retrieved elevations over vegetated terrain were not expected to represent "bald earth" surface elevation, but rather the elevations of various scatterers such as leaves and branches. Thus, in vegetated terrain, the DEM's represent neither the "bald earth" surface nor the canopy top surface, but some elevation between the two.

A technique attracting increasing attention for its ability to provide precise and accurate ground and canopy top elevations, as well as its efficacy for validating remote sensing data sets, such as those provided by the SRTM is lidar remote sensing. Lidar is an active remote sensing technique similar to radar, utilizing a focused pulse of short-wavelength (1064 nm) laser light. This short pulse (typically 5 to 10 ns at Full Width Half Maximum (FWHM)) is fired towards the Earth where it is reflected off various surfaces such as branches, leaves, and the ground before returning to the sensor. The time of flight of the laser pulse is measured and provides the range from the instrument to the reflecting surface. The combination of this range measurement with the position and pointing of the sensor allows the laser footprint to be geolocated (e.g., Hofton *et al.*, 2000). Because the laser pulse emitted by the system is

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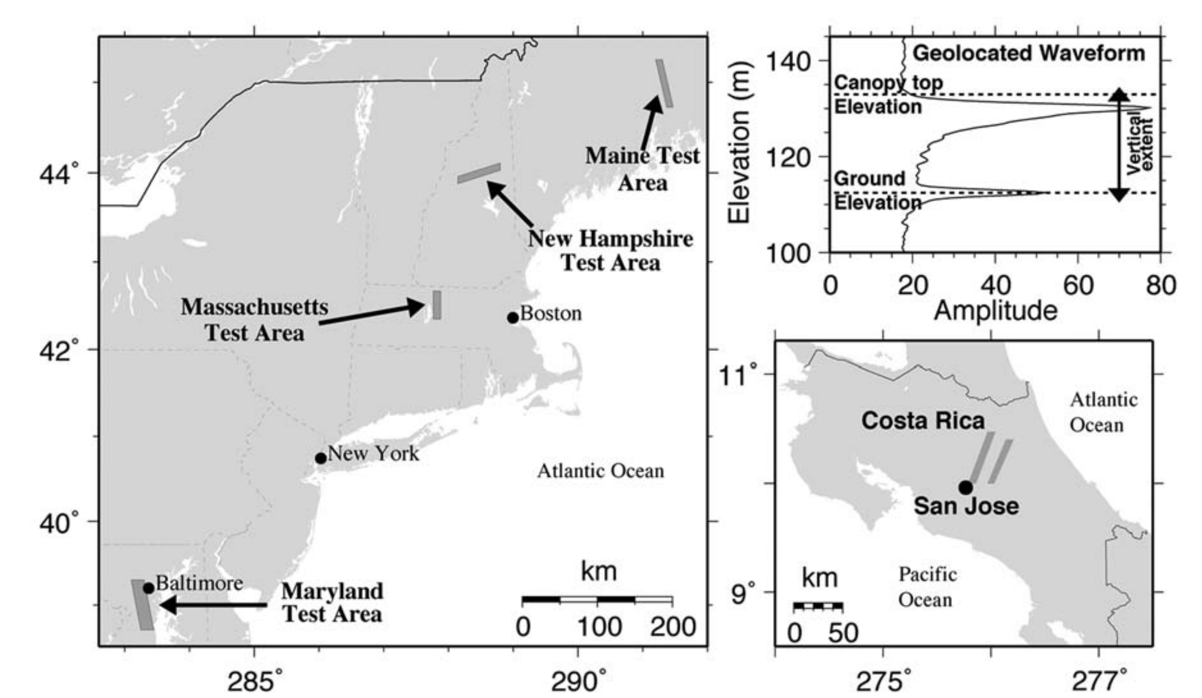

Figure 1. Maps showing study sites referred to in the text. Locations and characteristics of the study sites can be found in Tables 1 and 2. A schematic of a laser return waveform and its relationship to derived lidar data products is shown upper right. The waveform is vertically located relative to the WGS84 ellipsoid.

extended in time and space, and interacts with a vertically extended object, such as canopy, the return pulse is extended as well (Figure 1). The majority of existing sensors are small-footprint (<1 m wide) and record the range to one or multiple ambiguous reflecting surfaces on the ground. Such systems provide a wealth of data for validation of other remote sensing data sets such as those provided by the SRTM. However, in vegetated regions, reconstruction of the "bald earth" elevation surface must be done statistically (e.g., Pfeifer and Kraus, 1998; Sithole, 2003), potentially resulting in loss of both spatial resolution as well as accuracy.

In this study, we evaluate the accuracy of the SRTM C-band DEM's in various terrains by comparing them with coincident ground and canopy top elevation data obtained from NASA's Laser Vegetation Imaging Sensor (LVIS) (Blair *et al.*, 1999). LVIS is a medium-footprint (20 m diameter), laser altimeter system that fully digitizes the return laser signal, or waveform. Such systems provide both the "bald earth" and canopy top elevations, as well as the vertical structure of vegetation for each laser shot (e.g., Dubayah *et al.*, 2000; Zwally *et al.*, 2002). Spatial resolution is preserved, and precision and accuracy of both measurements are retained (since reflections from both surfaces are recorded in the waveform and can be identified post-flight using appropriate algorithms). Previous studies have shown the utility of the LVIS for precise and accurate measurement of surface topography and canopy height, even in dense, 98 to 99 percent closed tropical forests where horizontal accuracy of the system was found to be better than 2 m (Blair and Hofton, 1999), and vertical accuracy was found to be better than 2 m for sub-canopy topography (Hofton *et al.*, 2002) and canopy height measurements (Peterson *et al.*, 2005). In this study, we will compare SRTM elevations to LVIS ground and canopy top elevations to verify the accuracy of the SRTM elevations, and quantify SRTM elevation error as a function of canopy vertical extent. Relative horizontal accuracy of SRTM elevations will also be assessed by varying the relative positioning of the coincident data sets.

Data Set Characteristics

SRTM Data

Utilizing a 225 km wide swath from an altitude of 233 km above the Earth, the C-band sensor on board the SRTM imaged approximately 99.97 percent of the Earth's landmass between 60° north and 56° south at least once during the 11-day mission, with many areas receiving multiple over-passes (USGS, 2005a). Only six locations, all located within the United States, and totaling 50,000 km^2 were not imaged (USGS, 2005a). "Finished" (edited) digital elevation models (DEM's) were released at a spacing of 1 arcsecond (approximately 30 m at the equator) for the United States, and 3 arcseconds for all other regions (**http://seamless.usgs.gov**). Editing of the "finished" products consisted of delineating and flattening water bodies, better defining coastlines, removing "spikes" and "wells," and filling small voids (USGS, 2005b). Three arcsecond data were produced from the 1 arcsecond set by "subsampling," i.e., selecting the center value from the set of nine centered on a particular posting location. The horizontal datum of the SRTM DEM's is WGS84 (USGS, 2005b). The vertical datum is "mean sea level" as determined by the WGS84 Earth Gravitational Model (EGM96) geoid.

LVIS Data

In its nominal operating mode from an altitude of 10 km above ground level, NASA's airborne Laser Vegetation Imaging Sensor (LVIS) (Blair *et al.*, 1999), maps a 2 km wide swath filled with 20 m wide footprints that are contiguous along and across track. Areal coverage is increased by flying multiple adjacent but slightly overlapping swaths. Since 1998, the sensor has been used to generate maps of ground topography, canopy height, and structure in several regions including areas of Costa Rica (1998 and 2005), New Hampshire, Maine, Massachusetts (2003), and Maryland (2003 and 2004) (Figure 1). Data products, available at **http://lvis.gsfc.nasa.gov**, include the horizontal locations of both the ground and highest returns relative to the WGS84 ellipsoid (these can differ slightly if the laser beam travels at an off-nadir angle through the canopy), the elevations of the ground and highest return within the footprint (relative to the WGS84 ellipsoid) and metrics related to within-footprint structure such as quartile heights. In vegetated regions, the highest-return elevation and along-beam vertical extent products are commonly referred to as canopy top elevation and canopy heights, respectively. The released products are not gridded, but relate to each footprint. In order to facilitate comparison to the SRTM DEM's, LVIS ground and canopy top elevations were corrected to "mean sea level" using the EGM96 geoid (NGA/NASA, 2005). Studies to validate the horizontal and vertical precision and accuracy of LVIS data products in dense, 98 to 99 percent closed tropical forests in Costa Rica found that the horizontal accuracy of the system was approximately 2 m (1σ) (Blair and Hofton, 1999), and vertical accuracy was approximately 2 m (1σ) for sub-canopy topography (Hofton *et al.*, 2002) and canopy height measurements (Peterson *et al.*, 2005). In less densely-forested regions, data precision improves because the ground reflection is stronger and easier to interpret, and analysis of LVIS data at study sites in the U.S. using crossover analysis indicate a vertical precision of better than 0.25 m (1σ) and in flat, bare ground conditions as good as several centimeters.

Study Areas

The sites for this study are located in Costa Rica, New Hampshire, Maine, Massachusetts, and Maryland (Figure 1; Tables 1 and 2), and are areas where coincident LVIS and SRTM data exist. These sites include a variety of land cover conditions (for example, vegetated, non-vegetated, urban, wetlands, and sloped areas) and are areas that have been, and continue to be, sampled extensively using other remote sensing and ground-based methods. The site in Maine includes the Penobscot Experimental Forest and the International Paper Northern Experimental Forest. Plantations, natural forest stands (mixed evergreen and deciduous), clearings, wetlands, as well as urban landscapes are present. Topographically, the region varies from flat to gently rolling, with a maximum elevation change of less than 135 m and a mean slope of 3 degrees (obtained from the LVIS ground elevations) within the 60 km by 8 km study area. The Massachusetts site includes Harvard Forest, a mixed deciduous forest at approximately 300 m elevation. The area is dominated by red maple and red oak, with black birch, white pine, and hemlock also present. The region is gently rolling with a maximum elevation change of 200 m and a mean slope of 6 degrees within the 35 km by 10 km study area. The New Hampshire study site includes the Hubbard Brook Long Term Ecological Research site and Bartlett Experimental Forest located in the White Mountain National Forest. It has hilly terrain, ranging from 220 to 1,100 m altitude, has a mean slope of 13 degrees, and is covered by unbroken forest of northern hardwoods (sugar maple, beech, and yellow birch) with spruce and fir at higher elevations. Some urban sites are also present. The site is 80 km by 8 km. The Maryland study site includes the lower part of the Patuxent River watershed. Forests (deciduous and evergreen), wetlands, cultivated, and urban landscapes are present within the 60 km by 18 km area. The region varies from flat to gently rolling with a maximum elevation change of approximately 300 m and mean slope of 3 degrees. The Costa Rica site includes the La Selva Biological Research Station and parts of the Braulio Carillo National Park. The site consists of two, approximately 7 km by 60 km swaths from the central valley over the 3000 m high central cordillera to the Atlantic lowlands in the north of the country. The swaths are mostly covered in primary and secondary neotropical rainforest, although some cultivated and developed land is included. Average slope within the study site was 11 degrees. All study sites were overflown by LVIS during leaf-on conditions. Leaf-off conditions were prevalent at the study sites during the SRTM mission, except in Costa Rica.

Results

We assessed the accuracy of the SRTM elevation measurements by comparing them with the ground and canopy top elevations of near-coincident LVIS footprints. LVIS and SRTM measurements

TABLE 1. LOCATIONS OF STUDY SITES REFERRED TO IN THE TEXT

	Location (in WGS84)			
Site	Upper Left	Upper Right	Lower Right	Lower Left
Costa Rica	275.97E, 10.48N	276.90E, 10.80N	276.03E, 10.00N	275.87E, 10.18N
New Hampshire	288.17E, 43.96N	288.80E, 44.10N	288.80E, 44.03N	288.17E, 43.88N
Maine	291.20E, 45.25N	291.30E, 45.25N	291.47E, 44.74N	291.37E, 44.74N
Massachusetts	287.76E, 42.66N	287.88E, 42.66N	287.88E, 42.36N	287.76E, 42.36N
Maryland	283.10E, 39.30N	283.30E, 39.30N	283.44E, 38.70N	283.24E, 38.70N

TABLE 2. DATA SET CHARACTERISTICS. AVERAGE SLOPE WAS CALCULATED USING THE LVIS GROUND ELEVATION. AVERAGE CANOPY COVER VALUES WERE CALCULATED FROM THE MODIS VEGETATION CONTINUOUS FIELDS DATA SET (HANSEN *ET AL.*, 2003)

Site	*SRTM* Product	*LVIS* Footprint	Date of *LVIS* Flights	Average Slope (degrees)	Average Canopy Cover (%)
Costa Rica	3 arcsec	25 m	3/19/98–3/31/98	11	69
New Hampshire	1 arcsec	20 m	7/18/03–7/26/03	13	74
Maine	1 arcsec	20 m	7/26/03	3	66
Massachusetts	1 arcsec	20 m	7/20/03	6	74
Maryland	1 arcsec	12 m	10/23/04–10/29/04	3	36

within 5 m of one another horizontally were compared. The use of a small search radius was intended to minimize the influence of ground slope on the comparisons. For a large number of samples, the distribution of elevation differences should be Gaussian, with the mean, if it differs from zero, an estimate of the vertical offset between the two data sets.

Figure 2 shows the distributions of differences between SRTM and LVIS elevations from the five study sites. The summary statistics are given in Table 3. The comparisons were split based on the LVIS vertical extent (the distance between the ground and canopy top elevations) in order to quantify the effect of vegetation on the measurements. When the LVIS vertical extent was <5 m, the location was classed as "bare earth", i.e., the width of the LVIS return laser pulse was not extended temporally or spatially and vegetation was not assumed to be present. If LVIS vertical extent was ≥5 m, the location was classed as "vegetated" (although in urban settings, a vertical extent ≥5 m may also indicate a building). In "bare earth" regions, the differences between the SRTM elevations and LVIS ground elevations were Gaussian in distribution (Figure 2a). The mean differences varied between study sites, but were close to zero at the Maryland and Maine study sites, increasing to approximately 4 m and 3 m at the New Hampshire and Massachusetts study sites, respectively. The largest vertical offset (approximately 4.5 m) was observed at the Costa Rica study site. Standard deviations of the differences also varied with study site but were generally less than approximately 7 m (Table 3).

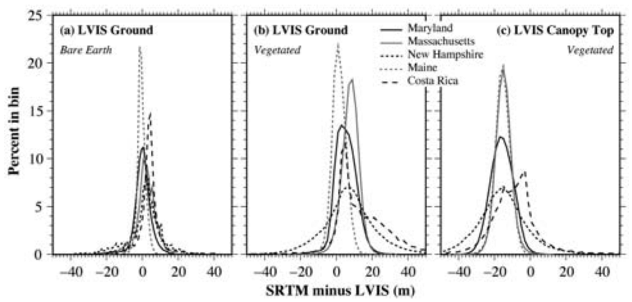

Figure 2. Histograms of the differences between SRTM elevations and LVIS ground in (a) "bare earth" and (b) "vegetated" conditions, and (c) between SRTM and LVIS canopy top elevations. Data within 5 m of each other horizontally for the five study areas are included. "Bare Earth" and "vegetated" regions are distinguished based on the LVIS vertical extent being <5 m or ≥5 m, respectively. Mean and standard deviation of the differences are given in Table 3. Non-Gaussian effects in the left hand side of (a) are caused by the lidar not penetrating through to the ground or by misidentifying the ground during processing (e.g., identifying vegetation as the ground).

In "vegetated regions", the differences between SRTM elevations and LVIS ground elevations for the Maryland, Maine, Massachusetts, and New Hampshire study sites were Gaussian in distribution (Figure 2b). However, the differences at the Costa Rican study site were bimodal in distribution, with the presence of a second mode centered at approximately 20 m indicating that a significant portion of the SRTM elevations fell above the LVIS ground elevations. At all sites, the mean differences were other than zero and varied site to site, indicating a varying regional, vertical offset between the SRTM elevations and LVIS ground elevations. The mean elevation differences were also higher than those for the corresponding "bare earth" comparison, indicating that in the presence of vegetation the mean SRTM elevation lay above the ground. As with the "bare earth" comparisons, the SRTM elevations and LVIS ground elevations had the smallest mean vertical offset at the Maine and Maryland study sites (approximately 2.5 m and approximately 6 m, respectively), whereas the differences between the SRTM and LVIS data sets in New Hampshire and Massachusetts had larger mean vertical offsets of approximately 8.5 m. The largest mean vertical offset occurred at the Costa Rican study site, and was approximately 16 m (Table 3). The standard deviations of the differences also varied with study site, and were <6 m for the Massachusetts, Maryland, and Maine sites, increasing to 14.5 m and 18 m in New Hampshire and Costa Rica (Table 3).

Similar results were observed when comparing the SRTM elevations to the LVIS canopy top elevations, except the mean vertical offsets between the data were approximately −14 m in the United States and approximately −8 m in Costa Rica. The average LVIS vertical extents were 16.5 m to 24 m (Table 3). Thus, the SRTM elevations fell below the canopy top but above the ground in vegetated regions. The LVIS vertical extent and SRTM-LVIS differences of a portion of the Maryland test site are shown in Plate 1. SRTM-LVIS differences are dependent on canopy vertical extent. When vertical extent is <5 m the SRTM elevations are within a few meters of the LVIS ground (Plate 1b and 1c), and the SRTM data represent well the "bare earth" terrain. However, SRTM-LVIS differences increase in the presence of an extended LVIS return; as vertical extent increases, SRTM-LVIS ground and canopy top elevation differences increase, and in vegetated/forested terrain the SRTM elevations correspond to neither the canopy top nor the ground (Plate 1c and 1d).

A scatter plot of SRTM-LVIS elevation differences against LVIS vertical extent shows the increase in magnitude of the elevation differences as vertical extent increases (Figure 3),

Table 3. Mean (μ) and Standard Deviation (σ) of the Elevation Differences Between the SRTM and LVIS Ground and Canopy Top Elevations in "Bare Earth" (LVIS Vertical Extent is <5 m) and Vegetated (LVIS Vertical Extent is ≥5 m) Regions. LVIS Vertical Extent is Obtained by Differencing the Ground and Canopy Top Elevations

	LVIS Vertical Extent <5 m			LVIS Vertical Extent ≥5 m						
	SRTM–LVIS Ground			SRTM–LVIS Ground			SRTM–LVIS Canopy Top			
Study Site	# obs	μ (m)	σ (m)	# obs	μ (m)	σ (m)	# obs	μ (m)	σ (m)	Mean Vertical Extent
Costa Rica	1,878	4.28	5.78	31,857	16.16	18.08	31,857	−8.03	15.75	24.19 m
Massachusetts	4,089	2.97	5.01	100,797	8.80	4.72	100,797	−13.84	4.52	22.65 m
New Hampshire	1,149	3.70	6.96	231,279	8.14	14.62	231,279	−14.40	13.82	22.54 m
Maryland	304,693	0.61	5.02	526,870	6.11	5.98	526,870	−14.46	6.52	20.58 m
Maine	6,137	0.03	2.49	133,329	2.54	3.84	133,329	−14.40	4.57	16.57 m

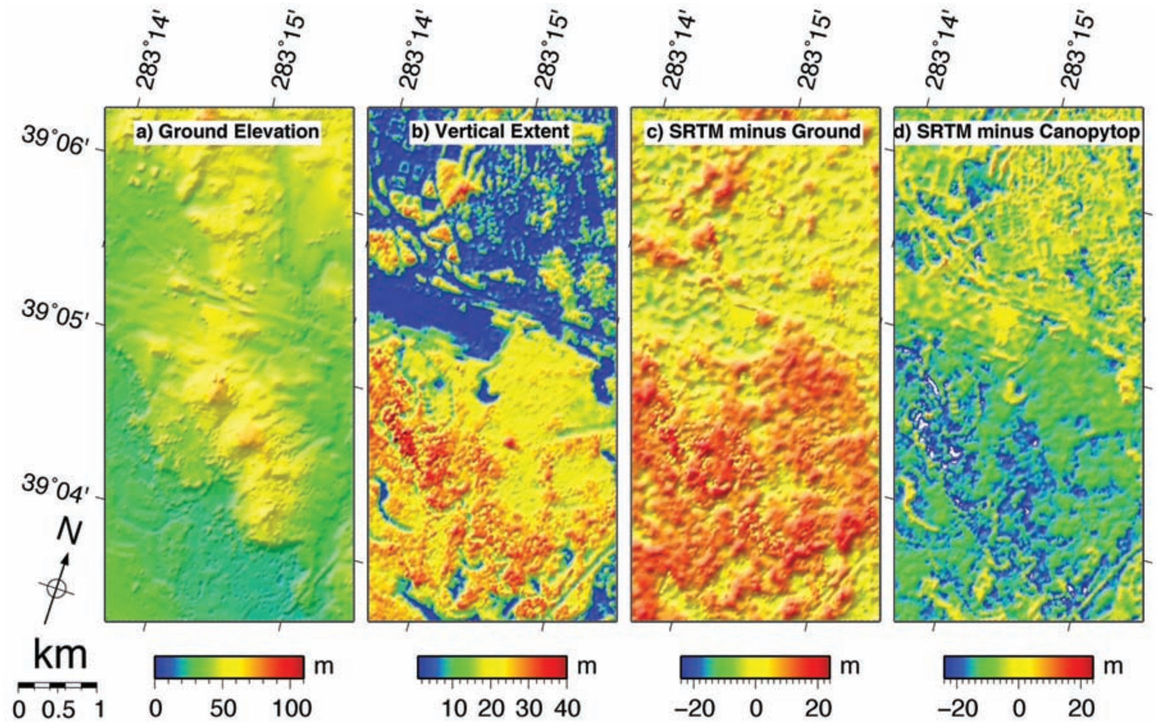

Plate 1. (a) LVIS ground elevation, (b) LVIS vertical extent, and SRTM minus LVIS (c) ground and (d) canopy top elevations for a portion of the Maryland study site. In vegetated regions, LVIS vertical extent is analogous to canopy height. The area is a mix of commercial, urban, and forested landscapes on gently rolling terrain. The outlines of buildings, roads, forested areas, and clearings can be discerned in the vertical extent image.

i.e., the elevation of the SRTM phase center below the canopy top increases with increasing vertical extent. Using a general linear least squares regression analysis, strong correlations between the SRTM-LVIS differences and vertical extent were found, with the strongest correlation ($R^2 = 0.74$) associated with the linear relationship of SRTM elevation minus LVIS canopy top elevation to LVIS vertical extent. The standard error between the predicted and observed differences was 5.61 m (Table 4). The average SRTM-LVIS elevation differences for every 2.5 m of LVIS vertical extent were also consistent between sites, except at the Costa Rica study site where average differences in each vertical extent class were larger by as much as 10 m (Figure 3). Least squares regression analyses were also performed using data from each study site. The linear relationships between SRTM elevation minus LVIS canopy top elevation and LVIS vertical extent for each of the five study sites are shown in Table 4. The strongest correlations occurred at the Maryland, Maine, and Massachusetts sites, and the weakest at the Costa Rica site.

To verify the relative horizontal positioning accuracy of the SRTM and LVIS data sets, we calculated the standard deviation of the differences between the SRTM elevations and LVIS canopy top elevations while varying the relative positioning of the two data sets. We expect the standard deviation of the differences to be minimized when the two data sets are aligned. Figure 4 shows the standard deviation of the SRTM elevations minus LVIS canopy top elevations as a function of horizontal offset between the data sets for the study sites in the United States, with the LVIS data set location kept fixed. Data from the Costa Rica study site were found to be insensitive to small relative changes in horizontal positioning because of the larger grid spacing of the SRTM data at this location and thus results are not shown. Clear minimums in the standard deviation images were seen, occurring to the west (in the x direction) and north (in the y direction) of the original positioning of all the four study sites (Figure 4). Total radial offsets of 15 m, 18 m, 25 m, and 21 m were required at the Massachusetts, New Hampshire, Maine, and Maryland study sites, respectively.

Discussion

Our results show that under "bare earth" conditions, elevation data from the SRTM are accurate measurements of LVIS ground elevations. A mean vertical offset was found that varied with region, a result that was not inconsistent with previous studies (e.g., Rodriguez, 2005; Kellndorfer *et al.*, 2004). The mean offset was better than approximately 3.5 m within the United States (1 arcsecond data) and approximately 4.5 m in Costa Rica (3 arcsecond data). Standard deviations of the differences (1σ) were better than approximately 7 m. In vegetated terrain (i.e., where the LVIS vertical extent was ≥5 m), the mean vertical offset increased and the SRTM elevations fell above the ground and below the canopy top. The standard deviations of the differences in vegetated terrain generally increased, particularly in Costa Rica where it was close to three times as large as in the "bare earth" case. Given the wavelength of the C-band sensor (5.6 cm) the loss in accuracy in vegetated terrain was not unexpected, as the elevation of the scattering phase center (the vertical position within the canopy from where the majority of backscattered energy is returned) reflects the interaction of the INSAR signal with various scatterers such as leaves, branches, and stems. The Costa Rica study site encompassed

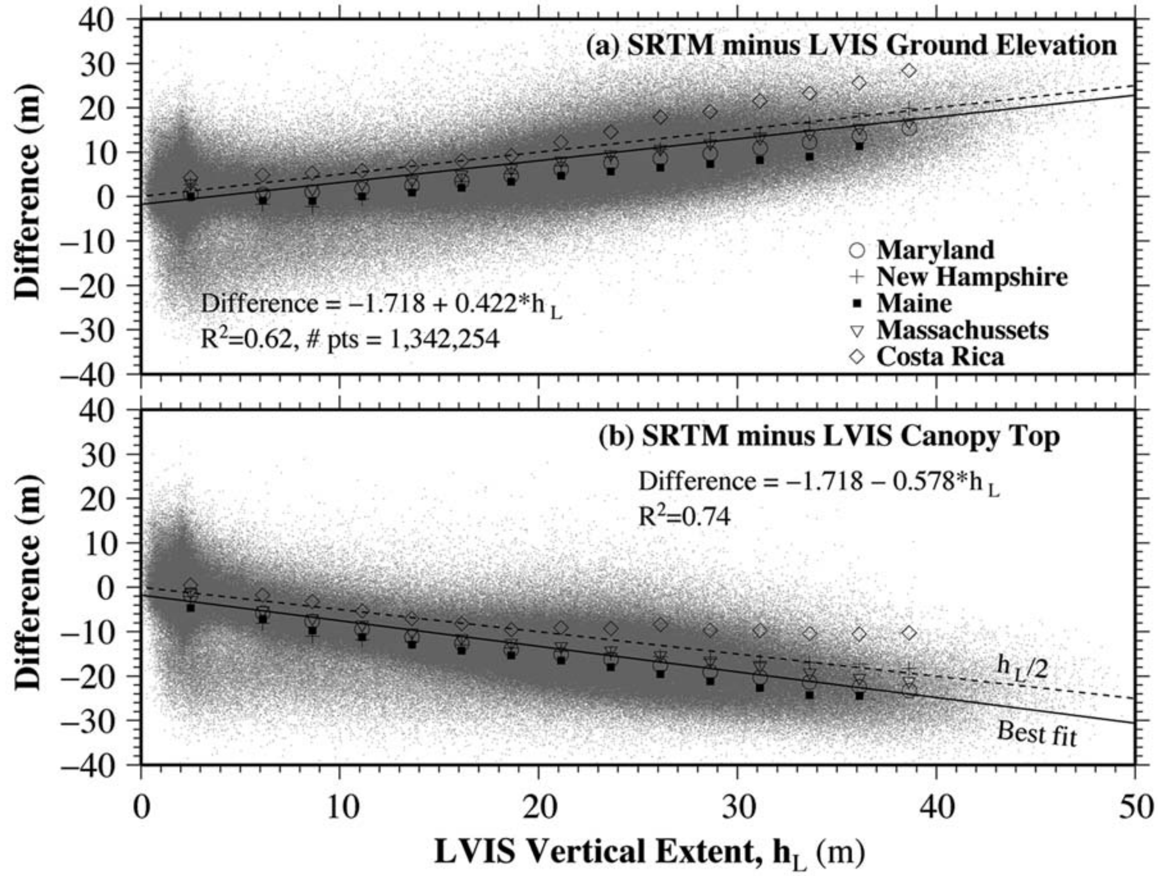

Figure 3. Differences between SRTM elevations and LVIS (a) ground and (b) canopy top elevations as a function of LVIS vertical extent (canopy top minus ground elevation, i.e., canopy height in forested regions). The best fit line to the data in the least squares sense is shown (solid), as well as LVIS vertical extent divided by 2 (dashed). The average SRTM-LVIS elevation differences based on linear 2.5 m binning of LVIS vertical extent are also shown for each study site. Site-specific linear relationships are given in Table 4.

Table 4. Least Squares Regression Results Describing the Relationships Between SRTM Elevations Minus LVIS Canopy Top Elevations and LVIS Vertical Extents (h_L) at the Five Study Sites as well as Overall

Study Site	# obs	Linear Fit (canopy top difference)	R^2	RMSE (m)
Costa Rica	33,735	−2.339–0.226 h_L	0.17	15.25
Massachusetts	104,886	−1.391–0.545 h_L	0.62	4.08
New Hampshire	232,604	−7.777–0.299 h_L	0.29	5.78
Maryland	831,563	−0.887–0.641 h_L	0.83	4.77
Maine	139,446	−3.697–0.619 h_L	0.79	2.97
All	1,342,254	−1.718–0.578 h_L	0.74	5.61

dense, closed (98 to 99 percent) tropical rainforest as opposed to the mixed evergreen/deciduous forests at the U.S. study sites, and such structural related differences between study sites can also be expected to have a differential influence on the elevation of the scattering phase center. The comparison at the Costa Rica study site used 3 arcsecond SRTM elevation data, generated by subsampling the 1 arcsecond SRTM data. Subsampling has been found to decrease the contribution of phase noise to the overall error (Kellndorfer *et al.*, 2004), so a comparison using 1 arcsecond data in Costa Rica could be expected to have much larger elevation differences. In vegetated terrain, the elevation of the SRTM phase center increased with increasing vertical extent. The dependence of elevation difference on vertical extent was similar at the four U.S. study sites, but was steeper at the Costa Rican study site, possibly due to the more complex nature of the canopy in this region. A linear model (R^2 = 0.74) was found sufficient to describe the relationship between elevation difference and canopy height using data from all five study sites indicating that if canopy height is known by some other method, then a data set-wide elevation correction could be applied to the SRTM data to increase its accuracy when describing either the ground or canopy top in vegetated regions. Local/regional corrections based on forest type could increase this accuracy still further. Although not the best fit in a least squares sense, a good approximation to the difference in vegetated regions is vertical extent divided by 2 (Figure 3). Our results indicated a horizontal offset between the SRTM and LVIS data sets, with SRTM data requiring shifting to the west and north by 10 to 20 m, or approximately half a pixel, in order to minimize the standard deviation between the elevation measurements. SRTM data used in this study were obtained from the USGS (**http://seamless.usgs.gov**) and coordinates were assumed to refer to the geometric center of each pixel. Coordinates relating to the top left corner of each pixel would resolve the offset observed here. The site to site

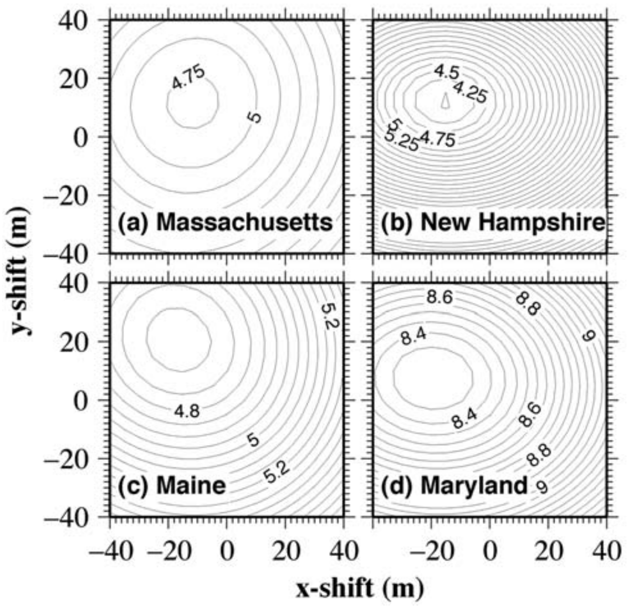

Figure 4. Standard deviation of the differences between SRTM and LVIS canopy top elevations as a function of relative changes in horizontal positioning between the two data sets for the (a) Massachusetts, (b) New Hampshire, (c) Maine, and (d) Maryland study sites. Standard deviations were minimized at distances of 10 m (*x*) and 12 m (*y*), 14 m (*x*) and 12 m (*y*), 16 m (*x*) and 20 m (*y*), and 20 m (*x*) and 8 m (*y*) at the four sites, respectively. The LVIS data locations were held fixed during the comparisons.

consistency of the direction of the offset implies that the horizontal positioning error is unlikely to be in the LVIS data sets as such an error could only be caused by an error in the position of the GPS base stations used when collecting data at all four sites. The research presented here demonstrates that the elevation data collected by the SRTM is an accurate representation of the Earth's surface at 1 and 3 arcsecond resolution.

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