Quantifying recent pyroclastic and lava flows at Arenal Volcano, Costa Rica, using medium-footprint lidar

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[1] Arenal volcano is a small, active stratovolcano in Costa Rica. In 1998 and 2005, NASA's Laser Vegetation Imaging Sensor (LVIS) was used to collect wide-swath 3-dimensional topographic images of the volcano. The LVIS is a full-waveform, scanning, medium-sized footprint, airborne laser altimeter system. By digitally recording the shape of the returning laser pulse (waveform), the LVIS provides a precise and accurate view of both the sub-canopy and canopy-top topographies as well as the vertical and horizontal structure of vegetation at 15–25 m horizontal resolution. By comparing georeferenced waveform data collected in 1998 and 2005, we mapped lava and pyroclastic flows deposited during this period. The active crater grew by 3.82 m yr^{-1}. A flow volume estimate of 2.19×10^7 m^3 (Dense Rock Equivalent of 1.89×10^7 m^3 or 0.085 m^3s^{-1}) was obtained for the period 1998 to 2005. Precise elevation and elevation change data such as those provided by the LVIS are essential to calculate eruption volume and to study magma-supply dynamics, as well as assess the danger posed by the volcano to the local population from hazards such as pyroclastic flows. **Citation:** Hofton, M. A., E. Malavassi, and J. B. Blair (2006), Quantifying recent pyroclastic and lava flows at Arenal Volcano, Costa Rica, using medium-footprint lidar, *Geophys. Res. Lett.*, *33*, L21306, doi:10.1029/2006GL027822.

1. Introduction

[2] Arenal volcano is a young (7,000 years old) stratovolcano [*Soto and Alvarado*, 2006] located in north-central Costa Rica (Figure 1). Its current period of activity began in July 1968 when an explosive eruption from three craters on the western flank resulted in 80 fatalities. Since this time, lava has been extruded almost continuously. From 1998 to 2005, activity consisted of continuous lava extrusion and small ash emissions from the active vents: in 1998 from the north vent of the summit crater C (Figure 2), and after 1999 from the vents located near the rim of the north vent of the summit crater C (NE, N and SW of the vent). Small infrequent pyroclastic flows also occurred down the northern and western flanks of the volcano. Considerable topographic changes have occurred to the volcano during its eruptive phase. Monitoring techniques have included radar interferometry, stereo photogrammetry, and field surveying [e.g., *Wadge et al.*, 2006]. The summit is estimated to grow at a rate of ~4.0 m per year (R. van der Laat, personal communication, 2006), and an estimated volume of 641 × 10^6 m^3 of magma has been extruded 1968–2004, at rates as high as 0.93 m^3s^{-1} [*Wadge et al.*, 2006].

[3] Accurate spatial and temporal mapping of the changes caused by frequent pyroclastic and continuous lava flows at Arenal volcano is essential for calculating flow volume and effusion rate to constrain and understand magma dynamic processes. Accurate elevation information is needed to study pyroclastic flows in order to evaluate their hazard to the local population. Remote sensing techniques provide many advantages over traditional, ground-based sampling methods, including easier remote monitoring, improved areal coverage, and improved accuracy of volume estimates since access is not restricted to the edges of lava flows where measurements of lava height are rarely representative of the total flow thickness. Sensors that make elevation measurements beneath vegetation also reveal subtle variations in local relief that may affect the path of the flows.

[4] Airborne laser altimetry (also referred to as lidar) has been used to monitor volcanoes in several locations (e.g., Long Valley, CA [*Hofton et al.*, 2000], and Mount St Helens, WA [*Carabajal et al.*, 2005]). Lidar is an active remote sensing technique in which a short-duration (typically 5–10 ns) laser pulse (1064 nm wavelength) is fired towards the Earth's surface 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 surfaces. 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].

[5] A small number of lidar systems digitally record the shape of the reflected laser pulse (return waveform). This enables post-flight interpretation of the waveform to characterize the elevation distribution of the ground and overlying surfaces for each laser footprint. Some systems utilize large footprints (>10 m wide) in order to penetrate consistently through to the ground, and generate multiple reflecting surface elevations for every laser footprint.

2. Lidar Remote Sensing of Arenal

[6] On March 19th, 28th and 31st, 1998, and March 31st, 2005, airborne surveys missions were conducted over Arenal volcano using NASA's Laser Vegetation Imaging Sensor (LVIS) [*Blair et al.*, 1999], a medium-large footprint (15–25 m), waveform-recording lidar system. In its current, nominal operating mode at an altitude of 10 km above ground level (agl), the LVIS is used to map a 2 km-wide swath filled with contiguous 20 m-wide footprints. Areal

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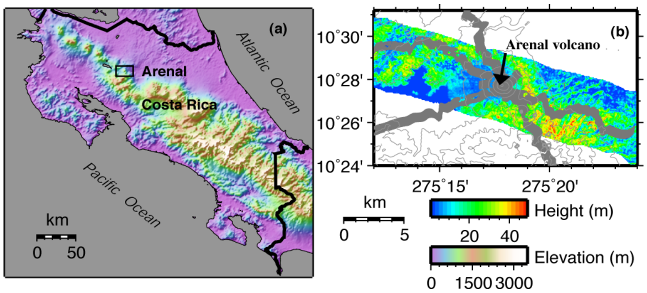

Figure 1. (a) SRTM-derived surface topography of Costa Rica. Study site location is outlined. (b) Close up of the study site. Colocated height and elevation (not shown) data were collected using the LVIS in 2005. The locations of 1998 LVIS data swaths are shown in gray.

coverage is increased by overlapping parallel swaths. During the 1998 mission, LVIS was used to generate a 900 m-wide swath comprised of ∼15 m-wide footprints from 7 km agl. During the 2005 mission, LVIS was used to generate a 1,600 m-wide swath comprised of ∼18 m-wide footprints from 8 km agl. Persistent cloud coverage during the 1998 mission resulted in only three swaths of usable data being collected over the volcano (Figure 1). Complete coverage of the volcano was achieved in 2005 (Figure 1).

[7] Available data products include the horizontal locations of both the ground and highest returns (or canopy top) relative to the WGS-84 ellipsoid (these can differ by a few meters caused by a non-nadir incident angle of the laser beam) and the elevations of the ground and highest return (or canopy top) within each footprint (relative to the WGS-84 ellipsoid). Intermediate products of the data processing, specifically "geolocated" laser return waveforms (i.e., ones whose horizontal and vertical locations are known relative to the WGS-84 ellipsoid) from which the data products are derived, are also available and were used in this study to eliminate potential problems associated with misinterpretation of the laser waveform (such as misidentification of the ground reflection).

[8] Previous studies utilizing the 1998 data in the dense (98–99% closed) tropical forests in Costa Rica found that the vertical accuracies were ∼2 m (1σ) for sub-canopy topography [*Hofton et al.*, 2002] and canopy height measurements [*Peterson*, 2000], and horizontal accuracy was ∼2 m (1σ) [*Blair and Hofton*, 1999]. Analysis of data collected following major instrument modifications in 2002 showed an improvement in data precision; crossover analysis utilizing data collected in the US indicated a vertical precision of better than 0.25 m (1σ) and in flat, bare ground conditions as good as several centimeters.

3. Topographic Change, 1998 to 2005

[9] To determine relative topographic change, we compared near-concentric LVIS return waveform measurements collected in 1998 and 2005. Using waveforms in their entirety to extract topographic changes, not some interpreted proxy, strengthened the comparison by involving the whole vertical structure, as well as eliminated possible problems associated with misinterpretation of the waveforms. Using a method dubbed "pulse correlation" [*Hofton and Blair*, 2002], we determined the relative vertical offset of two laser-measured surfaces by assessing the shape similarity (using the Pearson correlation) of the return waveforms. The method was individually applied to each waveform pair within the study region. The relative vertical offset between the two surfaces is a result of topographic change plus the effects of measurement errors in the GPS trajectory (estimated to be <10 cm) and those resulting from

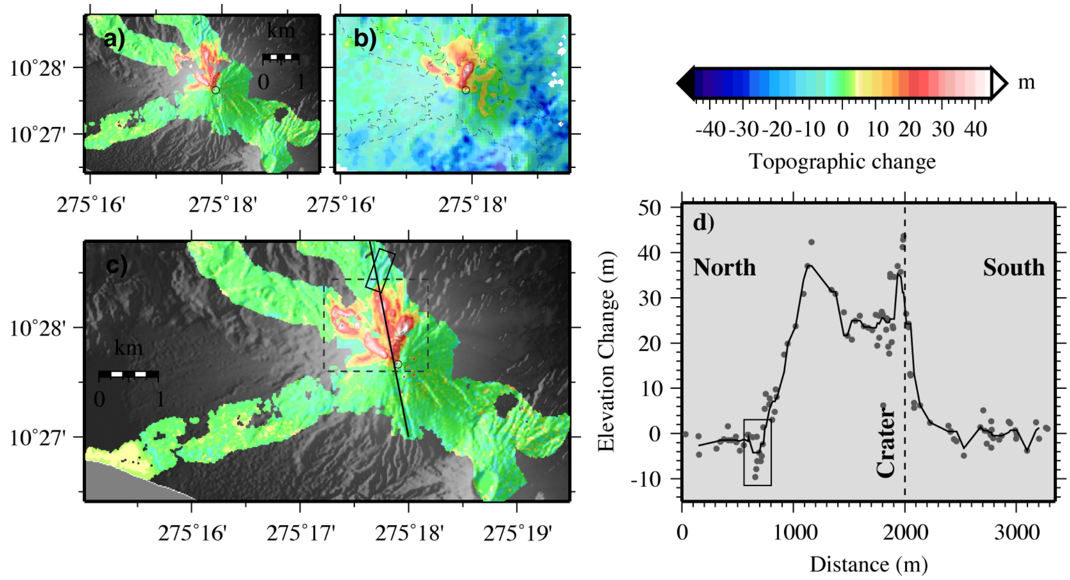

Figure 2. Topographic changes at Arenal volcano (a) 1998–200, (b) 2000–2005, and (c) 1998–2005 with cloud holes filled using the 2000–2005 data. The dashed and solid boxes outline the areas affected by recent flows and subsidence respectively. Data resolutions are 0.6 arcsec (∼18 m) (Figures 2a and 2c) and 3 arcsec (∼90 m) (Figure 2b). The area lower left undergoing ∼4 m of change is Arenal Lake. Shaded surface relief, generated from the 2005 LVIS data, is shown in the background. (d) Topographic change as a function of distance along the profile shown in Figure 2c. Solid line indicates the change after applying a median filter. Location of active crater C is shown by a dashed line.

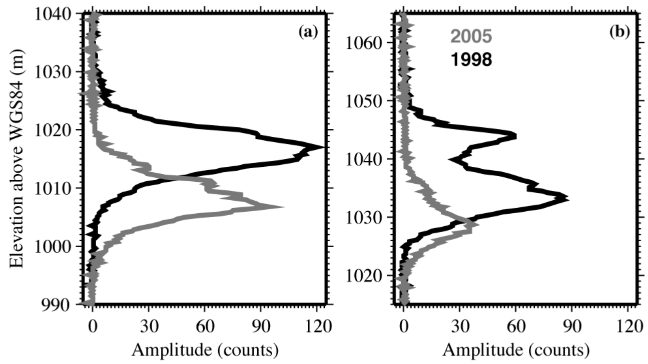

Figure 3. Coincident, geolocated waveform pairs from the north flank of the volcano where ground subsidence is indicated. Ground modes within each waveform pair are lower in the 2005 data (gray outline) than in the 1998 data (black outline). Waveforms are located at (a) 275.29968E, 10.47160N and (b) 275.29948E, 10.47109N.

comparing non-concentric footprints (contributing ~1 m of random error (zero mean) on steep slopes). These errors are considered small in comparison to the magnitude of the topographic change signal.

[10] Figure 2a shows the topographic changes at Arenal volcano, 1998–2005, measured using the pulse correlation method. Over 13,643 waveforms pairs whose center locations were within 3 m of each other were compared independently. The mean Pearson correlation before and after shifting of each waveform pair was 0.70 and 0.92 respectively. The poorer spatial coverage of the 1998 survey is evident (Figure 2a); only 3 data swaths were available for comparison. Small areas of missing data within a swath were caused by clouds or steam during the 1998 survey.

[11] The topographic changes 1998–2005 are very heterogeneous (Figure 2a). The largest changes are on the north and west flanks of the volcano, where up to 45 m of ground topographic change occurred. Topographic changes generally are at their maximum close to the center and approach zero at the flow margins (Figure 2a). The south and east flanks of the volcano underwent little or no topographic change, as did areas surrounding the volcano. Isolated, spurious ~4 m changes were a result of dissimilarly-shaped coincident waveforms caused by vegetation changes 1998 to 2005.

[12] From 1998 to 2005, numerous pyroclastic and active lava flows with little/no inflation or deflation of the volcano occurred [*Smithsonian Institution Global Volcanism Program*, 2006]. Since the majority of the lava and pyroclastic flow deposits were to the north and west of the crater [*Smithsonian Institution Global Volcanism Program*, 2006], we conclude that the topographic changes shown in Figure 2a represent the depths of lava and pyroclastic flows that occurred 1998 to 2005. Three distinct lobes are visible, extending west, northwest and north from the crater and approximately 800 m, 1500 m and 1300 m long (Figure 2a). The location of the north lobe, particularly the far north portion, likely corresponds to the path of the August 22nd, 2000, pyroclastic flow, as well as to the shorter, blocky lava flows issued from the NE cone.

[13] For comparison we included "finished" data from the Shuttle Radar Topography Mission (SRTM) [*Farr and Kobrick*, 2001], flown in February 2000. Digital elevation models (DEMs) for Costa Rica are available at 3 arcsec resolution. Horizontal and absolute vertical accuracies were better than 12 m and 9 m (90%) respectively for the C-band data [*Rodriguez et al.*, 2006]. Data represent surface elevations on the unvegetated summit of Arenal but correspond to the elevations of scatterers such as leaves and branches on vegetated areas. To facilitate direct comparison of the SRTM and LVIS DEMs, the SRTM DEMs were corrected to the WGS-84 reference frame using the WGS84 Earth Gravitational Model (EGM 96) geoid [*Lemoine et al.*, 1998]. LVIS ground elevation data were gridded to 3 arcsec resolution using nearest-neighbor interpolation.

[14] The differences between the 2005 LVIS and 2000 SRTM DEMs are shown in Figure 2b. Patterns and magnitudes of topographic change are similar to those observed 1998–2005 using LVIS alone. The majority of topographic changes occurred on the north and west flanks of the volcano where a maximum topographic elevation increase of 45 m was found. On the eastern and southern lower flanks of the volcano, significant elevation decreases appear to have occurred 2000–2005 (Figure 2b). These areas are vegetated and are where the SRTM elevations refer to somewhere in the canopy. Results in these areas are not estimates of ground elevation change. On the higher-elevation flanks of the volcano, two distinct lobes can be seen extending north and northwest from the crater (Figure 2b), suggesting that the pyroclastic and lava flows represented by the west-trending lobe in the 1998–2005 data (Figure 2a) occurred prior to February 2000. Analysis of eye-witness reports suggest that this lobe may correspond to the pyroclastic flow that occurred on 26th October 1999 [*Smithsonian Institution Global Volcanism Program*, 2006]. Figure 2c shows topographic changes 1998 to 2005 derived from the LVIS data with gaps filled using the LVIS–SRTM DEM differences.

[15] Topographic changes from 1998 to 2005 within a 55 m-wide transect along the north trending lobe are shown in Figure 2d. The lobe extended 1300 m from the crater (to ~900 m elevation). Maximum topographic changes (~44 m) occurred close to and ~900 m from the crater. Topographic changes close to the crater are likely caused by the growth (and destruction) of small cones on the north wall of the crater rim. The maximum LVIS-derived elevations of Arenal were 1674.87 m and 1648.08 m in 2005 and 1998 respectively, a difference of 26.79 m (3.82 m yr^{-1}). These are in good agreement with theodolite observations of the maximum elevation of Arenal from fixed points on flat areas outside the volcano flanks which indicated an elevation change of 32.6 m (4.08 m yr^{-1}) (R. van der Laat, personal communication, 2006) between January 1998 and February 2005.

[16] Immediately adjacent to the northern distal edge of the lobe, negative topographic changes of as much as −10 m are indicated for 1998–2005 (Figure 2d). This area can also be seen in Figures 2a and 2c. The total area affected was ~100 m by 400 m. Inspection of geolocated waveforms confirmed that the elevations of the lowest (ground) modes in each waveform pair were different, and that the ground mode in the 2005 waveform occurred below the ground mode in the 1998 waveform (Figure 3). The loss of a higher (vegetation) mode was also seen in some of the 2005 data

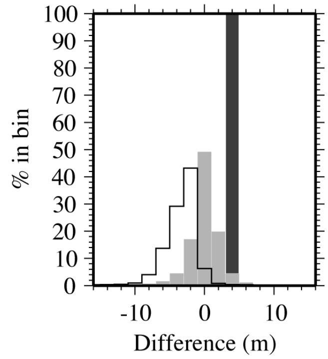

Figure 4. Distributions of change outside the area affected by recent flows (see Figure 2 for location) for 1998–2005 (light-shaded) and 2000–2005 (outlined). Differences at Arenal Lake 1998–2005 are shown dark-shaded.

(Figure 3b). These observations may be linked to the effects of acid rain as well as frequent pyroclastic and lava flows, particularly in August 2000 and March 2002, that have caused vegetation to die, fall and/or recede, leading to accelerated erosion on the flanks of the volcano [*Smithsonian Institution Global Volcanism Program*, 2006].

4. Flow Volumes and Effusion Rates

[17] Flow volume measurements corresponding to 1998–2005 and 2000–2005 were derived from the topographic changes shown in Figures 2b and 2c. Measurements above a 3 m threshold were included. For the 1998–2005 and 2000–2005 epochs, volume estimates of 2.19×10^7 m^3 and 1.95×10^7 m^3 were found, corresponding to Dense Rock Equivalent (DRE) volumes of 1.89×10^7 m^3 and 1.67×10^7 m^3 respectively (using a conversion factor of 0.86 [*Wadge et al.*, 2006]). The time-averaged DRE effusion rates were thus 0.085 m^{3}s^{-1} and 0.106 m^{3}s^{-1} for 1998–2005 and 2000–2005 respectively. These rates are in general agreement with those made using Interferometric SAR (InSAR) (0.24 m^{3}s^{-1} 1997–2000 and 0.086 m^{3}s^{-1} 2000–2004 (i.e., 0.14 m^{3}s^{-1} 1997–2004) [*Wadge et al.*, 2006]), and confirm the overall decrease in effusion rate since 1968 [*Wadge et al.*, 2006].

[18] Volume measurement errors were estimated using the topographic changes in the areas outside of the pyroclastic and lava flows. Figure 4 shows histograms of the change for various areas. Outside the area affected by recent lava/pyroclastic flows the topographic changes have a mean difference of 0.01 m and a standard deviation of 2.33 m for 1998–2005, and a mean difference of −6.99 m and standard deviation of 5.73 m for 2000–2005. These correspond to vertical accuracies of 4.57 m and 18.23 m at the 95% confidence limit, and volume estimate errors of 0.00015×10^7 m^3 and 0.015×10^7 m^3 for the 1998–2005 and 2000–2005 epochs respectively. Only SRTM data where the LVIS canopy heights were less than 5 m were included in the 2000–2005 comparison to minimize the effects of vegetation on the comparison involving SRTM data, however, the negative mean difference and large standard deviation indicate that vegetation effects may remain or that the SRTM elevation data contain a regional bias. For comparison, the topographic change results over a non-complex, flat surface such as Arenal Lake are shown (Figure 4). The standard deviation of the differences was only 0.12 m but the mean difference was 4.03 m, indicating the water level increased from 1998 to 2005.

5. Discussion

[19] Using a technique that uses colocated lidar return waveforms to determine vertical topographic change, we estimated flow volume and the average effusion rate for Arenal volcano for the period 1998 to 2005. Results were similar to those obtained by comparing SRTM elevations collected in 2000 with lidar data from 2005, and were in general agreement with estimates obtained using InSAR for 1997–2004. Measurement errors were significantly higher for the comparison involving SRTM data due to the effects of a regional bias or vegetation on the radar data. Our results show that repeated topographic imaging of an active volcano is possible using a medium footprint lidar. Lidar imaging can play an important role in monitoring active volcanoes by enhancing measurements made using other techniques such as ground or InSAR-based methods. Lidar offers several advantages over other remote sensing techniques such as InSAR since it is able to penetrate through vegetation to sense the ground, is unaffected by vegetation changes, erosion, the presence of fresh or flowing lava, high-relief and the passage of time. Waveform lidar also provides multi-dimensional data products. For example, in addition to topographic change estimates, lidar provides a precise and accurate DEM of the "bare earth" surface that can be used for determining topography-controlled hazards at volcanoes such as pyroclastic flows, as well as estimates of surface "texture" parameters such as roughness and slope within each footprint. Future advancements in lidar technologies will likely enable wide-swath, high-resolution imaging of the Earth's surface. Given these advancements and those in complementary technologies it seems likely that innovative methods of comparing and integrating the variety of ground, space and airborne measurements will facilitate enhanced volcanic deformation mapping and provide a better understanding of volcanic processes.

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