Quality of TOPSAR topographic data for volcanology studies at Kilauea Volcano, Hawaii: An assessment using airborne lidar data

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Abstract

We use airborne lidar data for the summit area of Kilauea Caldera, Hawaii, to explore the utility of topographic data collected by the TOPSAR airborne interferometric radar for volcanology studies. The lidar data are processed to a spatial resolution of 1 m/pixel, compared to TOPSAR with a spatial resolution of 5 m. Over a variety of fresh volcanic surfaces (pahoehoe and aa lava flows, ash falls and fluvial fans), TOPSAR data are shown to have a typical vertical offset compared to the lidar data of no more than ~2–3 m. Larger differences between the two data sets and TOPSAR data drop-outs are found to be concentrated around steep scarps such as the walls of pit craters and ground cracks associated with the Southwest Rift Zone. A comparison of these two data sets is used to explore the utility of TOPSAR to interpret the topography of volcanic features close to the spatial resolution of TOPSAR, such as spatter ramparts, fractures, a perched lava flow, and eroded ash deposits. Comparison of the TOPSAR elevation and the lidar first-return minus the return from the ground surface (the so-called “bald Earth” data) for vegetated areas reveals TOPSAR penetration into the tree canopy is typically at least 10% and no more than ~50%, although a wide range of penetration values from 0% to 90% has been identified. Our results are significant because they show that TOPSAR data for volcanoes can reliably be used to measure regional slopes and the thickness of lava flows, and have value for the validation of coarser spatial resolution digital elevation data (such as SRTM) in areas where lidar data have not been collected.

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1. Introduction

Digital elevation data are being used by the volcanology community to study such attributes as the shapes of volcanoes (Mouginis-Mark et al., 1996; Rowland & Garbeil, 2000), lava flow volume (Rowland et al., 1999; Rowland & Garbeil, 2000), lava flow rheology (MacKay et al., 1998) and lava flow hazards (Glaze & Baloga, 2003). Typically, these elevation data have been obtained from interferometric radars, either from the airborne TOPSAR instrument (Madsen et al., 1995; Zebker et al., 1992) or from the Shuttle Topographic Mapping Mission (SRTM) (Farr & Kobrick, 2000). Evans et al. (1992) first tested the utility of TOPSAR data for volcanology investigations at Hekla volcano in Iceland, demonstrating that the thickness of individual lava flows could be measured. Subsequently, Mouginis-Mark and Garbeil (1993) used a TOPSAR scene of Mt. Vesuvius (Italy) to study the erosional gullies on the flanks of the volcano. Similar features on other volcanoes (e.g., Ruapheu, New Zealand, and Mayon in the Philippines) have also been imaged by TOPSAR because these volcanoes are often prone to the production of debris flows (called “lahars”) that constitute significant hazards to the local communities. The use of TOPSAR to study both the geometry (width and depth) of the gullies, and the changes in gradient downslope, constitutes significant advantages over other field-based or air photography methods of collecting topographic information.

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There have been few studies that attempt to analyze the quality of the TOPSAR data over different volcanic features. Several studies of TOPSAR accuracy have been performed in non-volcanic terrain (e.g., Lin et al., 1994); notably, Izenberg et al. (1996) used field transits and an electronic distance meter (EDM) to validate TOPSAR data for a flood plain along the Missouri River. This flood plain was, however, very flat and had very different micro-topography characteristics compared to those of Hawaiian pahoehoe and aa lava flows.

The ability of TOPSAR to accurately measure lava flow thicknesses and identify flow paths for lava flows, lahars or water is of great importance for understanding volcanic processes. Rowland et al. (1999) performed a comparison between TOPSAR data for Kilauea caldera and field-derived elevation measurements from a total field station. They concluded that TOPSAR data are useful for the morphological and volumetric characterization of individual volcanic features such as faults, lava flows, and cinder cones, as well as large-scale flow fields. Their fieldwork indicated that, in areas of sparse vegetation, the TOPSAR elevations are good to 1–2 m. Multiple digital elevation models (DEMs) collected over the same area at different times (perhaps years apart) could therefore be used to measure changes in the volume of a volcanic landscape (such as a flow field) provided that the data sets are co-registered to a common datum and there is an absence of trees. But in instances where recent lava flows have entered forested areas (such as the Pu‘u O‘o lava flows of Kilauea; Rowland et al., 1999), the lack of knowledge of the degree of penetration of the TOPSAR signal into the canopy limits the ability of investigators to infer the total thickness and, hence, erupted volume of lava.

In January 2004, the Airborne 1 commercial lidar system collected elevation data over Kilauea caldera. These data permit a quantitative examination of the performance of the TOPSAR system. The Airborne 1 data set we use here provides elevation measurements that we have binned into 1 m pixels and have a nominal vertical accuracy of 2 cm. Here we make the assumption that these lidar data provide the “true” topography of the volcano. This assumption appears reasonable because the footprint of the lidar is 30 cm and, typically, because of the multiple flight lines that were flown over Kilauea caldera. Thus, any aircraft motions that were present in a single flight line would have been removed or suppressed during the creation of the lidar data.

Fig. 1. Map of the recent lava flows and structural features within Kilauea caldera, Hawaii. Inset shows location of the study area on the Big Island of Hawaii. Lidar coverage is indicated by the rectangular box. HVO is “Hawaii Volcano Observatory,” KMC is “Kilauea Military Camp,” SWRZ is “South West Rift Zone” and NP is “National Park” Headquarters.
DEM. Typically, there are 3–5 lidar shots within each of the 1-m pixels we have created by weighted interpolation. In this analysis, we use these lidar data to investigate the vertical offset of TOPSAR data compared to the lidar topographic data over fresh lava flows and forested volcanic features on Kilauea Volcano, Hawaii. To perform a direct comparison of data sets, the TOPSAR data (originally with a 5-m spatial resolution) were re-sampled to the same 1-m grid using a nearest neighbor approach.

2. Study area

Coincident lidar and TOPSAR data, as well as an abundance of other remote sensing data (e.g., Ikonos images), exist for the southern half of the summit caldera of Kilauea volcano, making it an ideal test area for the assessment of remote sensing instruments. In addition, a great diversity of volcanic landforms can be found within this part of the caldera. As shown in Fig. 1, there are numerous lava flows that were erupted between 1897 and 1982. Most of these flows are of the radar-smooth pahoehoe surface texture (Campbell & Shepard, 1996; Gaddis et al., 1990), although segments of the 1971 lava flow comprise radar-rough aa textures. We also include Halemaumau Crater, which is ~900 m in diameter and has been the source for several eruptions over the last century. Structural features are also common near the summit, with fractures a few meters wide associated with the southwest rift zone. Also in the summit area, one can find lava flows that traveled through rain forest (e.g., the 1971 flows) and many exposures of the Keanakakoi ash that was created in 1790 by the explosive eruption of Halemaumau (McPhie et al., 1990).

The summit of Kilauea volcano has also been used as a test area for orbital and airborne radar data (Campbell & Shepard, 1996), so that the validation of TOPSAR data has broader applications that include planetary geology and volcanology (Campbell & Campbell, 1992; Garvin et al., 1981; Shepard et al., 2001). Detailed studies of lava flow emplacement that rely on local topographic data have also been conducted within the study area (Heslop et al., 1989).

3. Data sets used

TOPSAR data were collected on October 12, 2000 during the PacRim 2 mission, and a commercial company, Airborne 1, collected the lidar data over a period of several days in January 2004. Analysis of the results from TOPSAR (Zebker et al., 1992) indicate that statistical errors are in the 2–4 m range, while systematic effects due to aircraft motion are in the 10–20 m range. The Airborne 1 lidar is a scanning system that collects 25,000 points/s. Range error from the laser system is expected to be on the order of 5–7 cm, independent of altitude. Data were collected from an altitude of 2000 m. A full description of the accuracy of the Airborne 1 lidar can be found at http://www.airborne1.com/technology/LiDARAccuracy.pdf. Supplemental data sets used here include a panchromatic Ikonos image (1 m/pixel) collected on November 11, 2000, and numerous air and ground photographs collected between 1984 and 2003. Used in conjunction, the lidar and Ikonos data (Fig. 2) clearly show the elevation difference between vegetated and un-vegetated parts of the volcano.

3.1. Qualitative comparison of data sets

The quality of the lidar topographic data is superb for geologic mapping the caldera. For example, in Fig. 3, we show a shaded relief image of Halemaumau Crater that shows many of the cooling features associated with the lava lake that was active in 1974. Also visible at the foot of the crater walls are numerous individual blocks that have fallen off of the walls and “benches” (which are former levels of the lava lake) mid-way up the walls. The smooth surface of the tourist parking lot is also recognizable on the southern rim of the crater. Numerous drainage gullies on the southern...
part of the caldera rim, and the several block faults on the western side of the caldera, can also be seen.

Shaded relief versions of both the lidar and TOPSAR data reveal the differences in the quality of the two data sets (Fig. 4). We now illustrate the quality of the lidar data with five comparisons of the lidar and TOPSAR data that have relevance to volcanology investigations at Kilauea or other basaltic shield volcanoes around the world. In each example, we also show one or more representative ground photo and compare topographic profiles obtained by the two instruments.

3.1.1. Spatter ramparts that formed during the April 1982 eruption

Here we test the ability of TOPSAR to measure the height and width of small cones that were produced by gas-rich lava during a fire-fountain eruption. The April 1982 line of cones was created during a 19 hour-long eruption within the caldera just to the east of Halemaumau crater (GVN, 1982a). Lava was erupted from an ENE-trending fissure ~1 km long, and prominent lava flow lobes formed to the north, east and south. The volume of new lava erupted was \( \sim 0.5 \times 10^6 \) m\(^3\) and comprised primarily pahoehoe flows.

The resultant spatter cones over the vents, which are 5–10 m high (Fig. 5c), are composed of welded spatter. Analysis of the shape of such cones and the height to which the fire fountain reached during the eruption have been shown by Parfitt et al. (1995) to be good indicators of the total volatile content of the erupting magma and the angle of ejection of material from the vent. Thus, the measurement of the height and shape of the cones provides a measure of the eruption conditions. Comparison of the lidar and TOPSAR data (Fig. 5d) shows that the primary difference between the two data sets is the inability of TOPSAR to measure the steep sides and absolute height of the cone. An area of generally higher (by ~2 m) relief is associated with the cones, but this underestimates the 7-m height and ~30-m width of the cone. While not common on Kilauea volcano, there are other basaltic volcanoes where cinder cones <100 m in diameter have been measured by TOPSAR (e.g., in Savai’i, Samoa; Kallianpur & Mouginis-Mark, 2002); geometric measurements of cone shape on these volcanoes is expected to give a height that is too small and a width that is larger than actually exists. Classification of the degradation state of a population of cinder cones (e.g., Wood, 1980) would therefore suggest erroneously high degradation states for the smaller cones because TOPSAR would indicate that they are lower and wider than is actually the case.

3.1.2. The 1974 lava channel on the south caldera rim

In this instance, we explore the use of TOPSAR to identify the difference in elevation along a lava channel, which has been used by Heslop et al. (1989) to estimate the speed and volume of the lava, as well as its rheology at the time of flow. This lava channel formed in July 1974 and was unusual because the vents were located on the caldera rim. Inspection of the TOPSAR data (Fig. 6b) reveals several areas where the radar was unable to measure the rapid changes in relief that are associated with the caldera rim and the northern wall of Keanakakoi pit crater. A number of preexisting fluvial channels were also located close to the vents, and the fluid lava flows were able to exploit these channels and flowed rapidly downslope onto the caldera floor. The result of this fast moving lava flow was the creation of a lava channel where the two sides are at different elevations as the channel made turns while going downslope (Fig. 6d).

Comparison of the lidar and TOPSAR data (Fig. 6e) shows several additional problems that would affect a volcanology investigation. First, a line of narrow spatter ramparts on the caldera floor is not visible in the TOPSAR data. Our observations suggest that TOPSAR should not be used to map structural features and linear vent systems a few tens of meters wide and only 2–4 m high. Second, the slope angle of the caldera wall is underestimated by TOPSAR. This could lead to the misinterpretation that the caldera walls had experienced collapse or other form of erosion. Finally, the lava channel studied by Heslop et al. (1989) is not clearly defined in the TOPSAR data but instead is a shallower depression with almost three times the width. TOPSAR would not be an appropriate data set to use in order to conduct flow modeling of the type conducted by Heslop et al. (1989).
3.1.3. Drainage channels on the southern caldera rim

The use of TOPSAR to measure surface flow on shallow slopes, and the degree of erosion of ash deposits can be investigated on the southern rim of the caldera, where numerous fluvial channels have formed in the Keanakakoi ash in 1790 (McPhie et al., 1990). Our field observations (Fig. 7d) indicate that these channels are typically 2–5 m deep and up to ~20 m wide and possess sharp edged walls where cemented ash has formed hard layers. This area provides a good test for TOPSAR data where they are to be used in surface flow models, such as the one developed by Glaze and Baloga (2003), which can be used either for water runoff or for the emplacement of new lava flows. Such models have relevance not only for understanding the emplacement of lava flows, but also for the assessment of downslope hazards.

Comparison between the lidar and Ikonos data (Fig. 7a and c) shows that the lidar data clearly illustrate the flow direction for the water. However, the TOPSAR data (Fig. 7b) reveal only the most general drainage pattern, which is further illustrated by a topographic profile across this area (Fig. 7e). Despite a surface made of ash (which might produce less of a radar return than solid lava), the TOPSAR data reproduce the general characteristics of the lidar profile, but miss the high-frequency (<5 TOPSAR pixels) topographic features. Drainage channels are either missed entirely, or their widths are overestimated. Such limitations are expected to dramatically affect any numerical model that predicts surface flow directions and thus indicate that TOPSAR should not be used to map drainage patterns at the scale found in this part of Kilauea volcano.
Fig. 5. Views of the April 1982 spatter ramparts. See Fig. 4 for location. (a) Top left: Lidar shaded relief (in this and all other shaded relief images the illumination from the right). The white rectangle marks the location of the ground photo shown in (c) and the line “A” to “B” denotes the profile displayed in (d). (b) Top right: TOPSAR shaded relief. (c) Bottom: Ground photo of a segment of the spatter rampart [see (a) for location]. Person sitting on the rampart crest provides scale. (d) Comparison of elevation data derived from lidar (dashed line) and TOPSAR (solid line). The location of the spatter rampart is marked by the arrow. The position of the profile is shown in (a).
3.1.4. The September 1982 lava flow

Correlating elevations across kilometer-scale distances has value when investigating the surface features that are formed when lava is trapped, or “ponds,” behind topographic obstacles. The September 1982 lava flow is such an example. Located in the southernmost part of the caldera floor, this flow was created during a 15 hour-long eruption (GVN, 1982b). The vent system was oriented in the usual ENE direction, nearly parallel to the nearby caldera wall. Field exposures indicate that there was significant drain-back of lava into the vents after the gas pressure was released during the eruption. An early estimate suggests that perhaps as much as $3 \times 4 \times 10^6$ m$^3$ of pahoehoe lava was erupted. Of this, possibly as much as $1 \times 2 \times 10^6$ m$^3$ drained back into the vent system (GVN, 1982b). The resulting collapse of the pond surface left a

Fig. 6. Views of the southern edge of Kilauea caldera where the July 1974 eruption took place to form a lava channel on the caldera rim. See Fig. 4 for location. (a) Top left: Lidar shaded relief image. The line “A” to “B” denotes the profile displayed in (e). (b) TOPSAR shaded relief image. Note the inability of the radar to measure the height changes over the rim of the caldera and the wall of the pit crater at lower right. (c) Air photo looking north across the same part of the caldera that is shown in (a). Black dot marks the location of the ground photo shown in (d). (d) Ground view of the central portion of the July 1974 lava channel. Note the super-elevated rim of the channel on the far wall behind the person. Location of photo shown in (c). (e) Comparison of elevation data derived from lidar (dashed line) and TOPSAR (solid line). “SR” identifies the spatter rampart that is missed by TOPSAR, and “LC” is the lava channel. Location of the profile is shown in (a).
Fig. 7. Views of drainage channels carved in ash deposits to the south of the caldera rim. See Fig. 4 for location. (a) Lidar shaded relief image. Note that channels can be identified at several scales in this image. The line “A” to “B” denotes the profile displayed in (c). (b) TOPSAR shaded relief image. Only the caldera rim (at top left) can be identified in this image. (c) Ikonos panchromatic image of drainage channels. Note that the albedo of the channels (caused by the amount of sediment on the channel floor) is quite variable, but does not correlate with depth of the channel as identified in (a). (d) Ground photo of a channel in the general vicinity of the area shown in this figure (the exact location of this image was not recorded). Note that the channel is ~3 m deep, and that the uppermost layers comprise layered, cemented, ash. (e) Comparison of elevation data derived from lidar (dashed line) and TOPSAR (solid line). Location of the profile is shown in (a).
bathtub “ring” on the order of 2–3 m high on the enclosing escarpments.

A key attribute of the September 1982 flow is that the flow ponded within the topographic depression, creating a very flat surface to the flow that is atypical for basaltic volcanoes. This unusually flat surface has been used by planetary volcanologists to predict the radar backscatter characteristics of lava flows on Venus, as measured by the Magellan and Arecibo radars (Campbell & Campbell, 1992; Shepard et al., 2001). Despite the small hills that formed over the vents as the lava level fell (Fig. 8d), which TOPSAR might have missed due to their narrow (<20 m) width, there is a good match between the lidar and TOPSAR data (Fig. 8e) for the main surface of the lava flow. Thus, we are confident that TOPSAR on its own could be used to determine the topographic roughness of lava flows such as the September 1982 flow in Hawaii as an aid to the analysis of planetary radar data. In addition, it is clear that TOPSAR correctly shows that the two sides of the lava flow, the elevation of the channelized lava flow that flowed through a topographic low on the southern side of the flow (Fig. 8f), and the top of the constructs over the vent, are all at the

Fig. 8. Views of the September 1982 lava flow on the southern edge of the caldera rim. See Fig. 4 for location. (a) Lidar shaded relief image. The line “A” to “B” denotes the profile displayed in (f). (b) TOPSAR shaded relief image. The caldera rim can be identified from its shadow in this image. (c) Oblique air photo looking north showing the September 1982 lava flow. The locations of the field photographs shown in (d) and (e) are denoted by letters. (d) Ground photo of the largest mound preserved over one of the vents for the September 1982 flow. See (c) for location. (e) Ground photo of the lava channel to the south of the caldera rim down which the September 1982 flow traveled. Note people in the middle distance for scale. See (c) for location. (f) Comparison of elevation data derived from lidar (dashed line) and TOPSAR (solid line). Location of the profile is shown in (a). Note that the two sides of the lava flow (“c” and “e”), as well as the top of the mound over the vent (“d”), are at the same elevation, confirming that the flow surface was once at a higher level.
same elevation. This confirms that, when active, the lava flow was originally at a higher elevation and that drain-back into the vent area has indeed taken place.

3.1.5. The fractures associated with the SW Rift Zone

Structural features such as fracture and faults are frequently used to investigate the recent deformation of a volcano or the formation of specific features such as pit craters (Okubo & Martel, 1998). One of the clearest examples of fractures at the summit of Kilauea volcano is the set of fractures that form the start of the SW Rift Zone. At least seven parallel fractures up to 400 m in length, ~13 m wide and 8–10 m deep can be found in this area (Fig. 9c and d). Mapping the occurrence and length of these fractures has been one of the goals of two Space Shuttle Radar experiments (Gaddis et al., 1989; Mouginis-Mark, 1995) because the results have immediate application to the interpretation of structural features on Venus using the Magellan radar (e.g., Blemaster & Hansen, 2004; Kaula et al., 1992).

Topographic profiles across these fractures (Fig. 9e) reveal the inability of TOPSAR to resolve depressions of this size. Either the fracture is not detected, or the width is over-estimated by a factor of ~5 (i.e., the original resolution difference of the two sensors). The absolute depth of the fracture (~10 m) is also under-estimated by TOPSAR by a factor of ~5. A comparison with the lidar data (Fig. 9a) demonstrates the inability of TOPSAR to identify both the length of these large fractures and the location of the narrower examples. However, the shaded relief version of the TOPSAR data (Fig. 9b) does at least allow the trend of the larger fractures to be identified. Thus, we would not recommend the use of TOPSAR for detailed structural studies on volcanoes, although at a larger scale (i.e., features at least several tens of meters wide or high, such as the caldera wall; Fig. 9b), the data set would be adequate.

In summary, these five qualitative comparisons show that care must be used when interpreting TOPSAR data of small volcanic landforms. Two key attributes of the TOPSAR data must be considered in any analysis: (1) the inability to measure elevations in steep terrain, such as the walls of pit craters or the rim of the caldera (Fig. 6); and (2) a smoothing of the topography (at a horizontal scale of ~20 m) that precludes the accurate measurement of spatter rampart heights (Fig. 5d), the flow direction of fluvial channels (Fig. 7b) or the depth of fractures along the SW Rift Zone (Fig. 9e). With these caveats, TOPSAR data should be adequate for most topographic studies of volcanoes, particularly over a large area such as that employed for “whole volcano” studies of the regional distribution of slopes on a shield volcano (Mouginis-Mark et al., 1996; Rowland & Garbeil, 2000).

3.2. Quantitative comparison of data sets

One of the most important uses of TOPSAR digital elevation data for volcanology investigations is the determination of the total volume of lava erupted. Often, this determination relies upon the measurement of flow thicknesses where lava has invaded a forest, but without a good knowledge of the degree of radar penetration of the tree canopy only a poor estimate of lava flow thickness can be obtained. Such a situation was encountered by Rowland et al. (1999) in their investigation of the lava flows from the Pu‘u O‘o cone of Kilauea, with the quantitative determination of a typical amount of TOPSAR penetration into the forest of greatest importance where fresh aa lava flows (typically ~10–15 m thick) have cut through a forest. To address this issue, we attempt here a quantitative comparison of the lidar and TOPSAR data for Kilauea caldera with a specific focus on the determination of TOPSAR penetration into typical Hawaiian forest.

Both the lidar and TOPSAR data sets used in this investigation were collected with GPS ground control and the data are referenced to the WGS84 datum. Thus, we have found that there is no need to manipulate or adjust the surface of one data set relative to the other. A comparison of the difference between the data sets (Fig. 10) reveals that in general the height offset is of the order of 2–5 m. Closer inspection of the difference image reveals that there are systematic height variations, seen as bands on the order of ~1 m across the floor of the caldera (Fig. 11a). We note that these bands of elevation difference are neither in the TOPSAR bearing’s along-track or cross-track direction. Such errors have also been detected in other TOPSAR data sets (e.g., the TOPSAR mosaic of Isabella Island, Galapagos; Mouginis-Mark et al., 1996) and are most likely due to uncompensated aircraft motions during data collection. As inferred from field measurements across the caldera (Rowland et al., 1999), most of the TOPSAR height differences over bare lava flows are in the ~2 m range. A profile across the 1919 and 1974 lava flows (Fig. 11a) reveals that almost all of the height difference between the two data sets is <3 m. Comparison of this profile with the map of lava flows (Fig. 1) shows that changes in the height difference (from positive to negative) are not associated with real changes in surface morphology.

In contrast to the bare lava surfaces, a profile across the forest in the eastern portion of the study area (Fig. 11b) reveals height differences of ±5–8 m. Indeed, elevation differences as great as ~12–15 m can be seen over forested areas in the eastern part of the study area (Fig. 10b). Such differences are most likely due as much to the difference in spatial resolution of the two data sets as to the penetration of the TOPSAR radar signal into the canopy of the trees. Because of the considerable diversity in the height and morphology of the trees in the Hawaii National Park (Mueller-Dombois et al., 1981), a 30 cm lidar footprint is quite likely to reach the ground surface without encountering a tree branch, while the 5 m TOPSAR footprint will very frequently encounter both the top of the trees and the understory foliage above the ground surface. Such blocking of the TOPSAR signal will also occur more frequently than with
the lidar measurements due to differences in the incidence angle of the two sensors. The lidar data are collected with a scan angle of nadir to 20° off nadir, whereas TOPSAR data are collected at 25° in the near-range and 60° in the far-range. Spatial variations in the difference between the lidar-measured elevation and the TOPSAR data may be due not only to the type(s) of vegetation in a specific area, but also to the maturity (and, hence, spacing) of the trees.

To mitigate the effect of the spatial resolution of the two data sets, we reprocessed the lidar DEM data to a spatial resolution of 5 m (i.e., the same as the original TOPSAR data). Only the first lidar return, which corresponds to the highest part of the tree that is measured in each pixel, is included in these reprocessed data. The maximum elevation within each 5 m grid location is assigned to that grid location. We compare this value to the TOPSAR elevation data (Fig. 4).
Fig. 10. Quantitative comparison of TOPSAR and lidar data for the study area. (a) Absolute difference in elevation between the first pulse of the lidar and TOPSAR. Scale bar at bottom left shows that differences range from −5 m to +15 m [note that the intervals here are different from those presented in (b) and (c), although the color sequence is the same]. The profiles A–B and C–D shown in Fig. 11 are marked. (b) Elevation difference between TOPSAR and the bald Earth lidar returns. The greatest differences occur over the forested areas in the eastern (right hand) part of the image. Maximum differences are on the order of 15 m. (c) Difference between the first return for the lidar data, smoothed to 5-m spatial resolution, and the TOPSAR data. This provides an elevation difference that varies from near zero over the bare lava flow surfaces to >12 m in the forested areas.
10c). In this instance, all of the TOPSAR pixels have a lower elevation than the lidar image. Because of the comparable spatial resolution of the two data sets, and the fact that we selected maximum values from 5 × 5 pixel boxes for the lidar value, the differences between the elevations is now smaller and typically ranges from 8 to 10 m, with maximum values <12 m.

Considerable theoretical work has been conducted to assess the ability of TOPSAR to measure tree heights (Kobayashi et al., 2000). By inspecting the lidar data across the forested area of Kilauea Caldera, it is also possible to determine the extent to which the TOPSAR measurements penetrated into the forest canopy. We use the following ratio to define radar penetration:

\[
\text{Penetration} = \frac{[(5 \text{ m first return} - \text{TOPSAR})]}{[(5 \text{ m first return} - \text{bald Earth})]} \times 100\%
\]

Where the “5-m first return minus TOPSAR” yields the penetration relative to the top of the tree, and the “5-m first return-bald Earth” provides the approximate tree height.

In Fig. 12a, we show the general trend of the degree of penetration into the entire forest. We use only a representative sample of the entire data set in this figure, selecting every 625th data point in the full data set (i.e., one pixel within a box measuring 25 × 25 pixels) to avoid saturating the graphical display. A wide range in tree height (1–23 m) can be identified from this sample, and the degree of radar penetration into the canopy extends over the entire range from 0% to 100% (Fig. 12a). There is a clear clustering of data from trees that are 6–18 m high and a degree of penetration that ranges from 10% to 80%. Striking differences in the spatial distribution of these attributes suggest variations in canopy morphology. We illustrate this point using three small test areas (Fig. 12b–d), each 10,000 m². We note that the trend in Fig. 12a is different from the other graphs because the smaller trees allow for a higher percentage penetration than the larger trees. It is also possible that there are different vegetation types within the entire forest that do not show up in the smaller sub-regions selected for Fig. 12b–d.

Area 1 (Fig. 12b) has the shortest trees (2–12 m high) and displays the greatest range of penetration values, with many samples within the 30–75% range. Area 2 (Fig. 12c) has the “cleanest” distribution of % penetration vs. tree height and covers the smallest range of height (10–16 m) and penetration (10–50%). There is a systematic increase in penetration with increasing height. This trend is generally similar to that of Area 3, but in Area 3 (Fig. 12d), the
maximum penetration is ~40% and there is a greater number of trees in the 12–18-m height range where penetration is ~10–20%. The highest trees (~20 m) are found in Area 3, and TOPSAR has a penetration of ~25–40% in these trees. These differences in TOPSAR penetration are surprising and suggest that important ecological information could be derived from the combined lidar and TOPSAR data sets; however, such studies are outside the scope of this volcanology study, and we leave such an analysis to a future investigation.

Penetration values such as the ones illustrated in Fig. 12a may not be true for all types of forest where TOPSAR may be used to study lava flows, but they may provide an approximation for refining the estimate of lava flow thicknesses on other parts of Kilauea volcano where new flows have entered forest, such as the Pu’u O’o flows. In this area, individual lava flows may be of the order of 6–13 m thick (Fink & Zimbelman, 1986) and are thus considerably thicker than the height error of the TOPSAR system. Knowing that TOPSAR elevations for the forest adjacent to the new lava flows have a known penetration percentage of the height of the trees, it would be a relatively simple task to obtain a few field measurements of tree height at the perimeter of the flow and thus calculate the actual ground surface measured by TOPSAR. Such a recalculation of the volume of the flows investigated by Rowland et al. (1999) is beyond the scope of this investigation, but this calculation illustrates the value of better understanding the capabilities of this interferometric radar system.

4. Conclusions

Our analysis has confirmed the value and limitations of TOPSAR data for several types of investigation of basaltic volcanoes such as Kilauea. In particular, TOPSAR data appear adequate for comparing point-to-point elevations of surfaces such as the perched September 1982 lava flow (Fig. 8). The results of this study provide high confidence in the accuracy of the TOPSAR system at the 1–2 m vertical scale, thereby increasing the utility of the TOPSAR system for the validation of other DEMs. DEMs produced from orbital radar interferometry, either using repeat-pass data sets such as those collected by the ERS-1 spacecraft (Burgmann et al., 2000; Zebker et al., 1994) or single-pass interferometers such as the Shuttle Radar Topographic Mapping (SRTM) mission (Farr & Kobrick, 2000), need to be validated. Because of the relatively large image size of a TOPSAR data take (typically 10 × 60 km), it is possible to co-locate TOPSAR data with orbital data that may have a spatial resolution between 30 and 90 m/pixel. The TOPSAR data used here have been processed at a spatial resolution of 5 m/pixel, so that the spatial resolution of the two topographic data sets may differ by a factor of 6–15.

This comparison of two DEMs at different scales will not only permit an evaluation of sensor performance, but will also facilitate new quantitative modeling of surface processes that cover areas that are larger than a typical lidar acquisition (say, >50 km²). Glaze and Baloga (2003)
have developed numerical models that predict the flow paths of lava flows across the flanks of a volcano. Using a combination of lidar and TOPSAR data presented here for Kilauea as a test case for the sensitivity of the model to meter-scale undulations in surface would give greater confidence to model predictions based exclusively either on TOPSAR or SRTM data.

We also note the potential value of the combined lidar and TOPSAR study that is reported here to the ecology community. There are clear spatial variations in the amount of canopy penetration that has been achieved with TOPSAR (Fig. 11). We infer that these differences are related either to the morphology of the canopy, the maturity or type of trees, or the spacing between individual trees. Using quad-pol radar data, attempts have been made to characterize forests to better understand their biomass (e.g., Dobson et al., 1995; Harrell et al., 1997). Similarly, lidar systems are also being used to characterize tree morphology (Blair et al., 1999; Dubayah & Drake, 2000). Our results show that additional characterization of forest canopies could be achieved using the combination of TOPSAR and lidar.

Finally, there is the value of a high-quality DEM as a “benchmark” in a volcanic area where topographic change is very common, either due to a new eruption or to the collapse of a crater such as Halemaumau. As demonstrated by Rowland et al. (1999, 2003), the subtraction of one DEM from another to obtain volume information of an individual lava flow opens the possibility of understanding the rate of magma production during a specific event. Comparing the thickness of a new lava flow as a function of slope enables the flow properties (i.e., rheology) to be studied. This “before and after” topographic change is not only important for lava flows because, given the large (>1 km) amount of vertical movement of the floor of Halemaumau Crater over the last 160 years (Walker, 1988), it seems likely that topographic change will occur here over the next decade or so. This topographic change could either be associated with slow subsidence of the floor due to withdrawal of magma down rift towards the on-going eruption site at the Pu‘u O‘o cone (Heliker & Mattox, 2003, and references therein), or to the occurrence of a new summit eruption such as the April 1982 event. For the summit of Kilauea Caldera, the Airborne 1 data are increasingly likely to serve as a critical “before event” data set as future activity occurs.

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