An assessment of shuttle radar topography mission digital elevation data for studies of volcano morphology

Robert Wright a,*, Harold Garbeila, Stephen M. Balogab, Peter J. Mouginis-Mark a

a Hawaii Institute of Geophysics and Planetology, Honolulu, Hawaii, U.S.A.
b Proxemy Research, Bowie, Maryland, U.S.A.

Received 10 February 2006; received in revised form 5 June 2006; accepted 7 June 2006

Abstract

The Shuttle Radar Topography Mission has provided high spatial resolution digital topographic data for most of Earth’s volcanoes. Although these data were acquired with a nominal spatial resolution of 30 m, such data are only available for volcanoes located within the U.S.A. and its Territories. For the overwhelming majority of Earth’s volcanoes not contained within this subset, DEMs are available in the form of a re-sampled 90 m product. This has prompted us to perform an assessment of the extent to which volcano-morphologic information present in the raw 30 m SRTM product is retained in the degraded 90 m product. To this end, we have (a) applied a simple metric, the so called dissection index ($d_i$), to summarize the shapes of volcanic edifices as encoded in a DEM and (b) using this metric, evaluated the extent to which this topographic information is lost as the spatial resolution of the data is reduced. Calculating $d_i$ as a function of elevation (a $d_i$ profile) allows us to quantitatively summarize the morphology of a volcano. Our results indicate that although the re-sampling of the 30 m SRTM data obviously results in a loss of morphological information, this loss is not catastrophic. Analysis of a group of six Alaskan volcanoes indicates that differences in $d_i$ profiles calculated from the 30 m SRTM product are largely preserved in the 90 m product. This analysis of resolution effects on the preservation of topographic information has implications for research that relies on understanding volcanoes through the analysis of topographic datasets of similar spatial resolutions produced by other remote sensing techniques (e.g., repeat-pass interferometric SAR; optical stereometry).

© 2006 Elsevier Inc. All rights reserved.

Keywords: SRTM; Volcanology; Geomorphometry; Dissection index

1. Introduction

The National Aeronautics and Space Administration’s Shuttle Radar Topography Mission (SRTM) was launched on 11 February 2000 with the aim of producing digital topographic data for 80% of Earth’s surface at a spatial resolution of 1-arcsec. SRTM, a single-pass interferometric synthetic aperture radar (IfSAR) system, used dual-frequency antennae to produce interferograms from which the topography of the imaged surface was determined (Farr & Kobrick, 2000). Over the 11 day mission SRTM mapped 99.97% of the Earth’s land surface between 60°N and 56°S at least once, and as many as four times, although coverage varied between the C-band (5.8 cm) and X-band (3 cm) radars. The near-global topographic dataset was processed at NASA’s Jet Propulsion Laboratory (JPL) using data obtained from the C-band SAR, which had a swath of approximately 220 km. Although the digital elevation models (DEMs) derived from the X-band SAR are of slightly higher relative height accuracy, the narrower swath (~45 km) means that they lack the contiguous coverage of the C-band product. As a result, the vast majority of Earth’s dormant, active and potentially active volcanoes were imaged only in the C-band mode.

The morphology of a volcano at any given time represents a temporal integration of the constructive (endogenic) and destructive (exogenic or geomorphic) processes that have operated up to that time (for the interested reader, Thouret (1999) reviews the role that knowledge of a volcano’s geomorphology can play in understanding volcanic processes and hazards). Clearly, a single dataset comprising digital elevation data for virtually all of Earth’s sub-areal volcanoes has the potential to make a significant contribution to the study of volcanic landforms.
Of course, the utility of SRTM data depends on the degree to which they record real variations in topography (Fig. 1). Although the C-band SRTM data were acquired at a spatial resolution of 1-arcsec (nominally equivalent to a spatial resolution of 30 m), such data are only available for a limited geographic area, specifically, the U.S.A. and its Territories. SRTM DEMs are available for the rest of Earth’s volcanoes, but only at a degraded spatial resolution (3-arcsec, or ~90 m; Farr & Kobrick, 2000). This has prompted us to perform an assessment of the extent to which the volcano-morphological information present in the raw 30 m product is retained in the degraded 90 m product.

We begin by describing the metric we use to quantify the morphological information contained within a DEM of a volcano. Using a high spatial resolution (10 m) DEM derived from an airborne IfSAR system we then assess the effect of decreasing spatial resolution on this parameter by using simulated datasets of increasingly coarse pixel size. Finally, we quantitatively compare SRTM data with 30 m and 90 m spatial resolution for a group of six Alaskan volcanoes to assess the effect that decreasing spatial resolution has on the ability of the SRTM data to resolve differences in morphology at these two spatial resolutions.

2. Method: quantifying volcano “shape”

A DEM constitutes a complete record of a volcano’s form from which a wide range of primary morphometric attributes, including slope, slope convexity and slope concavity can be computed directly (e.g. Mouginis-Mark et al., 1996; Rowland & Garbeil, 2000). More generally, the shape of any three-dimensional object is defined by its bounding surface. With respect to volcanoes this bounding surface can be approximated by the set of topographic contours that enclose the edifice. Major variations in volcano morphology are recorded in how the shape and complexity of these contours vary as a function of elevation (Fig. 2). Determining how well shape information is preserved as the spatial resolution of the topographic information is reduced requires an appropriate metric for quantifying the complex outlines of the set of contours. In other words, how can we summarize the essential shape information encoded within a set of contours in a manner that facilitates direct comparison of different volcanoes or different resolutions?

The analysis of combinations of simple geometric parameters, the so-called single-parameter shape descriptors, can be used to quantify and discriminate complex outlines. Amongst these the Dissection Index ($d_i$) is defined as (Kincaid & Schneider, 1983; Jensen, 2003):

$$d_i = \frac{p}{2a} \times \frac{\sqrt{a}}{\pi},$$

where $d_i$ is the dissection index, $p$ is the perimeter of the outline, and $a$ is the area enclosed within the outline. The $d_i$ has a value of 1.0 for any circle and increases as the complexity of the outline increases.

Jensen (1995) found the $d_i$ to be successful in quantitatively discriminating complex leaf shapes, a conclusion supported by the results presented by McLellan and Endler (1998). It is also simple to calculate and intuitive as a geometric concept. For this reason we have chosen the $d_i$ as a means of quantifying shape information in SRTM data, by using measurements of the perimeter of, and the area enclosed within, the set of topographic contours that enclose the volcano of interest, as derived from SRTM DEMs. Fig. 3 shows $d_i$ profiles calculated for two synthetic volcanoes. The open circles correspond to the $d_i$ calculated for the un-dissected DEM in the background (a). Here, the dissection index is close to 1.0 at all elevations. It will never be exactly 1.0 due to the fact that pixels are finite and square). The DEM in the foreground (b) has been “eroded” in two places, with the depth and width of the incisions being inversely proportional to elevation. The dissection index responds by increasing with distance from the summit (filled circles in Fig. 3c).

At this point it is necessary to clarify our terminology. Although referred to as the “dissection” index in the biosystemsitatics literature, we do not assume a priori that $d_i$ values greater than 1.0 are directly proportional to the degree of dissection of a volcanic structure in the strict geomorphologic sense (i.e., dissection: the destruction of a relatively featureless landscape through incision and erosion by streams; Thomas and Goudie,
Rather, we use the *d* to objectively quantify the complexity of the closed contours that bound a volcano as a means of satisfying the objectives stated in the introduction. In addition to the pervasive effect that fluvial erosion may have on contour complexity, other constructive and destructive geomorphic processes can result in the contortion of a contour. On a volcano such processes might include the emplacement of a viscous lava dome (which would serve to produce a convex arciform feature in a contour), or the occurrence of a rotational landslide (which would produce a concave embowment).

The *d* should only be determined for closed contours. In practice, this means that there are upper and lower limits to the height over which it makes sense to calculate the parameter. For example, some volcanoes form on the flanks of older volcanoes; others form on steeply sloping terrain. Both of these circumstances can make it impossible to construct closed contours all the way down to the base of the edifice, placing a lower elevation limit on the set of *d* that can be used to quantify the shape of the volcano in question.

The *d* expresses the complexity of a contour with respect to a circle. As a result, *d* can increase above the index value of 1.0 because either (a) a circular contour exhibits marked contortions, or (b) the contour is smooth, but highly elliptical. In either case, the parameter describes significant changes in volcano shape.

Fig. 4 shows how *d* varies for perfectly smooth contours of increasing eccentricity (*ε*; calculated by using $\varepsilon^2 = 1 - (b^2/a^2)$ where *b* and *a* are the semi-minor and semi-major axes of the ellipse, respectively). While the eccentricity of the contour lies below about 0.9, *d* is insensitive to *ε*, remaining close to the index value of 1.0. Contours with eccentricities greater than 0.87 (the *ε* at which the *d* of an un-dissected ellipse begins to increase markedly above 1.0) generally characterize elevations close to the summit. In this region, often due to the presence of breached or asymmetric craters and cones, contours can fail to circumvent the center of the volcano, and may assume a highly elliptical or even arcuate form. In addition, because the ratio between the perimeter of a contour and its enclosed area tend to be higher at the summit, individual geomorphic features begin to exert more control over contour shape and, hence, on the calculated *d*. For this reason we do not include *d* calculated for the extreme summit regions of the volcanoes we describe later in this contribution.

3. The “shape” of Merapi volcano, Indonesia: *d* as a function of spatial resolution

To test the effect of spatial resolution on *d* distributions we have analyzed a high spatial resolution DEM of Merapi volcano,
an active stratovolcano located on the Indonesian island of Java (Fig. 5a). The raw radar data used to generate the DEM shown in Fig. 5a were acquired with a spatial resolution of 2.5 m. When processed to the GT-3 (Global Terrain level 3) product used in this study, this corresponds to a DEM with a pixel size of 10 m, and a relative accuracy of 2.5 m in the horizontal and 3 m in the vertical.

Using Eq. (1), we calculated the $di$ for the Merapi Star-3i DEM at 10 m contour intervals (Fig. 5b). Here, $di$ was calculated for elevations between 1600 m and 2870 m, for reasons outlined in the previous section. In general, the trend is one of increasing $di$ with distance from the summit. However, superimposed on this trend are three inflections, denoted $x$, $y$, and $z$. The aim of this work is to quantify the effects of decreasing spatial resolution on the shape information contained within volcanic DEMs, we note that several aspects of the $di$ trend presented in Fig. 5b relate to variations in the morphology of the volcano. Elevations with lower average gradients tend to have higher $di$ than elevations with steeper slopes (Fig. 5c; also evident in Fig. 5a). A simple explanation for this may be that shallower slopes tend to characterize lower elevations which are further from the volcano’s summit; drainage is radial around the summit, the distance from which is proportional to the depth of, and the degree of erosion by, flowing water. We also note that the three prominent inflections in the $di$ trend coincide with the elevations of three morphologic features important in the structural evolution of Mount Merapi: ($x$) Gunung Bibi, which marks the remnant high point of the pre-Merapi edifice; ($y$) the remnant high point of the Batulawang series which is the avalanche caldera rim formed during a major sector collapse event; ($z$) the Pasarbubar crater rim, produced during the modern Merapi period (Fig. 5a; see Camus et al., 2000 for a detailed description of the structure of the volcano).

Fig. 6 shows the effects of decreasing spatial resolution on $di$, calculated using the raw Star-3i 10 m data set (a) and then the raw data re-sampled (using the bi-linear method) to 20, 40, 60, 80, and 100 m spatial resolution. Qualitatively there are several things to note. As spatial resolution decreases so do both the maximum and minimum $di$, as the high frequency morphological information contained within the contours is “smoothed-out”. The range also falls as pixel size increases,

![Diagram](image-url)
resulting in the $di$ trend becoming increasingly steep. Both effects reflect the increasing homogenization of the set of $di$ values with decreasing spatial resolution, as topographic information is lost via spatial averaging. This results in the three inflections in the $di$ trend visible in the raw 10 m data becoming increasingly less apparent. Significantly, there is little visible difference between the 10 and 20 and 40 m analysis; this indicates that the analysis can be replicated on 30 m data (i.e. of the kind provided by SRTM) with little loss of morphological information (although we cannot quantify the effect that spatial sampling during collection of the raw radar data and production of the 10 m DEM has had on the preservation of “real world” topographic complexity). At 80 to 100 m (which brackets the resolution of the SRTM 90 m data product) the two main inflections are still visible in the $di$ profiles. However, the inflection closest to the summit (i.e., the feature denoted “z” in Fig. 5a) is not evident at these resolutions, indicating that the topographic variation that produced it was removed from the DEM by the time the raw data had been re-sampled to these resolutions.

Fig. 6b shows how the $di$ calculated from the 20, 40, 60, 80, and 100 m data sets decreases relative to that obtained from the 10 m index DEM. The $di$ decreases as the pixel size of the DEM increases, as complexity is lost from the elevation contours during the re-sampling. The transition from 10 to 20 m pixel size results in a difference in $di$ (i.e., a loss of contour complexity) of between 2 and 9% ($\Delta_{10-20}$). When the raw data are degraded to 100 m spatial resolution ($\Delta_{10-100}$), the calculated $di$ are at least 5% and as much as 35% lower than in those obtained from the original 10 m data set.

Descriptive statistics support these qualitative observations (Fig. 7). As spatial resolution becomes increasingly coarse the $di$ histograms become narrower and move to the left; sample standard deviations decrease as real topographic detail and variability is lost as the spatial resolution of the DEMs worsens. For each resolution, the data can be assumed to be normally distributed about the mean (the standardized skewness and kurtosis lie in the interval $-2$ to $+2$, implying no significant departures from normality). Analysis of variance (ANOVA; Fig. 8g) indicates that while the mean $di$ are significantly different at the 95% level for the group as a whole, there is overlap between adjacent resolutions (i.e. between the 10 m data and the 20 m data; the 20 m and 40 m, etc.), and the degree to which the confidence intervals overlap increases with decreasing pixel size. This trend indicates that, as spatial resolutions increases, morphologic information is lost from the DEM at an increasing rate. In the
next section we demonstrate the extent to which the rate of information loss is volcano-specific over the range of DEM resolutions commonly encountered. The averaging of topographic complexity that occurs as spatial resolution is decreased results in the samples becoming, at least in terms of their gross statistical properties, increasingly similar.

Fig. 8 illustrates how these statistical observations manifest themselves in the raw data. Here, the $di$ calculated from the raw 10 m data (ordinate) are compared in turn against the $di$ values calculated for each of the sub-sampled DEMs (abscissa). The straight line indicates a one-to-one relationship (i.e. no loss of morphological information); departures from this line indicate a reduction in information content relative to the 10 m DEM. As the spatial resolution decreases from 20 to 100 m, there is a progressive increase in the scatter of $di$. In addition the $di$ of each dataset ($di_{20,40,60,80,100}$) decreases in relation to that calculated from the reference DEM ($di_{10}$). Interestingly there also appears to be evidence of increased curvature of the $di$ relationship as spatial resolution decreases, whereby higher magnitude $di$ appear to fall away from the one-to-one line more rapidly than do lower magnitude $di$, resulting in a prominent dog-leg in the $di$ trend, at a value of $\sim$2.2. This is because the loss of topographic information caused by spatial averaging is more obvious for more dissected contours than it is for smoother contours (i.e. a perfectly un-dissected contour will still be perfectly un-dissected when viewed at coarser resolution).
Crenulations in a contour can only be removed by re-sampling if they are there to begin with. This effect, whereby absolute change in high di values exceeds that in lower magnitude dis, is also reflected in the di distributions as a progressive decrease in skewness with decreasing spatial resolution (Fig. 7).

4. Dissection indices of several Alaskan volcanoes

Fig. 9 shows shaded relief images derived from the 30 m SRTM DEMs of six Alaskan volcanoes, and Fig. 10 shows the di profiles for each, calculated from the corresponding 30 m and 90 m SRTM data products. There are conspicuous differences between the di profiles of these volcanoes calculated using the 30 m SRTM DEMs. For most of their length the di profiles of Augustine, Cleveland and Carlisle are steep with a slope close to 1, although di does increase gradually towards the base of the profiles, giving these di trends a relatively simple arciform appearance. The profiles of Boborof, Gareloi and Segula are different, exhibiting a greater range of slopes and inflections.

Qualitative comparison of the di profiles calculated using the 30 and 90 m SRTM data for the same volcano gives the impression that the information contained in the di profiles at 30 m is preserved in, and obtainable from, the 90 m SRTM product.

Fig. 11 shows the di histograms for this group of volcanoes, while the box plots shown in Fig. 12 summarize the main properties of the di distributions. The data presented in Fig. 11 could not be transformed to conform to a normal distribution, and significant differences in variance prohibited a comparison using standard parametric tests. However, non-parametric analysis of variance (Kruskal–Wallis) confirms that the median di differs amongst this group of six volcanoes at the 95% significance level (Fig. 12c and d). Comparison of the medians shows that, at 30 m, the median di values are all significantly different from each other. At 90 m the same overall pattern is preserved, although the medians have a smaller range. As a result, although there is a statistically significant difference in the median di for Augustine and Cleveland when calculated using the 30 m SRTM data, this difference is not retained when

Fig. 7. Frequency histograms of di values calculated from the Star-3i Merapi dataset at spatial resolutions of (a) 10 m (raw data), (b) 20 m, (c) 40 m, (d) 60 m, (e) 80 m, and (f) 100 m, where n is number of variates, \( \bar{x} \) is sample mean, and s is sample standard deviation. Number of classes determined using Sturges’ rule. The normal curve is shown for comparison. (f) Analysis of variance of the means (ANOVA) results for the same datasets. Crosses denote the calculated means; horizontal bars correspond to the 95% confidence limits, calculated using Tukey’s HSD (honestly significant difference) method.
using the 90 m data, although the degree of overlap is relatively minor. In spite of this, we propose that this statistical analysis serves to substantiate our previous assertion: the decrease in spatial resolution from 30 to 90 m does not result in a significant deterioration of the topographic information contained in the SRTM DEMs.

In the previous section we demonstrated that the median $d_i$ of Merapi volcano decreased as the raw 10 m data were re-sampled to 20, 40, 60, 80, and 100 m, and indicated that such a trend was a measure of the rate at which the topographic information contained within a DEM decreases as increasing spatial resolution. Fig. 13 shows the equivalent statistic calculated for the six Alaskan
Fig. 10. $d_i$ profiles (10 m contour intervals) calculated for the group of Alaskan volcanoes referred to in the text, using the 30 m (left hand column) and 90 m (right hand column) SRTM data products. $d_i$ are plotted using the range 1.0 to 3.0 so that the reader can directly compare the trends presented here with those determined for Merapi volcano (Figs. 5 and 6). Also shown are the differences between these $d_i$ values, expressed as a percentage of the 30 m value.
volcanoes. In each case, the raw 30 m SRTM data were re-sampled down to 150 m, at 10 m increments. For each resulting DEM the set of \(d_i\) were calculated at 10 m contours intervals. Fig. 13 shows how the median \(d_i\) varies for each volcano as a function of spatial resolution. The volcanoes can be divided into two groups: those that exhibit a strong negative correlation, and those for which the slope of the median \(d_i\) trend is almost zero. For Augustine, Carlisle, and especially Cleveland, it appears that decreasing spatial resolution has almost no effect on the median \(d_i\). Although there is a slight negative relationship, the medians are not statistically different at the 95% confidence level. On the other hand, Bobrof, Gareloi and Segula, show evidence of decreasing median \(d_i\) as pixel size increases. These patterns can be explained with reference to the shaded relief images presented in Fig. 9 and the \(d_i\) profiles in Fig. 10. As a group, Bobrof, Gareloi, and Segula appear significantly more dissected than Augustine, Carlisle and Cleveland, both visually from the shaded relief images and from the complexity of the \(d_i\) trends. The reasons for this were discussed.
in the previous section. In summary, it takes more re-sampling “events” to remove the topographic information contained in a heavily crenulated contour than a comparatively smooth contour.

Augustine, Cleveland, and Carlisle all exhibit the form typical of a stratovolcano: steep concave-upwards slopes bounding a cone that is roughly symmetric about a central vent. The remaining three, Bobrof, Segula, and Gareloi are also classified as stratovolcanoes (Wood & Kienle, 1990). However, their morphology is decidedly different. Augustine, Cleveland and Carlisle are relatively smooth, un-dissected edifices, resulting in relatively low median $d_i$ values. In comparison, Gareloi, Segula and Bobrof do not exhibit the “classical” stratovolcano profile and as a result have higher median $d_i$ values, consonant with their less symmetric, more rugged, form. In addition, these three volcanoes are characterized by marked variations in $d_i$ as a function of elevation (Fig. 10), as a result of significant altitudinal variations in their morphology (Fig. 9). Augustine, Carlisle and Cleveland, on the other hand, have relatively featureless $d_i$ profiles.

Augustine and Cleveland are amongst the most active volcanoes in America; Carlisle less so, but several eruptions have been reported to have occurred at this volcano in the last 300 years (Wood & Kienle, 1990). The low dissection indices of these three cones is probably a result of their relatively high levels of eruptive activity; although geomorphic processes are constantly working to wither them, constructional forces serve to re-surface the cones and replace the volume lost via erosion and mass movements. In contrast Gareloi, Segula and Bobrof exhibit higher $d_i$, and the shaded relief images in Fig. 9 confirm that these three have more dissected appearance than the trio previously discussed. No eruptive activity has been observed at Bobrof or Segula during historic times, and although recent eruptions have occurred at Gareloi, it is thought that the most recent activity followed an extended hiatus in activity (Wood & Kienle, 1990) during which erosion would have proceeded unopposed.

This is, of course, a simplification of reality, and we cannot comment on the role that time has to play in explaining the different form of these volcanoes, as little is known with regard to the ages of these volcanoes, Augustine excepted. Nevertheless, it appears that variations in the dissection indices of these volcanoes can be sensibly explained in terms of simple geomorphic concepts.

5. Summary and conclusions

The SRTM project has provided high spatial resolution digital topographic data for most of Earth’s active and potentially active volcanoes. Although these data were acquired with a nominal spatial resolution of 30 m, such data are only available for volcanoes located within the U.S.A. and its Territories. For the overwhelming majority of Earth’s volcanoes not contained within this subset, DEMs are available in the form of a re-sampled 90 m product. Given that the highest resolution data are unlikely to be made available to the research community in the near future, the purpose of this paper was to evaluate the effect that this re-sampling has on the quality of topographic information that can be retrieved from the 90 m data. To this end, we have (a) applied a simple metric to summarize the shapes of volcanic edifices as encoded in a DEM and (b) using the resulting metric, evaluated the extent to which this topographic information is lost as the spatial resolution of the data is reduced. Our use of the dissection index provides a rapid and physically intuitive means of characterizing the morphologic changes as a function of elevation on an individual volcano. This index also provides a means for
comparing volcanoes and quantitatively evaluating the relationship between topographic resolution and information and how this relationship changes from volcano to volcano.

Our results indicate that although the re-sampling of the 30 m SRTM data obviously results in a loss of morphological information, this loss is not catastrophic. Analysis of a group of six Alaskan volcanoes indicates that differences in $d_i$ profiles calculated from the 30 m SRTM product are largely preserved in the 90 m product. This is of particular importance in the field of volcanic hazard assessment. During an eruption the topography of a volcano, or at least part of a volcano, can change dramatically over short periods of time. For example, the emplacement of a lava flow-field builds new topography that can affect the most likely path that a future lava flow may take; explosive eruptions can remove large volumes of material from the summit area and redeposit it down-slope as either ash deposits or as volcanic flows called ignimbrites and lahars. Realistic simulation of the paths of lava and other volcanic flows requires knowledge of the contemporary topography. Although very high resolution DEMs can be obtained from airborne SARs (e.g., Rowland et al., 1999) and LIDARs (e.g. Mouginis-Mark & Garbeil, 2005) the most realistic sources of up-to-date topographic data for use in an operational capacity are orbital SARs (see Zebker et al., 2000) or orbital sensors with an optical stereographic imaging capability (e.g. ASTER; Stevens et al., 2004). The DEMs obtainable from these sources have resolutions in the range of those upon which we have conducted our analysis. Of course, whilst the degraded 90 m SRTM data appear adequate for volcano-morphometric studies, their use in applications where precision is paramount, such as crustal deformation studies, has not been evaluated here.

Our results are significant because they demonstrate that the degradation of the raw 30 m SRTM data to 90 m does not preclude quantitative discrimination of volcanoes on the basis of their morphology. This conclusion has implications for other work that relies on understanding volcanoes and their properties through the analysis of topographic datasets acquired with these spatial resolutions.

Acknowledgements

This research was supported by grant NAG5-13729 from NASA’s Natural Hazards Program. STAR-3i data were obtained as part of the NASA Commercial Data Buy Program. We thank the reviewers for their comments. HIGP publication number 1450 and SOEST publication number 6816.

References


