Geomorphometry from SRTM: Comparison to NED

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Abstract

The Shuttle Radar Topography Mission (SRTM) produced near-global 1″ and 3″ DEMs. The cartographically-derived National Elevation Dataset (NED) provides a mechanism to assess SRTM quality. We compared 12 geomorphometric parameters from SRTM to NED for about 500,000 sample areas over the continental United States. For basic parameters like average elevation or relief, the two data sets correlate very highly. For more derived measures, such as curvature and higher moments (skewness and kurtosis), the correlations are much lower, with some parameters essentially uncorrelated between the two DEMs. Correlations improve after restricting analysis to region with average slopes greater than 5 percent, and the SRTM data set compares more closely to simulated 2″ NED than to 1″ NED. SRTM has too much noise in flat areas, increasing average slope, while in high relief areas SRTM over smoothes topography and lowers average slopes. The true resolution of 1″ SRTM DEMs proves to be no better than 2″.

Introduction

Digital elevation models (DEMs) represent the Earth's surface at a range of scales, and have been widely applied in uses from military terrain analysis through earth science and engineering practice to video games. Even before suitable computers or digital data sets existed, geomorphologists saw the potential of DEMs to enable geomorphometric quantification of ground surface relief and patterns (Evans (1980; 1998); Pike (1988; 2000; 2002)).

The Shuttle Radar Topography Mission (SRTM) allowed production of a publicly available, consistent, and comprehensive DEM covering approximately 80 percent of the Earth's surface. No other publicly available data exists at this resolution, and the SRTM dataset has instantly become the global standard for medium to small scale depictions of topography. Because of the varied applications for which the SRTM data is already being and will be used, we must evaluate and understand how it represents topography and surface morphology. Geomorphometric comparison of SRTM with the best comparable DEM, the National Elevation Dataset (NED, Gesch *et al.*, 2002) will demonstrate how the two sources represent the same surface morphology. The comparison will yield information about SRTM, its systematic characteristics, and its true resolution. Figure 1 provides a visual comparison of the two DEMs.

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Terrain Parameters from DEMs

Geomorphometric DEM parameters include point and area statistics. Simple point parameters, except for elevation, require a region or neighborhood around the point, usually the eight surrounding pixel values. Common geomorphometric computations such as slope, however, offer a range of possible algorithms, but for statistical aggregation all the slope methods correlate extremely highly (Guth, 1995; Hodgson, 1998; Jones, 1998). More complex point parameters, like terrain organization, require a larger neighborhood and the value of the parameter varies with the size of the neighborhood. Area parameters depend on the range or distribution of values within the selected neighborhood; examples include elevation relief, the hypsometric integral, or the moments of the slope and elevation distributions.

Many terrain parameters depend on the DEM spacing or horizontal resolution (Hodgson, 1995; Kienzle, 2004). Computed slope values generally decrease with increasing point spacing in the DEM (Guth, 1995). Elevation derivatives include slope (the rate of change of elevation), and curvature (the rate of change of slope in plan and profile view). Evans (1998) has long championed the four moments of the elevation, slope, and curvature distributions, even though he notes that the higher moments, like the higher derivatives, can reflect noise in the DEM.

Computing aspect statistics for the downhill direction would require circular statistics (Evans, 1998), and has not been attempted. A substantial literature exists on variograms, fractals, and power spectra for terrain characterization. These methods prove very hard to compute and interpret because of the need for preprocessing or filtering, and the need to pick values from confusing or complex plots (e.g., Malinverno, 1995; McClean and Evans, 2000).

Appendix A lists the 12 geomorphometric parameters discussed in this paper, with definitions and references for the computations. Supplemental material on the web at **www.asprs.org** lists the 33 parameters initially computed for the study with brief explanations for the omission of 21 parameters from the following discussion. The parameters omitted mostly duplicate slope or prove unreliable.

DEMs

The National Elevation Dataset (NED, Gesch *et al.*, 2002) provides a control to assess geomorphometric measurements

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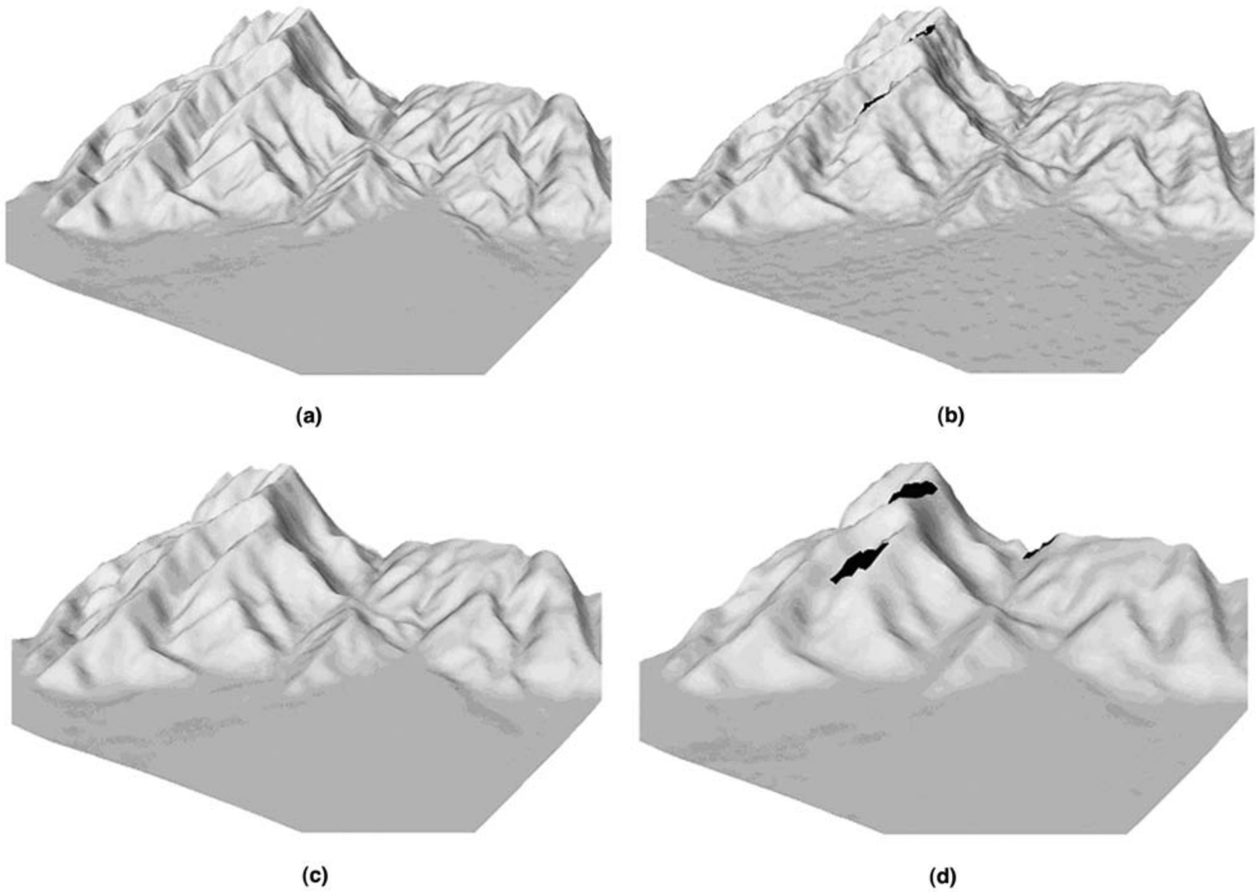

Figure 1. Block diagrams of part of Tucki Mountain, Death Valley, California, from two resolutions of NED and two of SRTM: (a) NED 1″, (b) SRTM 1″, (c) NED 2″, and (d) SRTM 3″. This graphical depiction shows the smoothing of SRTM in the mountains, and the radar noise in the flat alluvial fans. Decimation produced the 2″ NED to show that this resolution appears to better match 1″ SRTM data.

with SRTM. Complete coverage of the continental United States at 1″ resolution was downloaded in the summer of 2003 from **http://seamless.usgs.gov/**. NED represents the "best available" elevation data for the United States, and most of the DEMs used to create it are derived from scanned contour lines on 1:24 000 topographic maps (Level 2 in the USGS classification; Gesch *et al.*, 2002). Photogrammetric methods created cartographic contours, which were then vectorized, and finally underwent vector to raster processing to create the DEMs. NED is supposed to reflect bare earth beneath the forest canopy, although in dense vegetation cartographers always face challenges seeing through the vegetation in the original aerial photographs. At the time of data acquisition coverage of the United States with 0.333″ NED was incomplete; coverage at 0.333″ resolution is rapidly increasing but clearly offers much better spatial resolution compared to the SRTM and would not provide a good comparison.

The SRTM data set measures the top of the reflective surface using C-band radar, with a nominal resolution of 1″ and 3″. Users must be careful because the National Geospatial-Intelligence Agency (NGA) refers to SRTM-DTED® 2 (1″ spacing), SRTM-DTED® 1 (3″ spacing), and SRTM-DTED® 0 (30″ spacing), while many other users refer to SRTM-1, SRTM-3, and SRTM-30 in terms of the data spacing in arc seconds. The publicly available 3″ SRTM DEM covers the 80 percent of the earth imaged by the shuttle, but the only freely available 1″ data covers the United States. The 3″ data can be created from 1″ data in two ways: decimation or thinning, which retains every third elevation in every third column, and averaging, which uses the points in a neighborhood to create a new value at the desired postings. NGA uses decimation, which insures that the posting values in the 3″ data set are the same as those in the 1″ data set, while the creators of the 3″ research data sets feel that averaging creates a better data set. This study evaluated four versions of the SRTM data set:

- SRTM Unfinished Research Data. This data in both 1″ and 3″ data was downloaded from **ftp://e0mss21u.ecs.nasa.gov/srtm/** for this study. The 3″ data averages the 1″ data surrounding each posting. Our sample data set contains all of the cells in the United States.
- SRTM-DTED® 2 Finished Data: This version with 1″ spacing has lakes and rivers flattened and rivers smoothly descending toward the ocean, the oceans set to zero, and is currently the best data available because of the hydrologic accuracy and removal of water anomalies. Holes remain, and their removal constitutes an ongoing effort. This data was obtained from **http://edcsns17.cr.usgs.gov/srtmdted/**. Our sample contains about 90 percent of the cells in the United States.
- SRTM DTED® 1: We simulated this 3″ data by thinning (decimating) the 1″ unfinished research data, to investigate the different effects of decimation (thinning) and averaging on terrain statistics. NGA decimates 1″ data to get 3″ data, so the unfinished research data available worldwide might be different than 3″ data that NGA would provide. Our sample contains all of the cells in the United States.

All SRTM DEMs suffer from radar speckle, random noise in the elevations, although the thinning or averaging to get 3″ data decreases the effect of the noise compared to the 1″ data.

NED and SRTM data have a potential half pixel shift in the locations attributed to each elevation posting. NGA provides DTED® data, and SRTM DTED®, with a posting at each corner of the 1° cell, and subsequent postings every 1″. Each cell will overlap with its neighbors by a column or row. USGS provides NED with the first point displaced from the corner by 0.5″ in both latitude and longitude, and there are no points in common to adjacent cells. While this difference affects many comparisons between NED and SRTM, it makes no difference to the block statistics used in this study.

Methods

We processed the NED and SRTM DEMs, computing statistics for every 2.5′ × 2.5′ cell in the United States. At continental scale those regions can be considered random sampling areas, and the United States contains about 500,000 cells. We created raster grids with 2.5′ × 2.5′ spacing, for each of the 12 parameters in Appendix A as well as an additional 21 parameters discussed at **www.asprs.org**. Initial inspection of the results revealed statistical anomalies with NED, due to boundary conditions at the international boundaries. Many cells along the Mexican border incorporate old USGS 1:250 000 DEMs, with extreme generalization and terrain stair-stepping. Cells overlapping Canada contain zero elevation values that are not the ocean, and some locations in North Dakota had mis-attributed flags for missing data. As a result, we masked the data to remove:

1. Any points outside the boundaries of the United States as depicted on the state outlines available from the National Atlas (**http://nationalatlas.gov/atlasftp.html**);
2. Any points within the Great Lakes from the streams and water bodies outlines in the National Atlas, because the boundaries of the states extend into these lakes;
3. Any 2.5′ × 2.5′ regions with an average slope computed from NED of zero, which removes larger lakes;
4. Problem areas along the Canadian Border with incorrect missing data.

After the masking, our sample contains 470,965 cells.

We created a second mask, using only those blocks with an average slope greater than 5 percent in the NED. This mask addresses the problems in computing meaningful terrain statistics in flat terrain with this scale of DEM having large horizontal data spacing and integer precision for elevations. Applying this mask to the grids of terrain parameters reduces the sample size to 244,439 cells by removing all those with small average slopes. Figure 2 shows this mask, which eliminates many of the flatter physiographic provinces (Fenneman and Johnson, 1946; Hitt, 1996). Flatter topography will require higher resolution DEMs for detailed gemorphometric calculations.

To check the true resolution of SRTM, we created a 2″ NED data set by decimating (thinning) the 1″ NED, and created grids for the geomorphic parameters with this DEM as well. We ultimately had grids of geomorphometric terrain parameters for six DEM series (two NED and four SRTM) and 33 parameters, of which we will discuss 12 parameters in this paper.

Results

Figure 3 shows a map with the distribution of ELEV_RELF. The overlain boundaries of the Fenneman physiographic provinces (Fenneman and Johnson, 1946; Hitt, 1996) show that variations in this parameter correspond with accepted geographic boundaries. Many of the parameters, with all six DEM series, show a similar geographic pattern with the variation in parameters related to real changes in the terrain that have long been recognized by geographers.

Figure 4 shows part of the map with PROFC_STD for research grade SRTM 1″. All four SRTM data sets show this

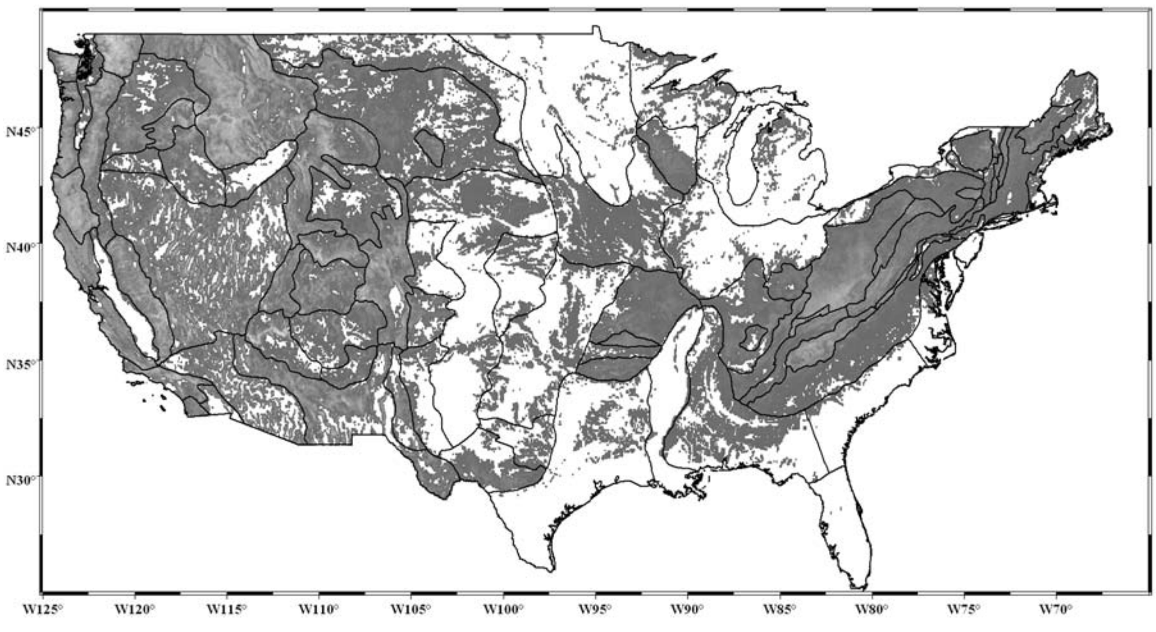

Figure 2. Mask of the United States, showing all areas where the average slope in a 2.5′ × 2.5′ region exceeds 5 percent, and their relationship to Fenneman's physiographic provinces. Flat areas in white were excluded from some calculations.

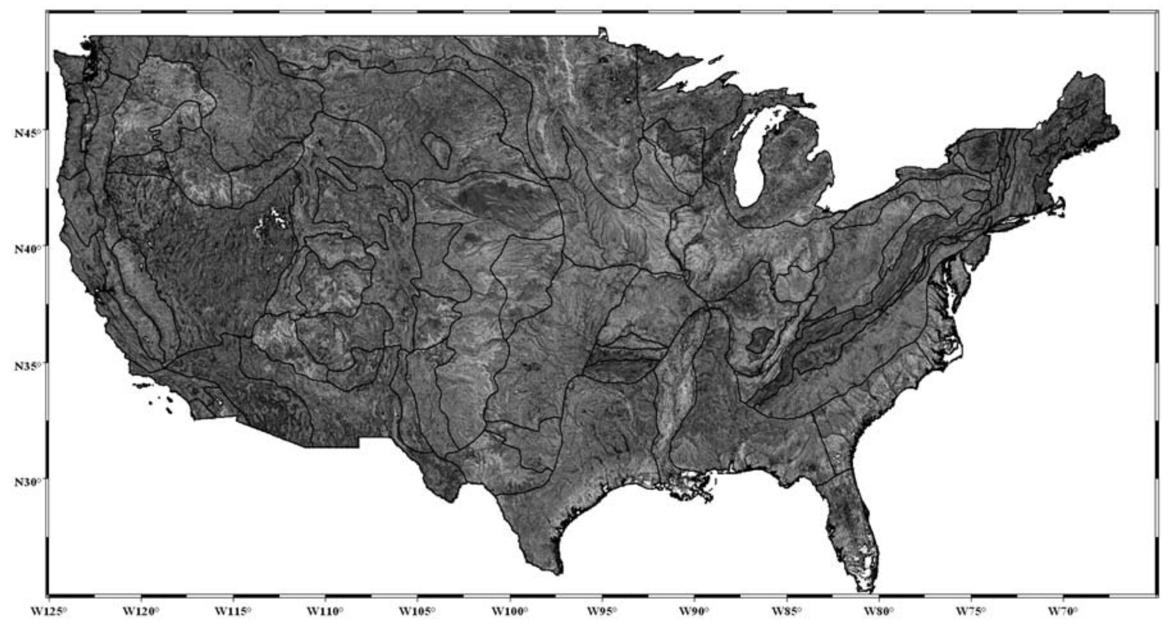

Figure 3. Map showing the distribution of Elevation-Relief ratio (ELEV_RELF) over the United States for 2.5′ × 2.5′ regions, computed with NED. Fenneman's physiographic provinces outlined to show the correspondence of this parameter to recognized boundaries. Color version available at the ASPRS web site: **www.asprs.org**.

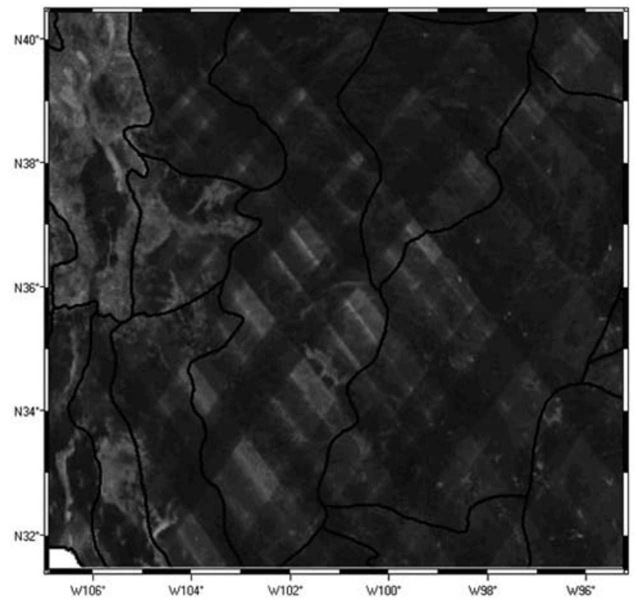

Figure 4. Map of the standard deviation of profile curvature (PROFC_STD) for part of the southwestern Great Plains, from the 1″ research grade SRTM. Fenneman's physiographic provinces outlined, but the most obvious features are the descending and ascending orbital swaths.

pattern for several parameters (e.g., S2S3 or average slope), which clearly follow the shuttle orbital paths as the patterns intersect at each of the SRTM gaps in Iowa, Florida, and the Carolinas. The anomalies occur only in flat terrain and disappear after application of the 5 percent slope mask.

These anomalies do not occur with NED, and clearly reflect either the SRTM processing or collection methodology. The anomalies have not been observed directly in the elevation data, but only in derived parameters which were likely not closely monitored during processing. However, the anomalies must be present in the elevation data to appear in the derived products.

Figure 5 shows the relationship between the average slopes in degrees computed with NED and SRTM-DTED® 2. The correlation coefficient R^2 is 0.976, and the slope of the best fit line is 0.85, but the graph is not linear. For flat areas, SRTM-DTED® predicts a steeper slope than NED, and for increasingly more rugged areas the slope less than one leads to under prediction of slopes from SRTM-DTED®. However, the average slopes computed with SRTM correlate strongly with those computed with NED; for all four SRTM data sets the correlation coefficient $R^2 > 0.97$.

Graphs similar to Figure 5 can be created for each parameter, and for each of the four SRTM data sets, and comparing SRTM to both 1″ and 2″ NED. Figures 6 and 7 summarize the results; Figure 6 shows the correlation coefficient R^2, and Figure 7 the slope of the best fit line. Each graph compares all four SRTM data sets to a single NED data set. On each figure there are four graphs, showing the 1″ NED for all of the United States, the 1″ NED restricted to slopes greater than 5 percent, 2″ NED for the entire United States, and 2″ NED for slopes greater than 5 percent. In Figure 7 slopes less than 1 indicate that SRTM statistics consistently record lower values than those computed from NED, true for almost all but two of the comparisons shown in Figure 7.

Discussion

As seen in Figure 6a, only one parameter has R^2 values > 0.90 when comparing the SRTM DEMs to 1″ NED: average elevation. Two other parameters, not discussed here (elevation standard deviation and relief), also had high correla-

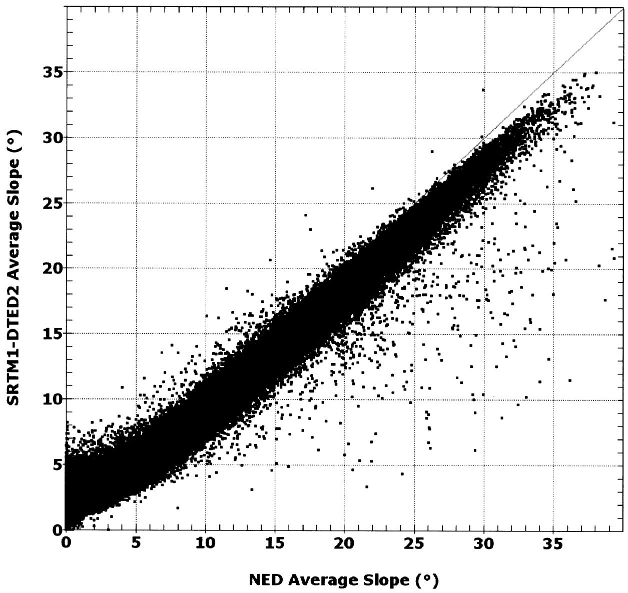

Figure 5. Scatterplot of the elevations from NED compared to SRTM-DTED® 2. Despite a correlation coefficient R^2 of 0.9764 and a slope of 0.85, a clear non-linear trend exists. SRTM is too steep in flatter topography, and too smooth in steep terrain.

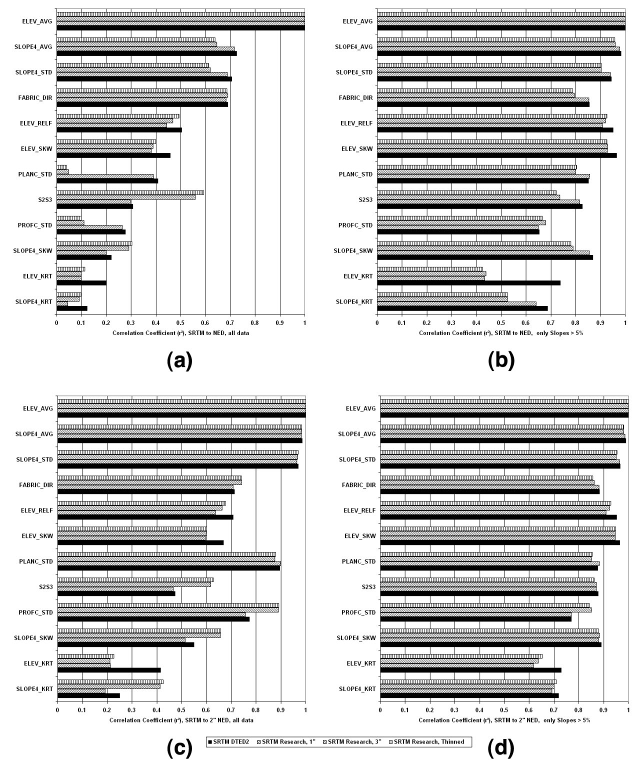

Figure 6. Correlation coefficients of the best fit line for the four SRTM data sets compared to NED: (a) shows 1″ NED and all data in the United States, (b) shows 1″ NED and only areas with average slope greater than 5 percent, (c) shows 2″ NED and all data in the United States, and (d) shows 2″ NED and areas with average slope greater than 5 percent. Decimation/thinning of 1″ NED created the 2″ NED. Note than restricting the analysis to slopes above 5 percent, or comparing SRTM to 2″ NED, improves the correlations.

tions. Four parameters have R^2 values < 0.30 (PROF_STD, SLOPE_SKW, ELEV_KRT, and SLOPE_KRT), suggesting that either the parameter does not measure a meaningful characteristic or that one of the DEMs does not adequately capture the parameter.

The correlations in Figure 6c are substantially higher than those in Figure 6a, showing that SRTM correlates better with 2″ NED than with 1″ NED. Some of the correlations are still poor, with SLOPE_KRT and ELEV_KRT having R^2 values between 0.2 and 0.4. By contrast, the correlation of SLOPE_KRT for 2″ NED and 1″ NED has an $R^2 = 0.8$, attributed solely to the change in resolution caused by data decimation, and showing that this parameter has the potential to accurately characterize the terrain.

With several exceptions to be discussed below, in almost all cases the SRTM-DTED® 2 correlates most closely with NED compared to the other SRTM data sets. However, the 1″ Research SRTM data set has almost as good correlations as the SRTM-DTED® 2, suggesting that it is the 1″ spacing rather than the water edits that provides the better agreement with NED.

The 3″ SRTM correlates noticeably better with NED than the 1″ SRTM data for three parameters when considering all the data and both NED spacings (Figure 6a and 6c). For S2S3 the 3″ SRTM correlates better with both 1″ and 2″ NED. The S2S3 parameter measures terrain organization (the azimuth alignment of ridges and valleys, and very high values occur in the folded Appalachian Mountains), and the reduced noise in the 3″ data better captures this parameter. For PROFC_STD and SLOPE4_KRT, the 3″ SRTM correlates better with 2″ NED than does the 1″ SRTM data. These two parameters correlate very poorly with 1″ NED, and the better correlation of the 3″ SRTM data with the 2″ NED probably reflects better noise reduction in 3″ SRTM. Curvature is the second derivative of elevation, and kurtosis is a fourth moment, so these measures prove relatively intolerant of DEM noise.

Figure 7a shows the slope for the best fit line relating the SRTM parameters to the NED parameters. Since many of the relationships are not linear (e.g., Figure 5), the slopes provide only a general indication of how the SRTM values match those computed with NED. Slopes less than 1 indicate that SRTM predicts lower values than NED, the case for all parameters. However, for two parameters (S2S3, SLOPE_SKW PROFC_STD) the 3″ SRTM data has a higher slope and hence more closely predicts the NED values than does the 1″ SRTM. These are some of the same parameters where the 3″ SRTM better correlates with NED than the 1″ data as shown in Figure 6a.

Figures 6b, 6d and 7b, 7d repeat the correlations and best fit line slopes for only those samples with an average slope greater than 5 percent. The R^2 correlations in Figure 6b improve dramatically compared to Figure 6a. Only one set of parameters show best fit line slopes greater than 1 (1″ SRTM compared to 2″ NED for PLANC_STD). In general Figure 6d shows that away from flat regions, SRTM geomorphometric parameters compare very closely with 2″ NED; all 12 parameters have $R^2 > 0.6$ for all four SRTM data sets.

As in evident from Figures 6, higher moments tend to be less robust. Press *et al.* (1986, p.457) recommend that skewness and kurtosis be used “with caution or, better yet, not at all.” Evans (1998) also noted that the higher moments,

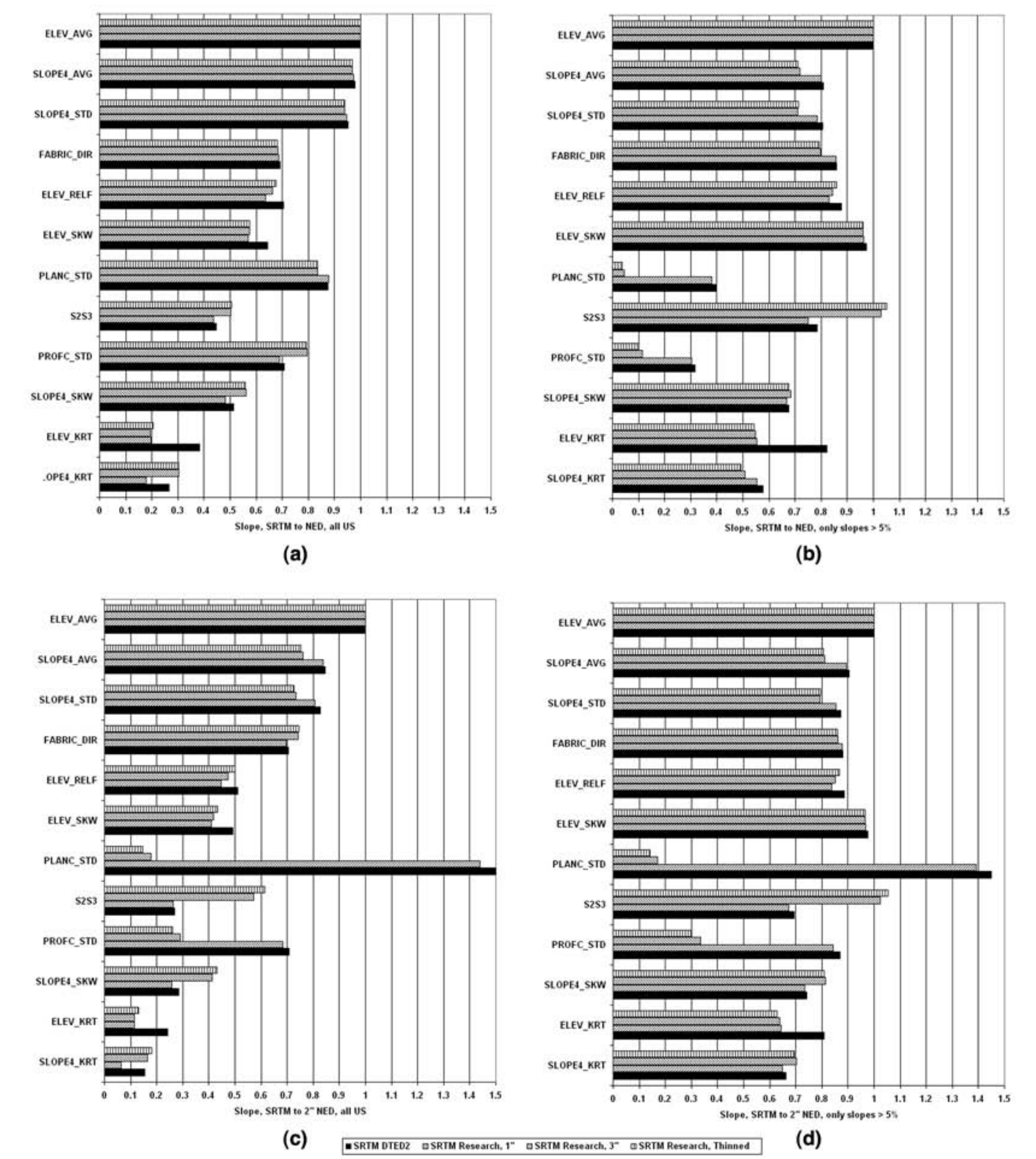

Figure 7. Slopes of the best fit line for the four SRTM data sets compared to NED: (a) shows 1″ NED and all data in the United States, (b) shows 1″ NED and only areas with average slope greater than 5 percent, (c) shows 2″ NED and all data in the United States, and (d) shows 2″ NED and areas with average slope greater than 5 percent. Decimation/thinning of 1″ NED created the 2″ NED. With the exception of the PLANC_STD parameter for the 2″ NED, the slopes are everywhere less than 1, meaning that SRTM always computes smaller values of the statistics than NED.

like the higher derivatives, reflect noise. However, the skewness and kurtosis values show dramatic increases in the R^2 values from Figure 6a through 6d, suggesting that for appropriate scales and in reasonably rugged terrain they might contain useful information about the terrain (Evans, 1998), and they have been widely used.

Table 1 lists the 12 variables, out of the 33 originally investigated in this study, that appear to be most important for terrain characterization. They are listed in rough order of importance, with those subject to noise in flat topography noted. Duplicate measures of slope, the most commonly measured of topography, have been omitted. Slope can be measured in degrees or percent equally effectively. Most of these variables relate to processes operating on the landscape, and will allow direct comparison with other areas. Two, the average elevation and the orientation of the fabric direction, are more descriptive, but will also affect microclimate and terrain shading and hence many landscape processes.

Radar speckle remains the most important limitation of the SRTM DEMs. The continental scale results of this study support the observations of Falorni *et al.* (2005) that the absolute vertical accuracy of SRTM presents few problems, but the relative accuracy has the most effect on users of

TABLE 1. SUGGESTED VARIABLES FOR TERRAIN DESCRIPTION

Parameter	Descriptive Name	Notes
SLOPE_AVG	Steepness or Roughness	Evans (1998). One of 15 contributing variables to the most important attribute of Pike (2001)
ELEV_RELF	Elevation-relief ratio or Coefficient of dissection	Pike and Wilson (1971). One of two contributing variables to the third most important attribute of Pike (2001)
S2S3	Organization	Guth (2003). Only in moderate to steep terrain.
SLOPE_STD	Heterogeneity	Evans (1998). Only in moderate to steep terrain.
PROFC_STD	Curvature in profile	Evans (1998). Only in moderate to steep terrain.
PLANC_STD	Curvature in plan	Evans (1998). Only in moderate to steep terrain.
ELEV_AVG	Average elevation	Largely descriptive only. Evans, 1998. One of two contributing variables to the secondmost important attribute of Pike (2001)
FABRIC_DIR `	Fabric direction	Largely descriptive only. Guth (2003).
ELEV_KRT	Homogeneity	Evans (1998). May be too noisy. Only variable in the fourth most important terrain attribute of Pike (2001).
ELEV_SKW	Massiveness (inverse)	Evans (1998). Only in moderate to steep terrain. One of two contributing variables to the third most important attribute of Pike (2001).
SLOPE_KRT	Modality	Evans (1998). Only in moderate to steep terrain, and may be too noisy
SLOPE_SKW	Limitation	Evans (1998). Only in moderate to steep terrain, and may be too noisy

derived products like hydrogeomorphic modeling, and that the problems become most acute in low slope areas like floodplains.

True Resolution of 1″ SRTM Data

Previous works have suggested the effective spatial resolution of the 1″ SRTM was 45 to 60 m (Hensley, 2005), 45 to 90 m (Rodriguez, 2005), or about 90 m in one case (Crippen, 2005). Smith and Sandwell (2003) found no significant power in spectra from the 1″ SRTM at wavelengths less than 180 m, and suggested that the data could be decimated to 60 m (2″ spacing) without losing any information, and that the 3″ data would probably capture almost all of the information in the SRTM dataset.

Figure 1 shows views of Tucki Mountain in Death Valley, California, with NED and SRTM. Decimation of 1″ NED produced the 2″ NED, which provides the best visual match for the 1″ SRTM. The SRTM lacks the crisp ridges and valleys present in 1″ NED, and the 1″ SRTM shows rough patterns on the alluvial fan that are not present in NED. In this subjective visual depiction, the 1″ SRTM clearly shows more detail in the mountains compared to the 3″ data, but the 3″ data does a better job in the alluvial fan by reducing noise.

Figure 7 show that SRTM consistently computes smaller terrain statistics than 1″ NED, suggesting over smoothing and a larger effective resolution than the 1″ postings should provide. To test this hypothesis, we created 2″ NED by decimating the 1″ data and repeated the geomorphic grid computations. Figures 6c, 6d and 7c, 7d show the results. The 2″ NED shows larger correlation coefficients for all parameters (compare Figure 6c to 6a), indicating that SRTM data more closely resembles 2″ NED rather than 1″ NED. However, as seen in Figure 7a and 7c, many of the slopes of the best fit lines are less for the comparison to 2″ NED, and two have slopes of about 1.5 when comparing the 1″ SRTM to 2″ NED. Figures 6d and 7d show the same relationships as 6b and 7b when restricting the comparisons to moderate relief regions; the SRTM has higher R^2 values and larger slopes when compared to 2″ NED than when compared to 1″ NED, indicating a better fit and closer agreement between computed geomorphic parameters.

Figure 8 shows the results of an experiment to determine the true resolution of SRTM DEMs, using a plot of the average slope by elevation. This rugged region in Death Valley, surrounding that shown in Figure 1, has no vegetation, so both NED and SRTM should show bare earth topography. Six resolutions of NED, produced by decimating the 0.333″ and 1″ data, show a clear trend in decreasing slopes as the data spacing increases. Decimation of the 0.333″ NED by a factor of 3, to 1″ spacing, produced nearly identical statistics to the 1″ NED, although the two resulting DEMs were not identical, and USGS does not create 1″ NED by decimating 0.333″ NED. The SRTM 1″ DEM plots essentially atop the 2″ NED, and the 3″ SRTM plots between the 3″ and 4″ NED, but closer to the 3″ NED. This suggests that 1″ SRTM DEMs really have a resolution of 2″ in terms of both their visual quality

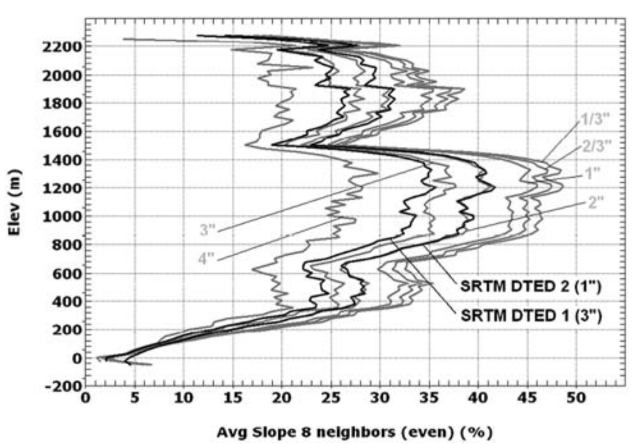

Figure 8. Average slope versus elevation for six resolutions of NED and two resolutions of SRTM in the area around Tucki Mountain in Death Valley. The NED DEMS were created by thinning (decimating) 0.333″ and 1″ data, and show a steady decrease in computed slopes as the horizontal spacing increases. Note that the SRTM DEMs best match NED with larger horizontal data spacing.

(Figure 1) and the terrain information they contain. Using 2″ SRTM DTED® instead of 1″ would decrease the required storage by a factor of 4. While the 3″ SRTM data comes close to capturing all the information in the 1″ data set, a noticeable difference remains.

The slope comparison in Figure 8 does not represent an artifact from NED. Figure 9 shows a similar computation for an area in southern Canada, with Canadian Digital Elevation Data (CDED) downloaded from **http://geobase.ca**. The 0.75″ data has been decimated (thinned) to simulate resolutions up to 3.75″, which show the same clear progression of smaller computed slopes as the spacing increases seen for NED in Figure 8. The 1″ SRTM calculated slopes lie between the CDED resolutions of 2.25″ and 3″. The Canadian area is significantly steeper than the area in Death Valley, which might account for different apparent resolution, because as already noted, the SRTM underestimates slope in steep topography.

Some participants at the June 2005 SRTM Data Validation and Applications Workshop suggested that to solve the problems with SRTM slopes shown in Figure 5, slope algorithms needed to average over a larger region than the nine pixel neighborhood used in standard GIS algorithms (e.g., Guth, 1995; Hodgson, 1998; Jones, 1998). However, such an algorithm will increase the under estimates of slope in steep terrain. The examples in Figures 8 and 9 confirm that the problem evident in Figure 5, based on regional statistics, also exists for local computations. At the lowest elevations, on the alluvial fans and valley floor, the SRTM slopes start to exceed the NED slopes, but at higher elevations SRTM consistently underestimates slopes. A slope algorithm for SRTM that smoothes the flat areas and sharpens the steep areas will be a significant challenge to write, particularly if the SRTM processing used local characteristics to determine the amount of filtering it applied to create the DEMs.

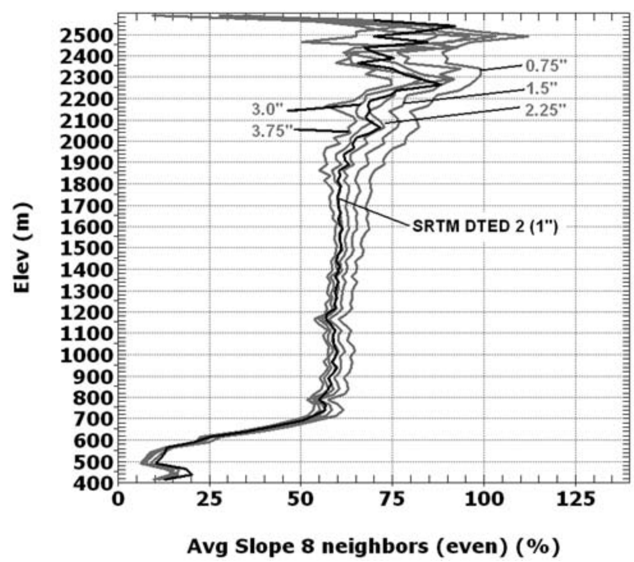

Figure 9. Average slope versus elevation for five resolutions of CDED1 and 1″ SRTM for both halves of cell 092H03. Thinning of the 0.75″ CDED1 data produced the other resolutions, which show a clear progression of decreasing slopes. Note that the SRTM DEMs best match CDED with larger horizontal data spacing.

Conclusions

The SRTM-DTED® 2 proves better than the 1″ research data because of the removal of noise along the coasts and in water bodies. This accounts for its slightly better correlations with NED, although in most cases the data sets will be very similar. Only about 6 percent of the 2.5′ × 2.5′ cells covering the United States had a different average elevation in the research and final SRTM datasets, all located along the coast or large water bodies. The newly available global SRTM water masks will greatly improve geomorphometric calculations, enabling masking of rivers and lakes which can prove difficult to identify in many DEMs.

Thinning (decimation) and averaging of 1″ SRTM to get 3″ SRTM produce very similar statistic measures. Filtering by averaging lessens the effect of radar speckle, but also averages the terrain by lowering peaks and ridges and raising valleys. Depending on the geomorphic parameter, some respond better to thinning and others to averaging in terms of how they compare with NED, but overall they produce very similar statistics.

Compared to cartographic DEMs like NED and CDED, the true resolution of 1″ SRTM is actually about 2″, while the 3″ SRTM data closely resembles 3″ NED and CDED. If the SRTM data were to be reprocessed, consideration should be given to supplying it in 2″ resolution for decreased storage requirements by a factor of 4 to provide the same information content. Applications that truly require 1″ resolution must understand that SRTM DTED® 2 does not really have the horizontal resolution implied in its stated 1″ spacing.

Table 1 shows a list of suggested geomorphometric parameters that are largely independent of each other and that appear to be captured in both cartographic DEMs like NED or CDED and radar DEMs like SRTM. Some of these parameters have too much noise in flat terrain, but they all appear to provide information in rougher terrain.

The SRTM data set provides an unprecedented view of the topography of most of the Earth's land surface. Its elevation distribution closely mirrors that of the best previously available DEMs at comparable resolutions. Nevertheless, artifacts from the radar noise and space shuttle orbital patterns remain in many of the geomorphic parameters derived from the elevation data and must be clearly understood by users of this data. Applications like hydrology, slope processes, contour line generation, and inter-visibility may behave very differently with SRTM DTED® compared to cartographic products like NED.

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Appendix A. Geomorphometric Parameters

ELEV_AVG, ELEV_SKW, ELEV_KRT: Moments of the elevation distribution (average, skewness, and kurtosis), computed with the formulas in Press *et al.* (1986).

SLOPE4_AVG, SLOPE4_STD, SLOPE4_SKW, SLOPE4_KRT: The first four moments of the slope distribution computed in degrees. Slopes were computed with an eight neighbors unweighted algorithm (Evans, 1998; Florinsky, 1998; Sharpnack and Akin, 1969). The algorithm has little effect on the results; Guth (1995) showed extremely high correlations between all available slope algorithms. Computation in percent would be equally effective.

PLANC _STD, PROFC _STD: The standard deviations of the plan and profile curvature distributions, computed with the formulas in Press *et al.* (1986). Curvature computed with the equations in Wood (1996) based on earlier suggestions from Evans.

S2S3, FABRIC_DIR: Computed after Guth (2003, following Chapman, 1952 and Woodcock, 1977) using logs of the eigenvectors of the normal vector distribution. S2S3 measures terrain organization, and FABRIC_DIR gives the dominant direction of ridges and valley. Because FABRIC_DIR measures circular angles, its statistics have anomalies.

ELEV_RELF: The elevation relief ratio ([AveZ-MinZ]/[MaxZ – MinZ]) is computed for a region (Pike and Wilson, 1971; Etzelmuller, 2000) and is equivalent to the coefficient of dissection (Klinkenberg and Goodchild, 1992, after Strahler, 1952).

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