Contour Line "Ghosts" in USGS Level 2 DEMs

Peter L. Guth

Abstract
Characteristics of digital elevation models (DEMs) differentiate those produced from digitized contour lines from those produced directly from imagery. Contour-to-grid algorithms produce more grid-node elevations with the same elevation as the contour lines compared to elevations different from contour line elevation; this "ghost" artifact reflects the DEM generation process and not the underlying topography. The effect ranges from extreme to slight. In new USGS Level 2 DEMs, elevations corresponding to the source map contours can occur twice as often as similar elevations between contour lines, and overall contour line elevations are over represented by about 30 percent. Three independent techniques demonstrate the contour line ghosts: visual examination of elevation histograms, the power spectrum from a fast Fourier transform of the elevation distribution, and direct computation of a contour ghost ratio. These artifacts do not diminish the significant improvement of the Level 2 DEMs over Level 1 products, but require users to carefully evaluate their data and analysis methodology, especially when computing derived surfaces from the DEM which magnify data irregularities.

Introduction
Digital elevation models (DEMs) provide a powerful data set for analysis of geomorphometry (Pike, 1988), hydrological and biological processes (Moore *et al.*, 1991), and a number of other applications. Users of these data sets must understand their production and resulting characteristics, in order to determine if the data support proposed analyses. DEMs can be created directly from stereo models of source imagery, or indirectly from existing contour maps. The production process may impart distinct patterns in the resulting DEM.

The sample of DTED (Digital Terrain Elevation Data) Level 2 from the National Imagery and Mapping Agency (NIMA, formerly the Defense Mapping Agency, DMA) publicly posted on the World Wide Web (WWW) contains a strong imprint from the contour maps used for its creation. Given the publicity DMA received for the contour line imprints in DTED Level 1, this discovery proved surprising. At the same time, a series of 30 U.S. Geological Survey (USGS) 7$^{1}/_{2}$-minute DEMs obtained for a study of faulting in the southwestern Great Basin revealed that about half of the DEMs—all 13 of the Level 2 data sets created in 1994 and 1995—also contained an imprint from the 40-foot contour lines on the topographic source maps. This discovery of contour line "ghosts" in current products from the two primary U.S. producers of DEMs prompted this investigation. Contour line ghosts represent unwelcome artifacts, relics from the contour lines in the source maps used to create the DEM.

A contour line ghost is an imprint of the source map contour lines that remains in a DEM after processing. Ghosts introduce unnatural patterns into the elevation distribution of the DEM, which may be amplified in derived computations such as slope or aspect. This work will test the hypothesis that analysis of a DEM's elevation distribution can reveal whether the DEM was created directly from imagery, or whether it came from an intermediate process of interpolation from contour lines. The analysis will further reveal whether the contour interval of the source maps can be recovered from the elevation distribution.

Department of Oceanography, U.S. Naval Academy, 572 Holloway Road, Annapolis MD 21402-5026 (pguth@nadn.navy.mil).

DEM Production
NIMA and USGS produce DEMs with different characteristics, and use different terminology. For the purposes of this discussion, the term "level" must be used with caution. NIMA uses "level" as an indication of the spatial resolution of the data. The original Level 1 DTED had a 3-second data spacing. A new Level 0 has been added for a thinned, world wide data set with a 30-second spacing, and higher levels of DTED will have better spatial resolution. DTED Level 2 has a 1-second spacing (National Imagery and Mapping Agency, 1996). USGS distributes older DTED Level 1 as the USGS 1:250,000-scale DEM.

USGS uses the term "level" to designate the quality of the data. Level 1 has the lowest quality and Level 3 would be the best quality, but such data have not been produced for civilian distribution (USGS, 1990). Level 1 data come from the National High-Altitude Photography Program, equivalent photography, or Gestalt Photo Mapper manual profiling. Interpolation from digital contours produces Level 2 data, and increasing amounts of Level 2 data are being produced. USGS Level 2 data carry a root-mean-square error (RMSE) of one-half contour interval, with no errors over one contour interval permitted. This compares to an RMSE of 15 m and absolute errors of 50 m for the Level 1 DEMs. Level 2 DEMs have been processed to "remove identifiable systematic errors" (USGS, 1990).

Previous Work
Other authors have looked at systematic errors in DEMs (e.g., Carter, 1989). Garbrecht and Starks (1995) noted 90-m striping in low relief (15 m vertical over 10 km horizontal distances) DEMs in Nebraska, attributed to the manual profiling from photogrammetric models used for some Level 1 USGS DEMs. This affect is most obvious on reflectance images in map view or draped on the terrain. This striping results from interpolating between the actual profiles, but this study was unable to identify any interpolated profiles in actual DEMs. An interpolated profile should have all its elevations intermediate between adjacent neighboring profiles, and this study could not find any DEM rows or columns with these characteristics. Garbrecht and Starks (1995) faced an additional challenge in a low relief region when every change in elevation, recorded to the nearest metre, will cause what appears to be a major terrace. In such regions DEMs should

Photogrammetric Engineering & Remote Sensing,
Vol. 65, No. 3, March 1999, pp. 289–296.

0099-1112/99/6503–289$3.00/0

perhaps record elevations in decimetres; even feet would provide better resolution than metres.

Brown and Bara (1994) used a 3 by 5 low-pass filter to decrease the anisotropy in derivative surfaces calculated from the DEM, but they did not consider whether slope and slope convexity might vary over a smaller scale than that represented by a 30-m DEM, and that the terrain might not be isotropic but reflect an underlying grain in the topography. Slope and convexity computed from a DEM vary significantly over short distances, reflecting the imperfect capture of small terrain variations in the DEM, and filtering will produce a more coherent picture of the gross terrain variations.

Methods

This study investigated three techniques to test for contour line ghosts in DEMs: (1) visual examination of elevation distribution histograms, (2) visual examination of the power spectrum from a fast Fourier transform of the elevation distribution, and (3) calculation of contour ghost ratios.

This study performed preliminary analysis of a number of DEMs from various sources, and detailed analysis of USGS $7^1/_2$-minute DEMs to demonstrate the universal presence of contour line ghosts in Level 2 DEMs. Data from seven DEMs of varying heritage illustrate the methodology and demonstrate contour line "ghosts." The seven DEMs in Table 1 include NIMA DTED Level 1 and Level 2, USGS Level 1 and Level 2 $7^1/_2$-minute DEMs, National Ocean Survey (NOS) gridded bathymetry of the U.S. Exclusive Economic Zone (EEZ), and Panorama data from the United Kingdom (Ordnance Survey, 1997). These particular DEMs provide a representative sample of over *3000* DEMs examined during this investigation, and include the standard data series from the three U.S.-Government producers of DEMs. Most of these DEMs record elevations to the nearest metre; about 10 percent of the USGS $7^1/_2$-minute DEMs record elevations to the nearest foot.

Detailed analysis of 30 USGS $7^1/_2$-minute DEMs tested for the presence of contour line ghosts in current Level 2 USGS DEMs. The 30 DEMs in the new Spatial Data Transfer Standard (SDTS) format cover 29 of the 32 1:24,000-scale quadrangles comprising the Last Chance Range 1:100,000-scale quadrangle. They are listed in Appendix 1; one quadrangle has independent Level 1 and Level 2 DEMs. For each DEM, this study computed the elevation histogram and its power spectrum, and determined whether it retained contour line ghosts. After that determination was made, the study checked the SDTS files for the DEM history. Further tests with 1374 USGS $7^1/_2$-minute DEMs from Pennsylvania and California confirmed these systematic differences between Level 1 and Level 2 DEMs.

Several methods exist to model the distribution of elevations in a DEM: standard histograms, cumulative distributions, or specialized diagrams like the hypsometric graphs of Strahler (1952). Standard histograms most easily show the contour "ghosts" in the DEM. Relief is plotted on the y axis of the graph. The difficulty in displaying and differentiating a histogram with several thousand categories often leads to binning of the data (i.e., lumping a range of elevations into a single category; Figures 1a or 2a). Bins can be chosen with particular sizes, or may be sized to attain a particular number of bins. Binning emphasizes the underlying distribution by masking random noise and artifacts of the digitizing process, and dramatically reduces the magnitude of the contour line ghosts if they exist. Unbinned histograms (Figures 1b and 2b) may need to have the y axis expanded to make small-scale patterns apparent (Figure 2c). Reporting elevation to the nearest metre itself leads to binning, but that binning should be random and should not preferentially highlight particular elevations.

The x axis of the graphs represents the elevation distribution relative to a uniform concentration of elevations (a value of 1 equals the total number of data points divided by the relief present in the DEM) because this allows easy comparison of DEMs. The scaling chosen for the x axis does not affect the shape of the distribution; equivalent results would appear if the x axis plotted the number or percentage of elevations in each interval. The use of a uniform concentration for scaling does not imply that the distribution of elevations should be uniform throughout the elevation range. The actual distribution will depend on the terrain, with high concentrations in flat valleys or plateaus and low concentrations in steep mountains, but should vary in a reasonably continuous fashion. For the DEMs listed in Table 1, the uniform concentration ranges from 48 to 4775 points for each elevation, ensuring reasonable statistics.

The elevation distribution (number of points per one-metre elevation bin in an ordered series) serves as input to compute the power spectra with a routine based on a fast Fourier transform (Press *et al.*, 1986). Power spectra frequently plot power versus frequency, the inverse of the periods plotted here, and which would slope in the opposite direction. A power spectrum for a series without periodicity will show increasing power with larger periods, and increasing noise (scatter) at shorter periods. If the input series shows periodicity (in this case, for preferred increases in the elevation distribution at the location of the source map contour lines), the power at that period will show a sharp spike. Figures 1c and 2d show peaks in the power spectra corresponding to contour line ghosts.

Because elevation anomalies will be amplified in derived values like slope or aspect, graphs such as Figure 1d and 2f were constructed to show the average slope versus elevation (Moore and Mark, 1992). Using unbinned elevations for these graphs best shows the effect of the contour ghosts. Average slope uses a steepest-neighbor algorithm (Guth, 1995); the use of other algorithms such as four or eight closest neighbors would slightly decrease the numerical results but would not change the patterns (Guth, 1995). Slope is reported as a percentage, 100 times the rise over run.

A final test, and the most suited to widespread automated analysis of large numbers of DEMs, computes the over-representation of source map contour lines in the elevation distributions. This test computes a contour ghost ratio, the percentage of points corresponding to contour line elevations divided by the percentage of elevations that correspond to contour line elevations. Ratios greater than 1.00 indicate over-representation of the contour lines, and values less than 1.00 indicate under-representation. While simple in concept, calculation of ghost ratio requires some care, and Appendix 2 presents a simple algorithm and example.

Results

Contour-Derived DEMs

Four classes of DEM listed in Table 1 display clear evidence of the source-map contours used to create them: first edition DTED Level 1 now available from USGS (Figure 1), Level 2 USGS $7^1/_2$-minute DEMs (Figure 2), DTED Level 2, and Ordnance Survey (OS) Panorama data. The periodicity often comes at intervals that make little sense (12.2 and 60 m) until converted into feet (40 and 200) when they are seen to be common contour intervals for maps. The USGS Level 2 DEMs and the DTED Level 1 have documented contour map sources, and apparently the other two data sets do as well. The contour ghost ratio for the contour-derived DEMs in Table 1 ranges from 1.26 to 3.27. The most severe ghosts occur in the old DTED Level 1, and the least severe in the USGS Level 2 DEM and the Ordnance Survey DEM. In contrast, the ghost ratio of the other DEMs in Table 1 is near 1.00.

First edition DTED Level 1 (Figure 1) exhibits extreme

Table 1. Representative DEMs Discussed

DEM	Source	Data Spacing	Data Points (non zero)	Relief (m)	Uniform Distribution (Points/m)	Contour Ghosts	Ghost Ratio	Figures
Indian Springs, NV (DTED Level 1)	NIMA (DMA) & USGS	3"	721, 801	2206	327.2	200 ft	3.27	1 a–d
Deep Springs, CA (DTED Level 1, Ed.2)	NIMA (DMA)	3"	721, 801	3519	205.1	*none*	1.03	3 a–c
Fort Hood, TX (DTED Level 2)	NIMA (DMA)	1"	811, 801	170	4775.3	20 ft	1.89	
Monterey Canyon & Shepard Meander	NOS	250 m	171, 325	3567	48.0	none	1.00	
Horse Thief Canyon, CA (USGS Level 1)	USGS	30 m	170, 668	1057	161.5	none	1.00	3 d–f
Gold Mountain, NV (USGS Level 2)	USGS	30 m	170, 947	982	174.1	40 ft	1.31	2 a–f
Wingate Wash West, CA (USGS Level 2)	USGS	30 m	174, 016	914	190.4	10 m	1.58	5 a–b
SS68, 20 km Panorama	OS (UK)	50 m	84, 646	370	228.2	10 m	1.26	

concentrations in the bins corresponding to the source-map contours. In the unbinned histogram (Figure 1b), the locations of the source map 200-foot contour lines stand out; concentrations at those intervals are an order of magnitude greater than at the intervening elevations. The peak at 975 m (3200 feet) has a concentration over 85 times a uniform distribution; the

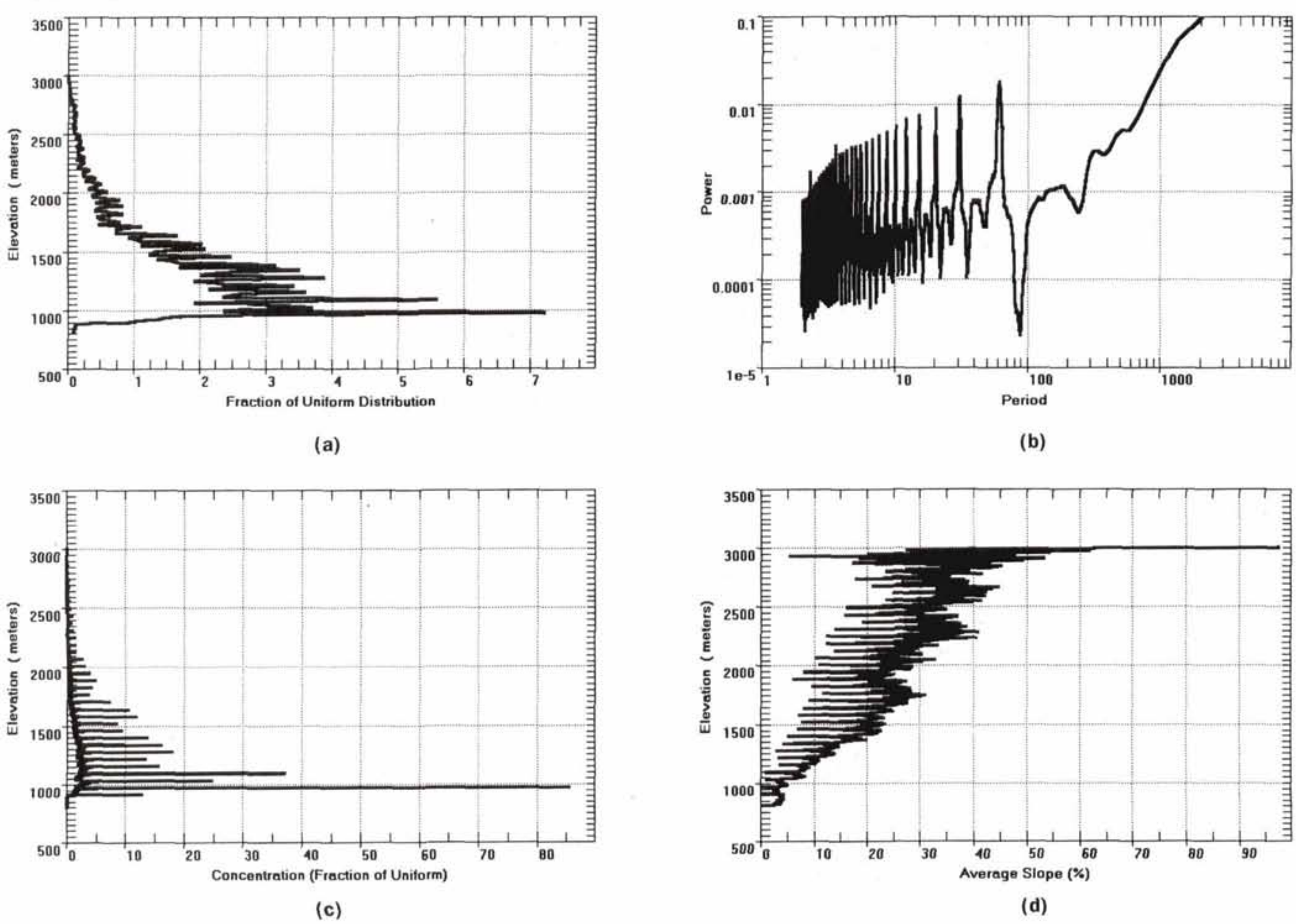

Figure 1. DTED Level 1 DEM of the Indian Springs, Nevada, region, half of a standard 1° cell. (a) Elevation histogram in 23-m bins. (b) Elevation histogram in 1-m bins. Compare the maximum concentration of 85 with the maximum in Figure 1a of less than 7.5. (c) Power spectrum of the distribution in Figure 1b, with periods in metres. Note the strong power at a period of 60 m (200 feet), corresponding to the contour interval of the old Army Map Service 1:250,000-scale maps. (d) Average slope versus elevation. Note the cyclic patterns of low slopes at the same elevations as the contour lines peaks in Figure 1b.

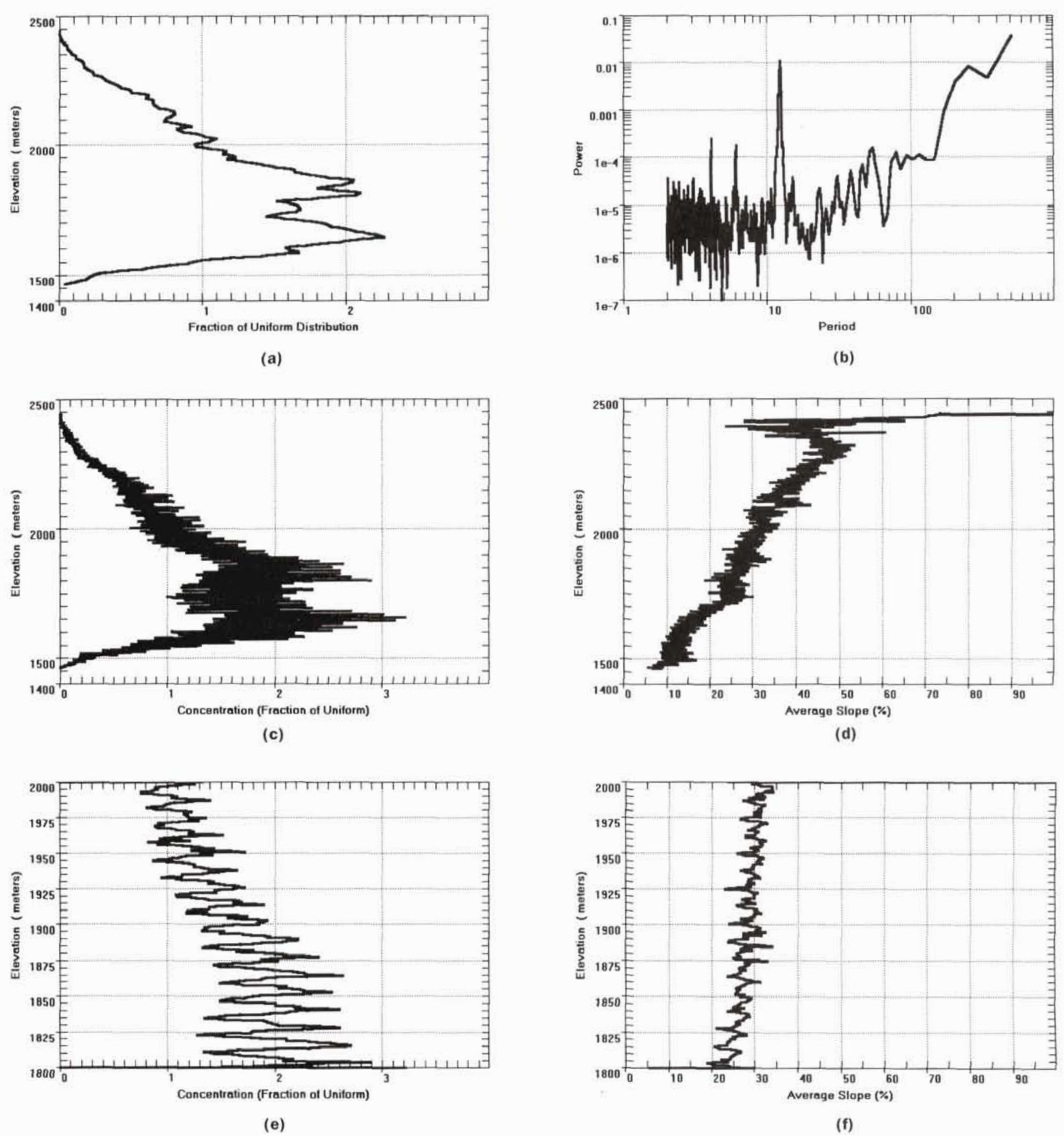

Figure 2. USGS Level 2 DEM of the Gold Mountain, Nevada, $7\frac{1}{2}$-minute quadrangle, showing contour line ghosts. (a) Elevation histogram in 10-m bins. (b) Elevation histogram in 1-m bins. Note the maximum concentration is about 50 percent greater than in Figure 1a. (c) Blowup of a portion of Figure 1b. Note the oscillations in values about every 12 m (40 feet), and that the high concentrations are about twice as great as the low values. (d) Power spectrum of the distribution in Figure 1b, with periods in metres. Note the strong power at a period of 12.2 m (40 feet), corresponding to the contour interval of the USGS 1:24,000-scale maps. (e) Average slope versus elevation. Note the cyclic patterns of low slopes at the same elevations as the contour lines peaks in Figure 1b. (f) Blowup of a portion of Figure 1e, corresponding to the same interval as Figure 1c. Note that average slope oscillates in the same fashion as the elevation distribution, with low slopes near the contour line elevations with their surplus of points.

desert playas amplify the ghost effect. Putting the elevations into 23-m bins (the smallest size that will allow 100 categories; Figure 1a) suppresses the spikes somewhat but they remain conspicuous. The power spectrum of the elevation

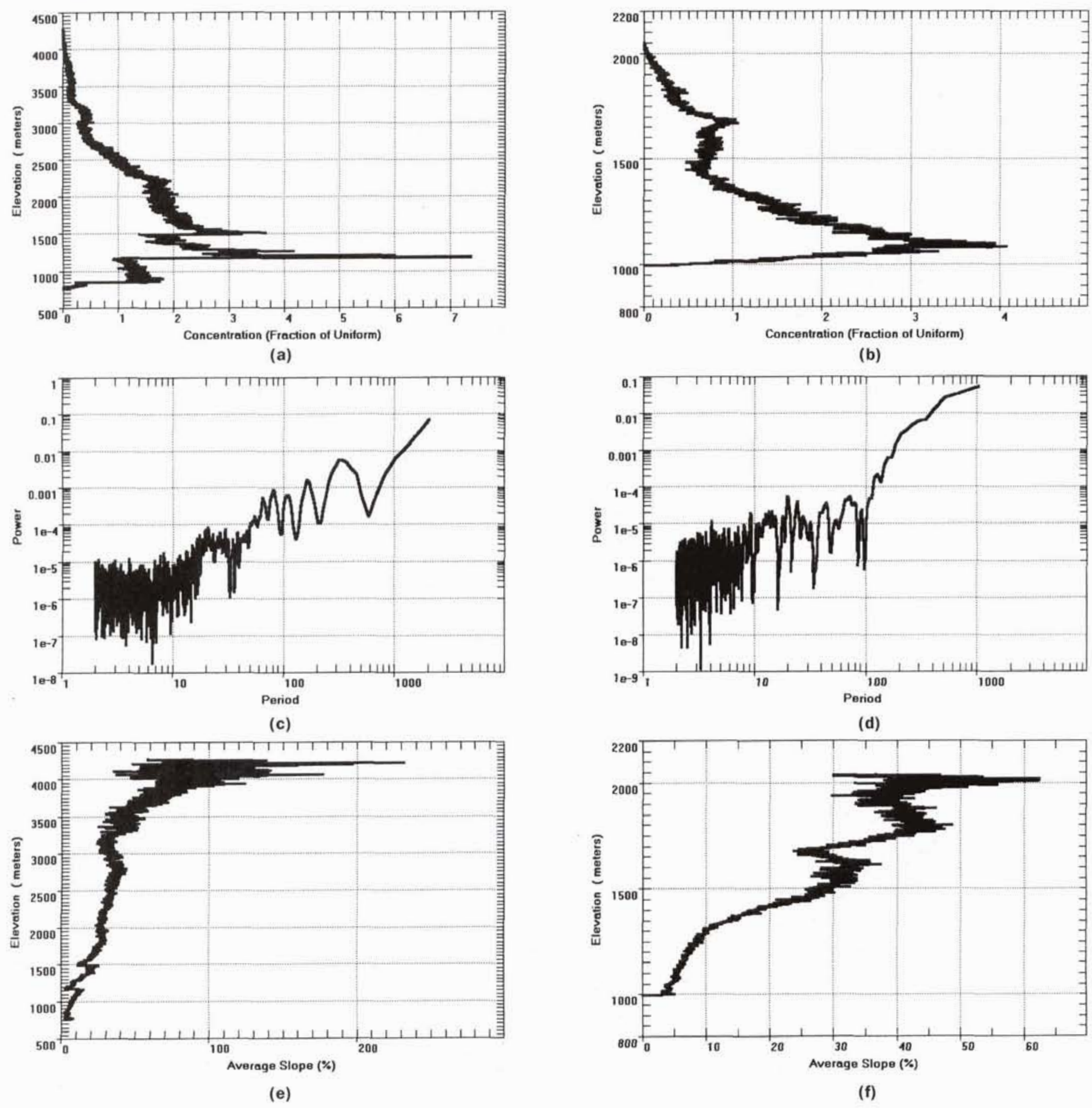

Figure 3. DEMs without contour line ghosts: DTED Level 1 DEM of the Deep Springs, California, region, a subset of several standard merged cells (left, a to c) and USGS $7^1/_2$-minute Level 1 DEM of the Horse Thief Canyon quadrangle, eastern California (right, d to f). Compare these distributions with Figures 1 and 2, and note the lack of contour line ghosts. (a) Elevation distribution. (b) Power spectrum of the elevation distribution. (c) Average slope by elevation. (d) Elevation distribution. (e) Power spectrum of the elevation distribution. (f) Average slope by elevation.

distribution (Figure 1c) shows strong power at the 60-m period and at lower period harmonics. Average slopes correspond closely with the source-map contours; the large number of points around the contour lines cause significantly lower computed slopes at those elevations (Figure 1d). The contour lines ghosts in this DEM stand out so clearly because of the large contour interval and the extreme clustering of elevation values on the contour lines.

The Level 2 USGS $7^1/_2$-minute DEM shows no anomalous elevation concentrations when plotted with 10-m elevation bins (Figure 2a; coincidentally very close to the 12.2-m or 40-foot contour interval, so that almost every bin includes one contour line). When plotted with 1-m elevation bins (Figure 2b), binning (or at least significant noise) becomes apparent. Zooming the *y* axis (Figure 2c) shows the regular pattern and shows that elevation values corresponding to the source-map contours occur roughly twice as often as elevations between contour lines. The contour ghost ratio of 1.31

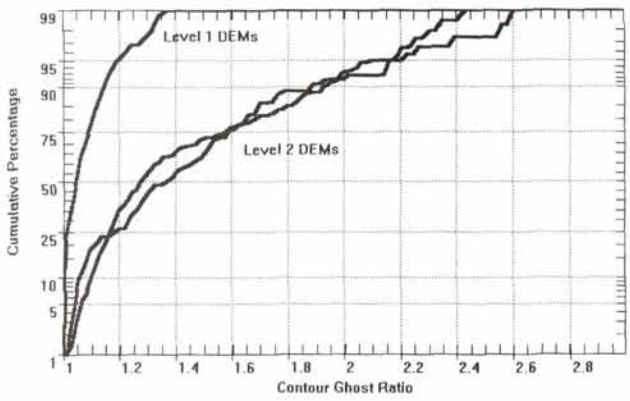

Figure 4. Contour ghost ratio cumulative distributions, plotted for Level 1 and Level 2 USGS 1:24,000-scale DEMs. Level 2 DEMs in feet and metres plotted separately, but they appear statistically identical.

for this DEM means that contour line elevations are about 30 percent over-represented, but Figure 2c shows that some intermediate elevations are severely under-represented. The power spectrum (Figure 2d) shows a substantial spike at the 12.2-m period. Average slopes at elevations corresponding to the contour lines show significant decreases (Figures 2e and 2f), often 20 percent compared to off contour line averages.

Image-Derived DEMs

Three classes of DEM in Table 1 show no periodicity in the elevation histogram and, by inference, no influence from contour lines in a source map. These include newer NIMA DTED Level 1 in eastern California (Figures 3a to 3c), a USGS Level 1 DEM derived from imagery (Figures 3d to 3f), and NOS bathymetry from multibeam soundings. Although DTED does not indicate its source material, this particular DTED Level 1 almost certainly was created from imagery rather than maps. All these DEMs share common characteristics on the three graphs: smooth variation in the elevation histograms and elevation versus slope graphs, and a lack of periodicity in the power spectra. They also have ghost ratios near 1.00.

DEMs derived from imagery have an elevation distribution with a relatively smooth, evenly varying curve. Isolated spikes mark real topographic features, for instance, the three valley floors in the Deep Springs DEM (Figure 3a), the valley floor in the Horse Thief Canyon DEM (Figure 3d), and the continental shelf and abyssal plains in EEZ bathymetry. Some random scatter shows up, most prominently in the bathymetry, which has the fewest points in each bin, making it the most subject to random noise.

The power spectra of these DEMs (Figures 3b and 3d) all show a lack of periodicity, reinforcing the subjective impression that there are no regular anomalies in the elevation distribution. The average slope versus elevation graphs (Figures 3c and 3f) also show no periodicity. Like the elevation distributions, they have relatively smooth variation. Scatter typically increases at high elevations due to the small number of values sampled (Moore and Mark, 1992).

Last Chance Range Quadrangle DEMs

The sample of 30 DEMs from the Last Chance Range quadrangle (see Appendix 1) supports the generalizations above. Fifteen DEMs did not have any contour line ghosts, and all are Level 1 DEMs created from aerial photography. The Horse Thief Canyon DEM in Figure 3 and discussed above typifies these DEMs. Thirteen DEMs, all Level 2 products created between November 1994 and August 1995 from DLGs (Digital Line Graphs) with the CTOG-8 interpolation routine, have strong traces of the contour lines at 12.2-m intervals that coincide with the source map's 40-foot contour lines. The Gold Mountain DEM shown in Figure 2 and discussed above is typical of this group. Two Level 1 DEMs were initially identified with weak periodicity from the power spectrum (one at 72, 36, 30, and 24 m, and the other at 9.8 m), but this periodicity proved much weaker than the 40-foot ghosts in the level 2 DEMs, and the contour ghost ratios did not support the presence of ghosts. If real, this weak periodicity probably does not represent source map contours and its source remains unclear.

Ghost Ratios from the Large Sample

Table 2 summarizes the contour ghost ratio results from the large sample of 1374 1:24,000-scale DEMs and, for comparison, the severe contour ghosts from 25 1:250,000-scale USGS DEMs (old DTED Level 1) covering Pennsylvania. Statistical results for the 1:24,000-scale USGS DEMs are broken into three categories: Level 1, Level 2 with metres for elevation units, and Level 2 with feet. The ghost ratio was selected as the largest of those computed with 11 potential contour intervals. Figure 4 shows the cumulative distribution, on normal probability axes, for the three $7^1/_2$-minute samples. Essentially, no DEMs (a total of three out of 1374, all with either very low relief or extreme modes in their elevation distributions) had ghost ratios significantly lower than 1.00, so contour line under-representation does not appear to be a problem with these DEMs. A Kolmogorov-Smirnov test of the means and standard deviations (Press *et al.*, 1986) shows that the Level 1 DEMs cannot be drawn from the same population as the Level 2 DEMs.

With rare exceptions, Level 1 DEMs have a ghost ratio very close to one. This means that their elevation distributions are random, and that contour lines elevations are not more likely to occur than other elevations. The small number of Level 1 DEMs with ratios much greater than 1 have extreme elevation distributions that fool the simple ghost ratio algorithm and greatly distort the statistics of the sample. Level 2 DEMs, on the other hand, whether with foot or metre elevations, have significant ghost ratios. Ghost ratios greater than 1.10 belong almost exclusively to Level 2 DEMs: 75 percent of Level 1 DEMs have ghost ratios lower than this value, while only about 15 percent of the Level 2 DEMs do. A ghost ratio greater than 1.2 identifies almost 75 percent of the Level 2 DEMs, while including only 5 percent of the Level 1 DEMs.

Discussion

The elevation patterns in DEMs derived from imagery differ from those interpolated from digitized contours, and do not appear to have been publicly recognized previously. Interpolation algorithms from digitized contours favor elevations near the contour lines (V.M. Caruso, personal communication, 1997). The result can be extreme (as in the old DTED Level 1) or very subtle (as in the new USGS Level 2 DEMs);

TABLE 2. CONTOUR LINE GHOST RATIO IN USGS DEMS FOR CALIFORNIA AND PENNSYLVANIA

Map Series	Sample Size (DEMs)	USGS Level	Elevation Units	Min	Max	Mean	Std Dev
1:24K	908	1	m	0.77	3.53	1.08	0.12
1:24K	120	2	ft	1.00	3.09	1.44	0.37
1:24K	341	2	m	0.99	2.62	1.41	0.34
1:250K	25	1	m	1.81	11.23	4.32	1.95

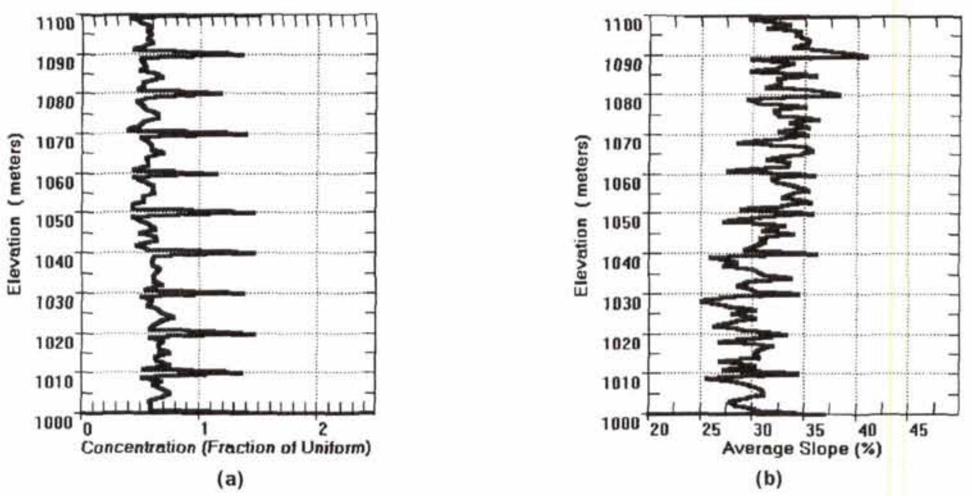

Figure 5. A portion of the elevation histogram for the Windgate Wash West $7^1/_2$-minute quadrangle, and the corresponding slope versus average elevation graph. Note the elevation concentrations corresponding to 10-m source-map contours, and the increased slopes at those elevations.

the magnitude of the effect varies dramatically between the two types of DEM as shown in Table 2. The old DTED Level 1 or USGS 1:250,000-scale DEM have contour ghost ratios averaging 4.3, while the Level 2 1:24,000-scale DEMs have ghost ratios averaging 1.4. Even with old DTED data, the artifacts do not appear obvious in topographic profiles, slope maps, or synthetic illumination reflectance maps in areas of moderate to high relief. Even with its biased elevation distribution, the DEM in Figure 1 provides a valuable tool for visualizing terrain and interpreting geologic structure. Synthetic terraces corresponding to contour lines severely limit the utility of some low relief DTED Level 1 DEMs, but DEMs with one-metre resolution will always face challenges in low relief regions.

Users of DEMs should be aware of the source of their data and plan their analyses accordingly. For a contour-derived DEM, graphs of the distributions should be binned with a binning interval that attempts to put one contour line in every bin. The effect of a biased elevation distribution will be magnified in derived surfaces like slope, aspect, or calculated reflectance, and the user must be aware of the spurious small-scale patterns in the parameter distributions.

The average Level 2 USGS DEM has a contour ghost ratio of 1.4, meaning that elevations corresponding to the source map contour intervals are 40 percent more likely to occur than they would if elevations were randomly distributed with respect to the contour line elevations. However, the concentration of elevations on the contour lines is also accompanied by non-random patterns of missing elevations, as shown in Figures 2c and 4a. These two DEMs show very different systematic patterns. The Horse Thief Canyon DEM (see Figure 2c), created with the CTOG-8 algorithm, has a sawtooth pattern between high values on the contour lines and low values (with concentrations typically half the peaks) between them. The Windgate Wash West DEM, by contrast, shows sharp spikes for the contour lines and relatively uniform distributions between them (Figure 5a). This DEM does not state that it used the CTOG-8 algorithm, and it is also unusual with a 10-m source-map contour interval. Given the paucity of USGS maps with metric contours and its location at Fort Irwin, this DEM probably came from a military map. The difference in its contour distribution may result from a different contouring algorithm, or from differences in the characteristics of the source map, likely a 1:50,000-scale product.

The ghost patterns in these DEMs affects the values of derived characteristics like slope that appear in slope versus elevation plots. For the old DTED Level 1, the contour line ghosts lead to low average slopes at the locations of the contour lines. This pattern holds for some of the Level 2 USGS $7^1/_2$-minute DEMs; the elevation spikes just below 1825 and 1925 m on Figure 2c correspond to lows for the average slope on Figure 2f. In contrast, the elevation spikes on Figure 5a clearly correspond to peaks in the average slope distribution on Figure 5b. Further work will be needed to quantify the magnitude of this effect on the computed slope distributions, and the reasons for the different patterns.

Even with a biased elevation distribution, the Level 2 USGS $7^1/_2$-minute DEMs represent a major improvement over the Level 1 product. They show an increased level of detail in the topography compared to the Level 1 DEMs, with almost as great an improvement over the Level 1 $7^1/_2$-minute DEM as the Level 1 DEM represents over DTED Level 1. Old DTED Level 1 (with the contour line ghosts) is available for free download over the WWW and the 1:24,000-scale DEMs, both Level 1 and Level 2, are now available free in SDTS format over the WWW. These provide powerful tools, and consideration of the data characteristics will maximize the validity of interpretations.

The contour line ghosts are not restricted to DEMs produced by the U.S. Government. The Ordnance Survey of the United Kingdom produces a 50-m grid DEM. Examination of five of those DEMs, including the sample on the WWW listed in Table 1, shows contour line ghosts at 10-m intervals.

Conclusion

Current Level 2 USGS $7^1/_2$-minute DEMs have anomalous elevation distributions related to the source-map contour lines, and Level 1 $7^1/_2$-minute DEMs do not share this peculiarity. A relatively simple algorithm can determine the type of DEM and identify the contour interval of the source map for contour derived DEMs. In this characteristic the new $7^1/_2$-minute DEMs resemble the old (and publicly available) DTED Level 1; this appears to result from the process of creating elevation grids from digitized contours. DEM users should consider the effects of the elevation distribution on their analyses, particularly the magnified effect on derived surfaces like slope or aspect. An unbiased contour-to-grid algorithm would further improve the Level 2 USGS DEMs and similar elevation grids produced by digitizing contour lines.

Acknowledgments

This analysis used the MICRODEM freeware program (Guth, 1995), available on the World Wide Web at http://www.usna.edu/Users/oceano/pguth/website/microdem.htm. I thank Kim Burns-Braidlow and Keith Athmer for help in obtaining the 1:24,000-scale SDTS DEMs covering the Last Chance Range 1:100,000-scale quadrangle which inspired this work. I thank Todd Bacastow for help in supplying the Pennsylvania 1:24,000-scale ASCII DEMs, and the Geography Department at California State University Northridge for posting the 1:24,000-scale DEMs of California on the WWW. Three anonymous reviewers for the journal provided critiques that helped to focus the paper.

References

Brown, D.G., and T.J. Bara, 1994. Recognition and reduction of systematic error in elevation and derivative surfaces from 7½-minute DEMs: *Photogrammetric Engineering and Remote Sensing*, 60(2):189–194.

Carter, J.R., 1989. Relative errors identified in USGS gridded DEMs: *Auto-Carto 9 Proceedings, Ninth International Symposium on Computer-Assisted Cartography*, Baltimore, Maryland, 2–7 April, pp. 255–265.

Garbrecht, J., and J. Starks, 1995. Note on the use of USGS Level 1 7.5-minute DEM coverages for landscape drainage analyses, *Photogrammetric Engineering & Remote Sensing*, 61(5):519–522.

Guth, P.L., 1995. Slope and aspect calculations on gridded digital elevation models: Examples from a geomorphometric toolbox for personal computers, *Zeitschrift für Geomorphologie*, N.F. Supplementband 101, pp. 31–52.

Moore, I.D., R.B. Grayson, and A.R. Ladson, 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications, *Hydrological Processes*, 5:3–30.

Moore, J.G., and R.K. Mark, 1992. Morphology of the island of Hawaii, *GSA Today*, 2(12):257–259, 262.

National Imagery and Mapping Agency, 1996. *Performance Specification Digital Terrain Elevation Data (DTED)*, MIL-PERF-89020A, 40 p., with draft amendment 1, 4 p.

Ordnance Survey (United Kingdom), 1997. *Land-Form PANORAMA User Guide v2.0*, variously paginated.

Pike, R.J., 1988. The geometric signature: Quantifying landslide-terrain types from digital elevation models, *Mathematical Geology*, 20(5):491–512.

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling, 1986. *Numerical Recipes: the Art of Scientific Computing*, Cambridge University Press, 818 p.

Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography, *Geological Society of America Bulletin*, 63(11):1117–1142.

United States Geological Survey, 1990. *Digital Elevation Models Data Users Guide 5*; Reston, Virginia, 51 p.

(Received 11 June 1997; accepted 25 February 1998; revised 20 May 1998)

Appendix 1

USGS 7½-minute DEMS in the Last Chance Range 1:100,000-scale Quadrangle

The following level 1 DEMs have no contour line influence: Bonnie Claire SE, East of Waucoba Spring, Gold Point, Gold Point SW, Hanging Rock Canyon, Horse Thief Canyon, Lida, Magruder Mountain, Mount Jackson, Scottys Junction NE, Scottys Junction, Scottys Junction, SW Sylvania Canyon, Sylvania Mountains, and Waucoba Spring. The graphs from the Horse Thief Canyon DEM in Figures 3d to 3f are representative of these DEMs. These DEMs have contour ghost ratios ranging from 1.00 to 1.03.

Two Level 1 DEMs may have weak periodicity in their elevation distributions, but, as mentioned in the text, it does not appear to result from contour lines: Joshua Flats and Stonewall Pass. These have contour ghost ratios of 1.00 and 1.03.

Thirteen Level 2 DEMs have strong influence from the source map contours: Bonnie Claire, Bonnie Claire SW2, East of Joshua Flats, Gold Mountain, Hanging Rock Canyon, Last Chance Mountain, Last Chance Range SE, Last Chance Range SW, Sand Spring, Scottys Castle, Soldier Pass, Tule Canyon, and Ubehebe Crater. The graphs from the Gold Mountain DEM in Figure 2 are representative of these DEMs. These have contour ghost ratios of 1.10 to 1.35.

Appendix 2

Calculation of the Contour Ghost Ratio

(1) An "on contour line elevation" is defined to be the closest elevation in a DEM corresponding to a contour line on the source map. This definition allows DEMs in metres with source contours in feet.
(2) Require that five source map contours appear within the DEM. The method does not require a uniform elevation distribution, but does require enough relief for the assumption of equal probabilities of elevations lying on contour line elevations and adjacent off contour line elevation. It has problems with data sets with very strong modes in the elevation distribution.
(3) Exclude sea level, lakes, and playas, because they can constitute a large fraction of the DEM and influence the results depending on whether or not they happen to coincide with a contour line. A simple exclusion routine ignores all points with the same elevation as their eight surrounding neighbors.
(4) Compute the percentage of the remaining points on contour lines, NumPoints.
(5) Compute the percentage of elevations in the DEM relief range that lie on contour lines, NumLines.
(6) Compute the contour ghost ratio, NumPoints / NumLines.

The algorithm tests for a variety of likely contour intervals (5; 10; 20; 40; 80; 100; 200 feet and 5; 10; 20; 50 m) and reports the contour interval with the largest ghost ratio.

To illustrate the ghost ratio, consider a map with an elevation range from 53 to 76 m. There are 24 possible elevations (53 to 76 inclusive), and, for a contour interval of 10 m (contour lines at 60 and 70 m), 8.33 percent (2/24) of the points should lie on contour lines. If 10.83 percent of the points in the DEM had elevations of 60 and 70 m, the ghost ratio would be 10.83 / 8.33 or 1.30. This example would in fact be excluded by criterion 2 above, but it illustrates the method.