DIGITAL ELEVATION MODEL ERROR DETECTION AND VISUALIZATION

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ABSTRACT:

A digital elevation models (DEM) can be created using a variety of interpolation or approximation methods. Depending on the algorithm chosen, different kinds of errors may be present in the final DEM. In this paper, we present two methods for visualizing errors in a DEM. One method begins with the standard root mean square error (RMSE) and then highlights areas in the DEM that contain errors beyond a threshold. A second method computes local curvature and displays discrepancies in the DEM. The visualization methods are in three dimensions and are dynamic, giving the viewer the option of rotating the surface to inspect any portion at any angle. Displaying the surface and the errors together give the viewer a better feel for the surface in general and enhance the possibilities for determining the reason behind the occurrence of errors. The methods are tested and compared using DEMs computed from contours by several published methods.

1 INTRODUCTION

There are a variety of interpolation and approximation methods for creating a digital elevation model (DEM) from sparse or contour data. However, no matter how the DEM is created, the resulting surface may not be optimal. Gross errors may be seen by simply representing the DEM via a shaded-relief map. Qualitative assessments can be improved by viewing and manipulating the DEM in a three-dimensional, perspective view. This can be done in traditional geographic information systems (GIS) such as ArcView (ESRI, no date). There also have been a variety of quantitative assessments proposed; many of these measure the overall accuracy of the DEM.

In many cases, there has been a disconnect between the quantitative and qualitative measures. We describe a visualization system that computes two quantitative error measures and gives the user a three-dimensional representation of the DEM in conjunction with the computed errors. The methods were tested with DEMs computed from USGS contour data using several published interpolation/approximation methods.

2 PREVIOUS WORK

It is well known that DEMs computed from sparse or contour data contain errors. In this paper, we focus on methods dealing with DEMs created from contour data; a good review of assessment approaches can be found in (Wise, 2000).

Various approaches to ascertaining the extent of the errors have been proposed. One standard error measurement has been the root mean square error (RMSE), which compares a DEM height point with a corresponding elevation from an accurate source (Rinehart and Coleman, 1988):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i - w_i)^2}$$

where
u_i = interpolated DEM elevation of reference point i
w_i = true elevation of reference point i

While RMSE is a generally good error estimate, it is problematic in that it only gives a *global* measure of the validity of a DEM. Carrara et al. (1997) used several analysis techniques, including determining if DEM heights fall between contour elevations. One way to determine this is to create profile plots with the contour elevations highlighted, as done in Gousie and Franklin (2005). Using elevation histograms to show if there is a linear fit between contours is another technique described by Carrara et al.; a similar method was shown in Reichenbach et al. (1993), which also used shaded-relief for visualization. The overall smoothness can be computed by finding the total squared curvature Briggs (1974):

$$C_{sq} = \sum_{i=2}^{n-1}\sum_{j=2}^{n-1}(u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{i,j})^2$$

An indication of local smoothness can be found by the average absolute curvature Gousie and Franklin (2005). Wise (2000) compared drainage networks determined from special properties of contours; such networks are of particular importance when a DEM is used for hydrological purposes. Fisher (1998) computed several statistics after comparing a DEM with established spot heights and computes the probable viewshed.

The above methods, while very useful, result in either a single error value (such as RMSE), a range of values in a histogram or plot, or a two-dimensional visualization. Wood and Fisher (1993) compared several interpolated DEMs by displaying visualizations of slope direction (aspect), Laplacian filtering that highlights sudden changes in elevation, RMSE, and shaded relief. These give the viewer very good insight not only to what the problems are, but exactly where they lie. However, these visualizations were rendered in only two dimensions, making it more difficult to determine why an artifact might have occurred in a certain area.

3 ERROR VISUALIZATION

We have implemented an error visualization system that displays:

1. an interactive, three-dimensional, shaded DEM
2. the 3D DEM including elevation discrepancies compared with the source data (local difference)

3. the 3D DEM including curvature errors

4. the RMSE of the DEM compared with the source data

5. the total squared curvature, C_{sq}

The test DEMs were created from contours derived from USGS digital line graph (DLG) data. The first method produces a DEM by repeatedly finding intermediate contours in between existing ones until the surface is filled (Gousie and Franklin, 2003). Gaps are filled with interpolating Hermite splines and the entire surface is smoothed with a Gaussian filter. The second approximation first finds "gradient paths;" these are interpolated splines that follow the fall line and that are computed across contours (Gousie and Franklin, 2005). The final DEM is computed using a thin plate spline, found in (Briggs, 1974; Smith and Wessel, 1990; Jain et al., 1995; Eklundh and Mårtensson, 1995) and others. The last set of DEMs were found using the well-known TOPOGRID method devised by Hutchinson and found in ArcInfo (Hutchinson, 1988). This approach also uses a thin plate spline, but enhances the results by incorporating information that indicate water flow lines as well as ridges.

Table 1: Color corresponding to p.

p range	color
$0.20 < p$	purple
$0.15 < p \leq 0.20$	red
$0.10 < p \leq 0.15$	orange
$0.05 < p \leq 0.10$	yellow
$0.00 \leq p \leq 0.05$	green

The three methods above were applied to a contour file. The RMSE and total squared curvature, C_{sq}, were computed for each resulting DEM, yielding a general indication of their quality. Each contour height point was compared to the corresponding elevation in the DEM, and the absolute value of the difference d was stored. The value of d may also be called the *local difference*, as it reflects not an overall error but rather the error at a single location. Following Carrara et al. (1997), d should not be greater than five percent of the contour interval, c. Any difference greater than 5% indicates a significant deviation from the source data and should be highlighted. The visualization portion of the system uses various colors draped over the 3D surface to indicate problem areas. The color generated for a height point is shown in Table 1, where p is the percentage difference $p = \frac{d}{c}$.

Displaying the color based on p creates an error visualization that shows discrepancies between a DEM and its source data. While this is useful, it may be difficult to ascertain the validity of the original source data itself. The second error visualization computes the absolute curvature at each point (similar to the Laplacian):

$$C_{abs} = |(u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{i,j})|$$

This value shows how much a point at location i, j differs from its neighbors. A high difference indicates a potential localized problem in the DEM. There are cases where high curvature is desirable, such as the top of a mountain or the start of a cliff face. C_{abs} was calculated for each point in the DEM, and a color was generated following Table 2. In this case, the cutoff values are in meters, but can be altered in the system to suit the requirements specified by the DEM.

The system produces a 3D visualization complete with lighting and shading and with toggles for the local difference (d) and curvature (C_{abs}) errors. The user may also rotate the DEM to any angle as well as zoom in and zoom out. To facilitate real-time rotation/zooming, the surface can be switched from the usual tessellated rendering to a point rendering by toggling the triangles in the menu. The latter may show some gaps in the surface while performing a transformation, but the user can simply toggle back to the more realistic rendering after a good viewing angle is found.

Table 2: Color corresponding to curvature.

C_{abs} range (m)	color
$1.5 < C_{abs}$	red
$1.0 < C_{abs} \leq 1.5$	orange
$0.5 < C_{abs} \leq 1.0$	yellow
$0.0 \leq C_{abs} \leq 0.5$	green

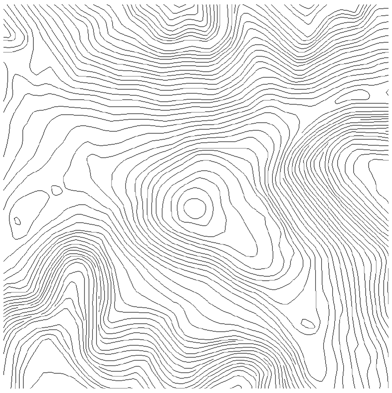

Figure 1: Mt. Washington contours

4 RESULTS

Figure 1 shows an 800×800 contour grid of Mt. Washington, NH. The elevations are in meters with a contour interval of 20 meters. Table 3 shows the quantitative errors of the DEMs computed from the contours using each of the three approximation methods described earlier. The intermediate contours (IC) method generates a DEM with the lowest C_{sq}, thus making the surface the smoothest. However, that smoothness comes at the price of overall accuracy, as reflected by the RMSE. The TOPOGRID DEM is not as smooth nor as accurate as either the IC DEM or the gradient paths (GP) DEMs.

Figure 2 shows the 3D rendering of the IC DEM of Mt. Washington including the local difference results. Toggling the curvature error yields the surface shown in Figure 3. Similarly, Figures 4 and 5 show the local difference and curvature errors in the GP DEM. The TOPOGRID local difference and curvature results are shown in Figures 6 and 7, respectively.

In all cases, the total area where errors occur matches the quantitative results shown in Table 3. For example, the IC DEM is the smoothest, and has the smallest area of curvature error and the fewest "red" spots (Figure 3). However, its accuracy is lower as shown by its higher RMSE compared with the GP DEM (Figures 2 and 4). The TOPOGRID DEM fares worse than the others,

Table 3: Quantitative results using Mt. Washington data.

DEM approximation method	C_{sq}	RMSE	% contour interval
Intermediate contours (IC)	12274	1.4	7.0
Gradient paths (GP)	15617	0.6	3.0
TOPOGRID	134142	3.4	17.0

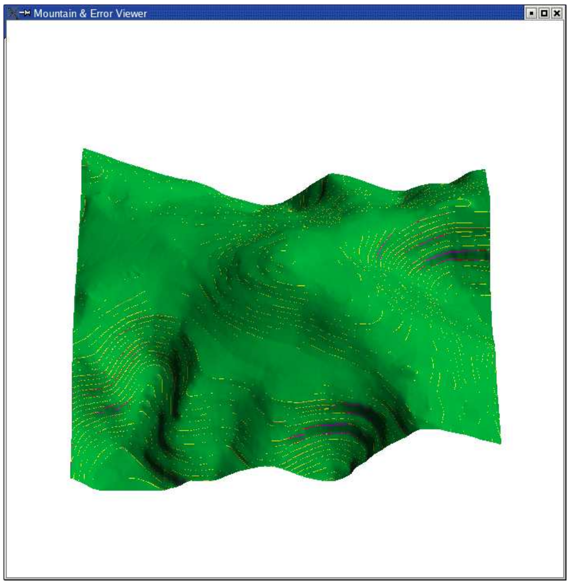

Figure 2: IC DEM showing local differences.

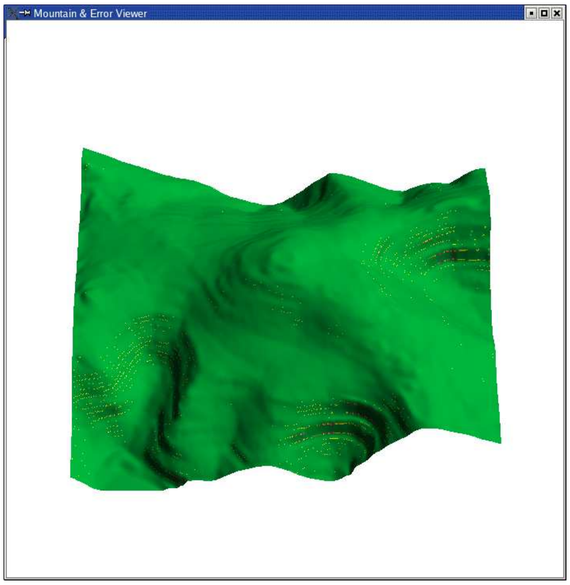

Figure 4: GP DEM showing local differences.

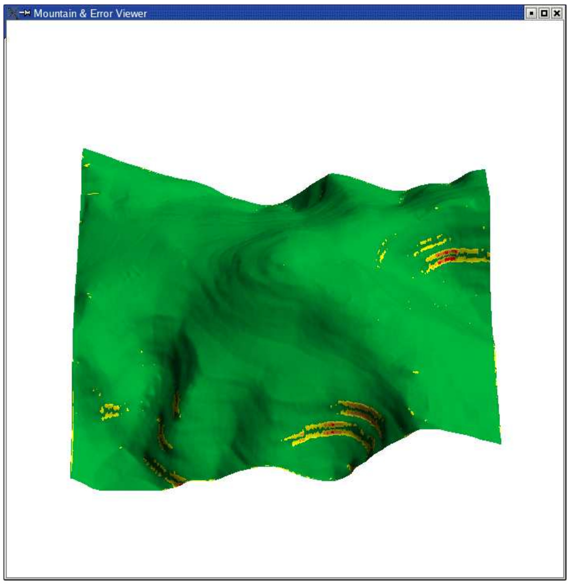

Figure 3: IC DEM showing curvature errors.

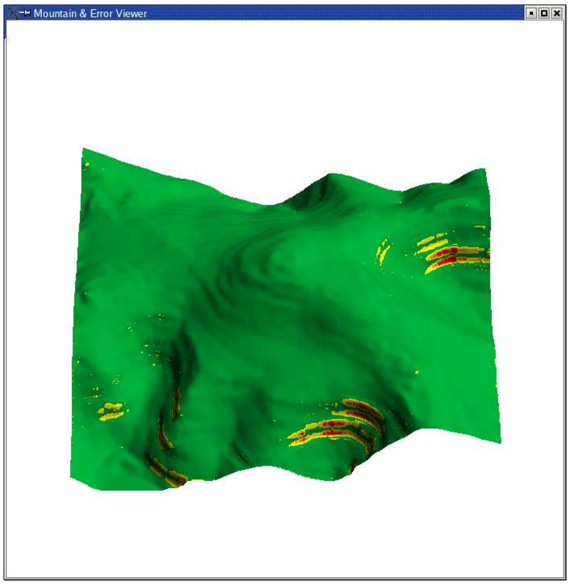

Figure 5: GP DEM showing curvature errors.

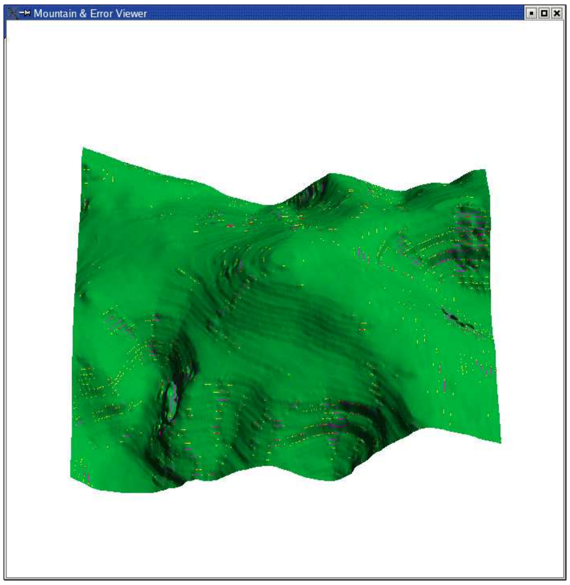

Figure 6: TOPOGRID DEM showing local differences.

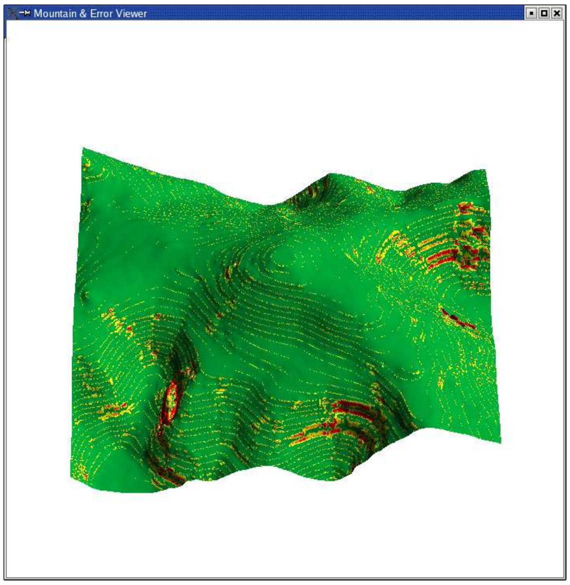

Figure 7: TOPOGRID DEM showing curvature errors.

showing some purple areas indicating high local differences (Figure 6) while at the same time having a greater area of curvature errors (Figure 7). In any case, the curvature errors are clearly discernible in all of the DEMs, and show that all three DEM approximation methods fare poorly in steep areas and better in areas with more moderate grades. Note that it is possible that the areas in the bowls highlighted in Figures 3 and 5 may have naturally high curvature. However, the TOPOGRID DEM shows curvature errors scattered throughout the surface, including areas where the slope seems to be quite consistent.

All three methods show at least some local differences along many contours. The profusion of differences in the IC DEM (Figure 2) is likely due to the Gaussian smoothing function, which has more of an impact the closer contours are to one another. In contrast, the GP method (Figure 4) smooths the surface with a controlled thin plate spline, and thus has fewer errors along the contours. TOPOGRID is also thin plate based, but adds additional processing to improve the modelling of ridges and watersheds. This yields a mix of difference errors, some rather severe (Figure 6). TOPOGRID also seems to have a few local artifacts, shown in the middle of the southwest quadrant. As can be seen from the 3D visualization alone, the methods all have some problems computing a smooth surface near contours and peak areas.

5 CONCLUSIONS AND FUTURE WORK

Approximating a DEM from contour data results in a surface with some errors. We have described a visualization system that displays a DEM in three dimensions, including realistic lighting and shading. The DEM may be rotated to any desired position in real time; zooming can be performed as well. The system computes total squared curvature and RMSE; these values, however, only globally define a surface. The novel part of the visualization system displays local difference and curvature errors in various colors depending on the magnitude of the error, while preserving the 3D surface representation. The different error values may be toggled by the user. The local nature of the errors may give the user a better understanding of the problems of the underlying DEM production software. As a whole, the system gives a researcher another visualization tool to examine a DEM and its errors closely, which, in turn, may help to produce better DEMs in the future.

In the next iteration of the system, we wish to extend the error capabilities to other source data. It should be noted that in the tests above, the final surfaces are compared to the same contour data that was used in the approximations. Thus, these data sets are not independent, which yields a less than ideal error metric, as is evident in all of the activity near contours. Initial experiments using an independent data set, in this case a 30m resolution USGS DEM overlaid on the approximated DEMs described above, yielded unsatisfactory error visualizations. This is due to the low resolution of the USGS DEM as compared with the computed DEM. Thus, comparison points are far apart so that only tiny, hard-to-see dots rather than clusters of color displayed. However, better test DEMs are being produced rapidly, using data from newer remote sensing sources such as photogrammetry, SPOT imagery, or LIDAR. The use of such data should yield more accurate error evaluations.

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