A System for 3D Error Visualization and Assessment of Digital Elevation Models

Michael B. Gousie
Department of Math & Computer Science
Wheaton College
Norton, MA 02766 USA
Email: mgousie@wheatonma.edu

Sarah Milewski
Department of Math & Computer Science
Wheaton College
Norton, MA 02766 USA

***Abstract*—A digital elevation model (DEM) can be created using a variety of interpolation or approximation methods, any of which may yield errors in the final result. We present DEMEV (DEM Error Viewer), a visualization system that displays a DEM and possible errors in 3D, along with its associated contour or sparse data and/or a comparison DEM. The system incorporates several error visualizations. One method compares the test DEM to source data and highlights discrepancies (difference error) beyond a user-variable threshold. A novel, vertical cutting tool can slice the DEM to create a profile view that shows the surface of the test and comparison DEMs simultaneously, allowing the user to discern small errors between the two files in minute detail. The cutting tool is semi-transparent so that the profile is seen in the context of the 3D surface. Another novel error visualization uses height classes to display possible problems with slope in a DEM computed from contours. Other features of the system include visualizations for local curvature and slope, a display of computed statistics such as RMSE, total squared curvature, etc., in addition to typical GIS tools. The system is designed as an error-visualization tool; the above functions are displayed and readily available on the user interface. The system has been tested with USGS data files to show its efficacy.**

I. INTRODUCTION

The digital elevation model (DEM) is a mainstay in computer geo-processing. However, a particular DEM may be created via one of many methods, such as bilinear interpolation, thin-plate approximation, and so forth. The source elevations may be sparse (point sampled), in the form of contours, or converted from LIDAR, shuttle radar topography mission (SRTM), or other data. No matter how the DEM is computed, it will invariably contain systematic or other errors, either from the interpolation or from the conversion of the raw data to the DEM format.

DEM errors may be displayed by any number of visualization or geographical information systems (GIS). These visualizations range from simply rendering the DEM via a shaded-relief map, to overlaying colors/textures representing the magnitude of various quantified errors, to adding special glyphs to indicate additional information such as direction. No matter what the visualization, two problems can manifest themselves: it is often difficult for the viewer to perceive small scale problems within the context of an entire DEM and it may be quite time consuming to find the desired functions in a large system. We describe a visualization system built solely for the purpose of viewing DEMs and assessing errors. Among the novel features is a "profile cutter" that allows the viewer to see small scale details in 2D within the context of a 3D DEM visualization.

II. RELATED WORK

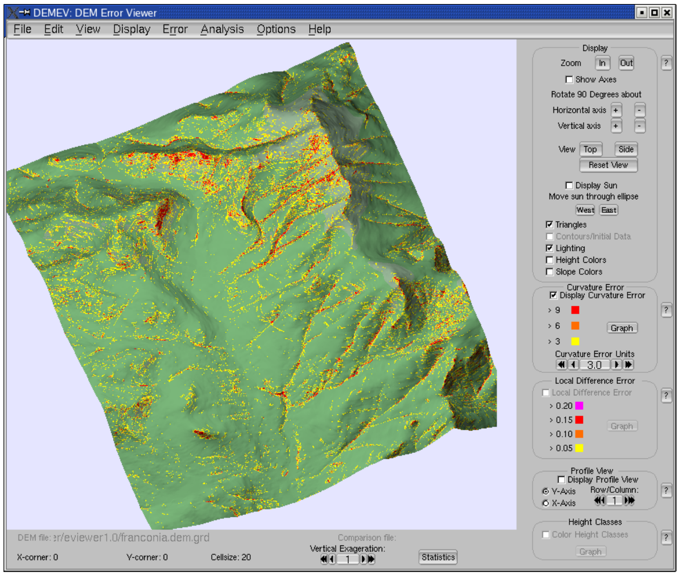
It is well known that DEMs computed or converted from various data sources contain errors. Our focus then is to ascertain the extent of those errors. The problem can be broken into two parts: quantifying the error and producing a visualization for assessed errors. Various approaches to ascertaining the extent of DEM error have been proposed; a good review can be found in [1]. A standard uncertainty measure is the root mean square error (RMSE), which compares a DEM height point with a corresponding elevation from an accurate source [2]. However, RMSE gives only a global measure of the validity of a DEM. Carrara et al. [3] use several analysis techniques, including determining if DEM heights fall between contour elevations. Elevation histograms can be used to show if there is a linear fit between contours [3], [4]. One can also compute the smoothness of a DEM by computing the total squared curvature [5] or, similarly, finding local curvature. Fisher [6] computed several statistics after comparing a DEM with established spot heights and computes a probable viewshed. Errors, based on grid bias, can be found by comparing drainage networks extracted by multiple rotations of the DEM [7]. Rigorous statistical models have been proposed as well [8].

Many of the above methods require the user to interpret the resulting error data. A visualization of the error gives the viewer immediate feedback to potential problems. Wood and Fisher [9] were early proponents of such visualizations; they compared several interpolated DEMs by displaying visualizations of aspect, Laplacian filtering that highlights sudden changes in elevation, RMSE, and shaded relief. Much work has been done in uncertainty visualization, such as using glyphs, translating/rotating surface patches to highlight potential error, altering lighting parameters, and so forth [10], [11]. MacEachren et al. give a comprehensive overview of the state of visualizing uncertainty in geospatial domains [12].

There are many GIS that have good 3D visualization capability and at least some uncertainty visualization features, of which the following is a sampling. Textures are shown to be useful for terrain visualization [13]. Terrafly [14] displays satellite imagery and other data in various resolutions. GeoZui3D [15] is a 3D marine GIS that supports multiple linked views; that is, the user can view the overall area and a smaller portion at much greater resolution. A GIS that integrates 2D and 3D views of the same data is described in [16]. A system that incorporates some error capabilities is LandSerf [17], including shaded relief, curvature visualization, peak classification, and others. LandSerf is also very useful in generating contours and reading/writing many file formats. Another tool dedicated to displaying topography and some errors using orthoimages is described in [18]. A thorough statistical comparison between a DEM computed from contours and LIDAR shows that DEM error is indeed present and comes from several sources [19]. This work highlights the usefulness of visualizations in detecting and evaluating errors. VisTRE [20] is a system designed expressly for visualizing terrain errors. The work is guided by psychophysical studies to maximize the effectiveness of the visualizations while limiting perceptual biases.

III. DEMEV: DEM ERROR VIEWER

DEMEV is a system for DEM error visualization, written in C++ with the OpenGL Application Programming Interface (API) for the graphics rendering and FLTK (Fast Light Toolkit) [21] for the graphical user interface (GUI). Figure 1 shows the system displaying one of the study areas, a 1200 × 1000 10-meter DEM taken from the 7.5' USGS National Elevation Dataset (NED) covering Franconia, NH. Elevations are in feet. Contours, using a 20 foot interval, were computed using LandSerf. The program reads data files in standard ArcInfo ASCII grid format.



DEM file: ɜr/eviewer1.0/franconia.dem.grd
Comparison file:
X-corner: 0
Y-corner: 0
Cellsize: 20
Vertical Exageration: 1
Curvature Error Units: 3.0
Row/Column: 1

Fig. 1. DEMEV showing DEM of Franconia, NH; curvature error visualization is turned on.

A distinguishing feature of this visualization system is that the GUI is designed specifically for visualizing uncertainty in DEMs. All options are displayed on the front panel at all times; they are available through menus as well. The system includes the usual functionality of DEM visualization systems, such as rotation, zooming, and the like. Common positions, such as top/side view or 90 degree rotation, can be achieved through one button click instead of much mouse manipulation. The Triangles check box indicates whether the surface is displayed via triangles (accurate but slow) or points (not as smooth but faster). Contours or sparse data can be overlaid on the DEM. The latter can often be difficult to see on large DEMs; in DEMEV, sparse data is displayed using cubes that are easily seen, no matter what the slope at that point. Figure 1 shows the DEMEV GUI displaying the Franconia DEM.

A. *Curvature and Local Difference Error Visualization*

The overall smoothness of a DEM can be computed by finding the total squared curvature, C_{sq} [5]:

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

The total squared curvature may be biased if there are large problem areas in a DEM. To mitigate this, an indication of local smoothness can be found by averaging the local, or absolute, curvature which is found at a point i, j:

$$C_{abs} = |(u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} - 4u_{i,j})| \quad (2)$$

Curvature error can be displayed via different hues, where the green surface indicates no error and progressing through yellow, orange, and red for the highest error (see Figure 1). This is in accordance with other visualization systems [20] and color perception studies [22]. The user may choose to have these errors categorized into discrete levels or displayed via a change in hue/saturation proportional to the error.

To visualize error between source data and DEM, each source height point is compared to the corresponding elevation in the DEM to find the local difference error d at point i, j:

$$d_{i,j} = |u_{i,j} - v_{i,j}| \quad (3)$$

where v is the elevation in the comparison DEM.

Following [3], 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; however, the user may choose any value for c. As with curvature, different hues indicate the severity of the error.

B. *Height Class Frequency Visualization*

If contours comprise the source data, then the DEM values within an area bounded by a contour pair should vary almost linearly, indicating an absence of artifacts such as terracing. DEM elevations are grouped into integer intervals between two contours and then reclassified into relative elevations [3]. For example, if 1200-1220 represents a contour pair, then the relative elevations, or height classes, would be 0, 1, 2, ..., 19 corresponding to the elevations of 1200, 1201, 1202, ..., 1219. The height classes are computed and the surface is displayed in green with the absolute frequency of the relative heights shown in graduated color from green to orange. The brighter the orange, the higher the absolute frequency of that height class, indicating that the slope is not linear between successive contours. The actual absolute frequencies are displayed as well for graphing purposes. It must be noted that the absolute frequency is a global measure that is applied to individual points, and thus the visualization is only a guide as to where errors may be. In other words, all points with the same color indicate they are all in the same height class. Ideally, there should be no orange in the surface at all.

The histogram in Figure 2 shows the frequency of the height classes for Franconia. Notice that height class 18 is higher than the others, indicating a possible problem with slope near the lower side of a contour. Figure 3 shows a portion of the north-west quadrant of Franconia using our novel height class visualization, in which some orange is speckled about but where there is one obvious area of high concentration. This orange color draws one into this area for further inspection. In this case, this area represents Echo Lake and has a uniform elevation of 1938 feet, which corresponds to height class 18 in the histogram, and which therefore explains its higher frequency.

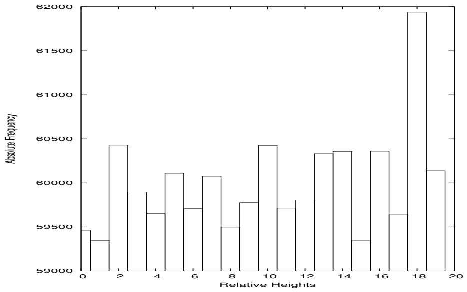


Fig. 2. Height class frequencies of Franconia DEM with 20 foot contour interval.

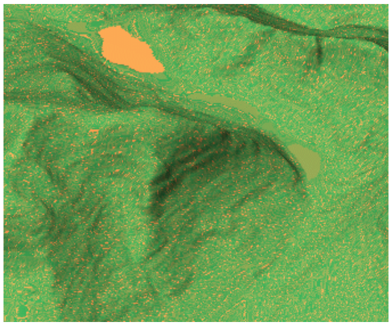


Fig. 3. Visualization of height class frequency.

C. The Profile Cutter

While many systems offer visualizations that enable the viewer to see errors in general, it is often difficult to zoom in on a small area to ascertain minute differences between a DEM and comparison data. The profile cutter is a planar rectangle orthogonal to the surface that enables the viewer to make a vertical "slice" through the DEM to better see the profile at any x or y position. The general idea is similar to the functionality included in LandSerf [17] in which a profile with any two endpoints can be displayed; however, the surface context of the profile is lost. In DEMEV, alpha blending makes the cutter semi-transparent, thus showing the profile within the context of the remaining DEM in the background. Profiles from multiple surfaces can be displayed simultaneously, thereby allowing direct comparisons. Figure 4 shows the profile cutter slicing through the Franconia, the primary DEM along with a comparison surface. The profile is shown in white for the primary DEM or where the two DEMs match perfectly. A second profile or profile portion is shown in blue or red if the primary DEM is above or below the comparison DEM, respectively.

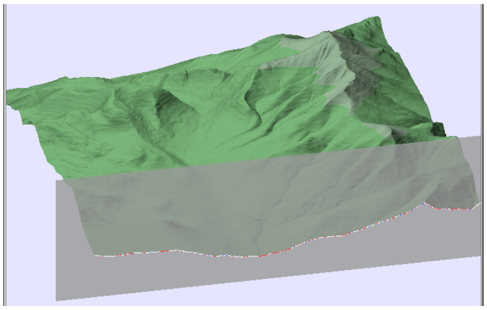


Fig. 4. The profile cutter slicing through the Franconia DEM.

Many DEMs are interpolated or otherwise computed from sparse data. The profile cutter can also be used to compare a DEM to such data. Figure 5 shows the profile cutter on a 800 × 800 DEM of Mt. Washington, NH and the 20 foot contours from which it was interpolated. As before, the profile is shown in white; the vertical lines show where the contours intersect the surface. A blue line indicates that the surface dips below the contour at that point, while a red line indicates the DEM has a higher elevation than the contour data. If contours are very close together, the profile visualization reverts to the method described above.

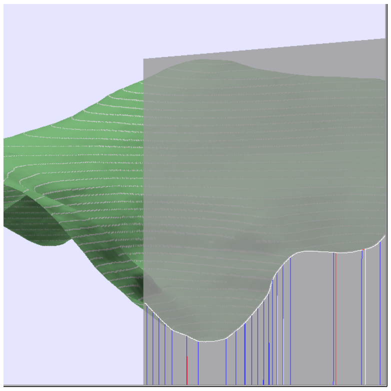


Fig. 5. Profile of Mt. Washington with comparison to contour data.

Figure 6 shows another example of the profile cutter. In this case, the data is another 800×800 DEM of Mt. Washington, this time computed from contours using the TOPOGRID method [23], [24], available in ArcInfo. The red displayed on the surface in the background (behind the cutter) indicates severe curvature anomalies. Comparing the TOPOGRID DEM to the one shown previously (Figure 5) and applying the profile cutter, the problems are immediately apparent. The TOPOGRID profile is shown in white and appears to have an unnatural undulation, while the comparison DEM's profile is smooth, with a portion above the white shown in red and a portion below shown in blue.

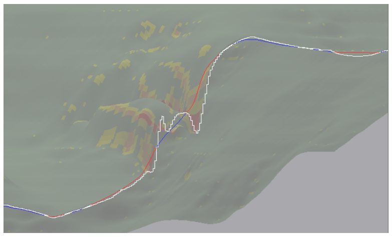


Fig. 6. Profile cutter displaying clear discrepancies between two DEMs of Mt. Washington.

IV. CONCLUSIONS AND FUTURE WORK

DEMEV is a DEM and error visualization system that incorporates curvature, local distance error, and height class frequency error visualization capabilities. The system includes a "profile cutter" that can be used to view a profile in two dimensions, enabling the viewer to see possible problems in the DEM slice that may otherwise not be possible in a 3D environment. In particular, the profile slice allows the layering of two data sets, the primary DEM and a comparison file, in the same context space, giving the viewer new visualization options for comparing the files. The system, which is purpose-built for DEM error visualizations, has tools for visualizing difference error, curvature, and height class frequencies, as well as traditional options such as shading, slope coloring, and so forth. The system also computes and displays statistics, such as RMSE and total squared curvature.

In the future, we wish to extend the capabilities of the profile cutter; in particular, it should work for arbitrary profile directions, the color saturation for errors should be improved, and the profile comparison with sparse data should be enhanced. Finally, a usability study should be conducted.

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REFERENCES

[1] S. Wise, "Assessing the quality for hydrological applications of digital elevation models derived from contours," *Hydrological Processes*, vol. 14, no. 11-12, pp. 1909–1929, 2000.

[2] R. E. Rinehart and E. J. Coleman, "Digital elevation models produced from digital line graphs," in *Proceedings of the ACSM-ASPRS Annual Convention*, vol. 2. American Congress on Surveying and Mapping, American Society for Photogrammetry and Remote Sensing, 1988, pp. 291–299.

[3] A. Carrara, G. Bitelli, and R. Carla', "Comparison of techniques for generating digital terrain models from contour lines," *International Journal of Geographical Information Science*, vol. 11, no. 5, pp. 451–473, 1997.

[4] P. Reichenbach, R. J. Pike, W. Acevedo, and R. K. Mark, "A new landform map of italy in computer-shaded relief," *Bollettino Geodesia a Scienze Affini*, vol. 52, pp. 22–44, 1993.

[5] I. Briggs, "Machine contouring using minimum curvature," *Geophysics*, vol. 39, no. 1, pp. 39–48, February 1974.

[6] P. Fisher, "Improved modeling of elevation error with geostatistics," *GeoInformatica*, vol. 2, no. 3, pp. 215–233, 1998.

[7] J. Charleux-Demargne and C. Puech, "Quality assessment for drainage networks and watershed boundaries extraction from a digital elevation model (dem)," in *8th ACM Symposium on GIS*, Washington, D.C., 2000, pp. 89–94.

[8] B. H. Carlisle, "Modelling the spatial distribution of DEM error," *Transactions in GIS*, vol. 9, no. 4, pp. 521–540, 2005.

[9] J. D. Wood and P. F. Fisher, "Assessing interpolation accuracy in elevation models," *IEEE Computer Graphics and Applications*, vol. 13, no. 2, pp. 48–56, March 1993.

[10] A. T. Pang, C. M. Wittenbrink, and S. K. Lodha, "Approaches to uncertainty visualization," *The Visual Computer*, vol. 13, no. 8, pp. 370–390, 1996.

[11] C. R. Johnson and A. R. Sanderson, "A next step: Visualizing errors and uncertainty," *IEEE Computer Graphics & Applications*, vol. 23, no. 5, pp. 6–10, 2003.

[12] A. M. MacEachren, A. Robinson, S. Hopper, S. Gardner, R. Murray, M. Gahegan, and E. Hetzler, "Visualizing geospatial information uncertainty: What we know and what we need to know," *Cartography and Geographic Information Science*, vol. 32, no. 3, pp. 139–160, 2005.

[13] J. Döllner, K. Baumann, and K. Hinrichs, "Texturing techniques for terrain visualization," in *Proceedings of the 11th IEEE Visualization 2000 Conference (VIS '00)*. Salt Lake City, UT: IEEE, 2000, pp. 227–234.

[14] N. Rishe, Y. Sun, M. Chekmasov, S. Andriy, and S. Graham, "System architecture for 3d terrafly online gis," in *Proceedings of the IEEE Sixth International Symposium on Multimedia Software Engineering (MSE2004)*, 2004, pp. 273–276. [Online]. Available: terrafly.com

[15] C. Ware, M. Plumlee, R. Arsenault, L. A. Mayer, and S. Smith, "Geozui3d: Data fusion for interpreting oceanographic data," in *Proceedings of the MTS/IEEE Conference and Exhibition(OCEANS 2001)*, vol. 3, 2001, pp. 1960–1964.

[16] S. Brooks and J. L. Whalley, "A 2d/3d hybrid geographical information system," in *Proceedings of ACM GRAPHITE*, Dunedin, New Zealand, 2005, pp. 323–330.

[17] J. Raper, J. Dykes, J. Wood, D. Mountain, A. Krause, and D. Rhind, "A framework for evaluating geographical information," *Journal of Information Science*, vol. 28, no. 1, pp. 51–62, 2002.

[18] M. Wiggenhagen, "Development of real-time visualization tools for the quality control of digital terrain models and orthoimages," in *International Archives of Photogrammetry and Remote Sensing (IAPRS)*, vol. 33, Amsterdam, 2000, pp. 987–993.

[19] J. Oksanen and T. Sarjakoski, "Uncovering the statistical and spatial characteristics of fine toposcale DEM error," *International Journal of Geographical Information Science*, vol. 20, no. 4, pp. 345–369, 2006.

[20] C. G. Healey and J. Snoeyink, "Vistre: A visualization tool to evaluate erros in terrain representation," in *Proceedings, 3rd International Symposium on 3D Data Processing, Visualization and Transmission (3DPVT 2006)*, Chapel Hill, North Carolina, 2006.

[21] Easy Software Products, "FLTK: Fast light toolkit," http://www.fltk.org/index.php; last accessed 13 March 2007. [Online]. Available: http://www.fltk.org/index.php

[22] CIE, *CIE Publication No. 15, Supplement Number 2 (E-1.3.1, 1971): Official Recommendations on Uniform Color Spaces, Color-Difference Equations, and Metric Color Terms*. Commission Internationale de L'Èclairge, 1978.

[23] M. F. Hutchinson, "Calculation of hydrologically sound digital elevation models," in *Proceedings of the Third International Symposium on Spatial Data Handling*. Columbus, Ohio: International Geographical Union, 1988, pp. 117–133.

[24] M. F. Hutchinson and J. C. Gallant, "Representation of terrain," in *Geographical Information Systems: Principles and Technical Issues*, 2nd ed., Longley, Goodchild, Maguire, and Rhind, Eds. Wiley, 1999, vol. 1, pp. 105–124.