

Recent Progress in the ANUDEM Elevation Gridding Procedure

Michael F. Hutchinson, Tingbao Xu and John A. Stein

Fenner School of Environment and Society
Australian National University
Canberra, Australia
michael.hutchinson@anu.edu.au

Abstract—Topography plays a fundamental role in modulating land surface and atmospheric processes across a wide range of spatial scales (Hutchinson 2008). Thus digital elevation models (DEMs) have played a key role in supporting mesoscale representations of surface climate as well as in supporting finer scale representations of surface hydrology and catchment processes. The ANUDEM locally adaptive elevation gridding procedure (Hutchinson 1989, 2007) is commonly used to calculate these elevation models in regular grid form. Key features of the method include its computational efficiency, allowing it to be applied to very large data sets, and a range of locally adaptive features, including a drainage enforcement algorithm that attempts to maintain connected drainage structure in the interpolated DEM, and algorithms to incorporate data streamlines, lakes and cliffs. This paper describes current progress in the ANUDEM procedure to better represent lakes and to effectively process noisy, high resolution elevation data. Such data are becoming increasingly common. The underlying multi-grid interpolation procedure remains effective in effectively representing lakes and cliffs and in stably interpolating high resolution elevation data. Correlated errors in source elevation data can also be specifically accommodated. The multi-grid procedure also plays a crucial role in enabling the application of drainage enforcement and in initializing heights on data streamlines. This can prevent corruption of stream heights by noisy elevation values and improve the overall representation of drainage structure in the presence of dense noisy elevation source data.

I. INTRODUCTION

Digital elevation models play a central role in environmental modelling across a range of spatial scales [1]. The regular grid mode of representation has become the dominant form for digital

elevation models used in these applications. This form is directly compatible with remotely sensed geographic data sources and can simplify terrain-based analyses, including assessments of spatial scale. A distinguishing feature for many applications, particularly those that operate at finer scale, is a primary requirement for information about terrain shape and drainage structure, rather than elevation. DEMs with connected drainage structure can be used to calculate hydrologically relevant topographic indices such as specific catchment area [4] and to support a wide range of hydro-ecological analyses [5]. For this reason, elevation contours and streamlines have remained popular sources of primary topographic data, especially when supplemented by cliff and lake data to further refine the representation of landscape structure. The locally adaptive ANUDEM gridding procedure [2], as implemented in Version 5.2 [3], can make effective use of all of these source data types.

Remotely sensed digital topographic data, from both airborne and spaceborne sensors, are an emerging source of fine scale digital elevation data. A major impetus for this development has been the goal of generating high resolution DEMs with global coverage. This has been achieved with the completion of the 3 second (90 m) DEM for the globe obtained from the Shuttle Radar Topography Mission [6]. These data have two generic limitations. The sensor cannot measure ground elevations underneath dense vegetation cover or underwater or under man-made structures, leading to significant errors, particularly in vegetated areas. Secondly, all remotely sensed elevation data have significant random errors that depend on the inherent limitations of the observing instrument, as well as surface slope and roughness [7]. The product specification for the SRTM data is that 90% of the elevations have error within $\pm 16\text{m}$. These errors require appropriate filtering, without degrading shape and drainage structure, to maximize the utility of the data in environmental applications, particularly in areas with low relief or with significant surface cover.

Traditional elevation sources, such as elevation contours, can be characterized as being relatively sparse and having negligible elevation error. Remotely sensed elevation data, on the other hand, are relatively dense and do have significant elevation error. Applying the ANUDEM procedure to these data raises a number of issues, particularly with respect to reliable initialization of elevations on data streamlines in a way that is consistent across the borders of neighbouring map tiles in low relief areas. These issues have been addressed by developing and applying a modified version of ANUDEM to 1 second SRTM data for a low relief area in the Murray-Darling Basin, as described in [8]. Drainage structure was enforced in the filtered DEM by using corrected 1:250K streamline data, in association with automated drainage enforcement. These streamline data have been used with point elevation data to produce Version 3 of the 9 second DEM [9]. This DEM has standard elevation error no more than 10 m for around half of the continent. However, 1:250K streamline data are not sufficiently accurate for application at the fine scale of 1 second.

As with traditional data sources, the process of producing an accurate DEM requires careful attention to both the accuracy of the source data and the quality of the interpolated DEM. A prime requirement for hydrological applications is that the filtered DEM accurately represents shape and drainage structure. Shaded relief views and the number of remaining depressions in the filtered DEM are simple and effective shape-based measures of DEM quality that do not require the existence of separate reference elevation data. Remaining depressions can also be readily plotted to greatly assist in detecting and remedying data errors. The number of remaining depressions was the principal measure of DEM quality in the production of the national 9 second DEM. It has also been used as a key measure of progress here in the development of the modified locally adaptive gridding procedure.

II. KEY FEATURES OF ANUDEM

The ANUDEM program can process arbitrarily many different input data files, each of arbitrary size. The only size limit imposed by the program is the size of the fitted DEM which needs to be stored in the memory of the computer running ANUDEM. Each data file may be one of eight types:-

- Point elevation data
- Sink point data
- Streamline data
- Coastline data
- Contour line data
- Lake boundary data
- Cliff line data
- Mask boundary data

The program reads input data points from each input data file, trims the data to the user-specified map limits and then generalizes the data to the user-specified grid resolution. Point elevation data are generalized by using the average elevation of up to 100 data points per grid cell and discarding any remaining points.

Line data are generalized by accepting at most one line data point per grid cell and removing unnecessary kinks. Lake polygons, coastlines and cliff lines are essentially divisions between different data points, and are hence incorporated into the grid so that lines are placed *between neighbouring* grid points. On the other hand, streamlines and elevation contours are naturally incorporated into the grid so that the lines are placed *on contiguous* grid points. This strategy enables space-efficient incorporation of competing data types over the same area.

Underlying interpolation algorithm

The underlying interpolation algorithm is described in [1,2,11]. The program interpolates the accepted elevation data onto a regular grid by minimizing the sum of a user-specified roughness penalty and a weighted sum of squares of the residuals from the elevation data of the surface represented by the grid. A simple multi-grid method is then used to calculate grids at successively finer resolutions, starting from an initial coarse grid, until the final, user-specified grid resolution. For each grid resolution, the accepted data points are allocated to the grid and the grid values are calculated by Gauss-Seidel iteration with over-relaxation (SOR method) subject to the user-specified roughness penalty, while simultaneously respecting ordered chain constraints associated with the drainage enforcement algorithm and data streamlines, cliffs and lakes. The computational cost of the interpolation algorithm is optimal in the sense that it is proportional to the number of grid points [2].

Iteration terminates at each successive grid resolution when the user-specified maximum number of iterations (normally 20) has been reached. Starting values for the first coarse grid resolution are set to the average elevation of all elevation data points. Starting values for each successive finer grid are simply interpolated from the preceding coarser grid. On completion of all iterations, the program calculates the sink points remaining in the fitted grid and writes a summary to an output log file. The remaining sink points are written to an output file for plotting to aid in detection and correction of input data errors. Streamline and cliff line data, as incorporated onto the grid, and other diagnostics, are also written to output point and line diagnostic files to facilitate quality assessment of the gridding process.

Drainage enforcement algorithm

The drainage enforcement algorithm attempts to remove all sink points that have not been identified as input sink data. This imposed global drainage condition has been found in practice to be a powerful condition that can significantly increase the accuracy of a fitted digital elevation model, especially in terms of its drainage properties [2]. The global drainage condition minimizes the need for detailed manual editing of interpolated elevation grids to remove spurious drainage features. The essence of the drainage enforcement algorithm is to find for each sink point the lowest adjacent saddle point that leads to a lower data point, sink or edge. Provided a conflicting elevation data point has not been allocated to the saddle, the algorithm then enforces a descending chain condition from the sink via the intervening saddle to the lower data point, sink or edge. This action is modified by the systematic application of a user-supplied elevation tolerance to adjust the strength of drainage enforcement in relation to both the accuracy and density of the input elevation data.

Drainage enforcement is also obtained by incorporating streamline data. This is useful when more accurate placement of streams is required than what can be inferred automatically. The program checks for closed loops in data streamlines and provides appropriate diagnostics. Side conditions are also set for each streamline. These ensure that the streamline acts as a breakline for the interpolation conditions so that each streamline lies at the bottom of its associated valley. The program has also been extended to accept stream distributaries. These abound in many low relief areas of the Australian continent.

III. REFINEMENT OF THE REPRESENTATION OF LAKES

The representation of lakes by ANUDEM has been revised to respect the gridding strategy for polygon data described above. In former versions lake polygons were assigned to a continuous line of successive grid points. The areas within and outside the lake were then decided by their locations each side of the gridded lake polygon. This procedure led to stable automated estimation of the elevation of the lake boundary – essentially inferred from the surrounding elevation and streamline data. However, the lake inclusion status of the points on the gridded polygon line itself was then indeterminate, and the gridded representation of the boundary of the lake was somewhat approximate. This also gave rise to minor problems when representing closely separated lakes and islands within lakes.

The lake algorithm has been thoroughly revised to incorporate lake polygons as lines *between* neighbouring grid points. The lake inclusion status of every grid point is then unambiguously defined in relation to this line. The associated

process that estimates the height of the lake surface has undergone consequent extensive revision. This has given rise to a more robust lake incorporation procedure that makes more effective use of interconnecting streamlines, as well as efficient use of the available grid points. This is especially valuable when the procedure is applied to closely separated lakes and islands.

IV. APPLYING STREAMLINES TO DENSE NOISY ELEVATION DATA

Elevations on streamlines are currently initialized for each successive grid resolution by linearly interpolating along streamlines between descending elevation points located on the streamlines. Data points on streamlines that are higher than upstream data points are normally removed. This process becomes problematic when the elevation data have significant errors, giving rise to occasional upstream data points that are too low. These can remove accurate downstream elevation points and give rise to streamlines that are too low with respect to the neighbouring landscape.

The streamline initialization procedure is being revised to take initial streamline heights from the preceding coarser grid in the multi-grid interpolation process, rather than from the error prone actual data point heights that lie on the streamlines. The program then ensures that all initial heights on the streamlines linearly descend down each stream segment between successive stream junctions and disjunctions. The revised initialization appears to give rise to stable elevations on streamlines when applied to neighbouring tiles, as demonstrated in [8]. This is critical in building a continent-wide high resolution DEM with consistent overall drainage structure from a series of overlapping map tiles [10].

V. DISCUSSION AND CONCLUSION

Revisions to the initialization of streamlines in the ANUDEM multi-grid elevation interpolation procedure appear to have addressed former problems in interpolating DEMs from noisy SRTM data in low relief regions with extensive distributary streamline networks. Current work is aimed at developing an appropriate associated data smoothing process that can allow for the ill-defined error structure often associated with remotely sensed elevation data. These errors can be strongly spatially correlated at close range due to the overlapping footprint of the elevation sensor. The error structure can be further complicated by initial filtering to remove vegetation and other sampling artifacts.

Additional work on ANUDEM is aimed at strengthening the automated drainage enforcement algorithm in the presence of dense noisy elevation data to remove the large numbers of spurious depressions that tend to arise in low relief landscapes.

With dense high resolution data sets the number of spurious depressions can be as high as hundreds of thousands. ANUDEM's processing of sinks is fundamentally computationally efficient because it restricts the required searching process to just the critical points of the landscape, viz. sink and saddle points. However, in the presence of such large numbers of spurious depressions, the drainage enforcement process can dominate the required computational time. An alternative approach is being developed to reduce the number of spurious depressions while still allowing genuine depressions.

The representation of stream distributaries has been an important factor in producing accurate representations of the Australian landscape, particularly in arid low relief areas with extensive braided streamline networks, and also for particular major stream disjunctions in the Murray Darling Basin. The ANUDEM program outputs an associated multi-directional flow direction grid. This grid can accurately represent multi-directional streamline structure but it goes beyond the standard functionality of current GIS. There is a clear need to develop an enhanced data format standard to incorporate multi-direction flow grids and to develop methods to support their hydrological analysis. Such analyses need to be able to support dynamic aspects such as flow paths differing between times of low and high flow. Multi-flow networks arise in many parts of the World. Their hydrological analysis has depended on somewhat *ad hoc* methods to date.

A final practical consideration when applying drainage enforcement to high resolution elevation data is the possible lack of appropriate streamline data. Australia has comprehensive continent-wide streamline data coverage at 1:250K scale. These data were entirely appropriate for use in developing the 9 second (250m) national DEM [9], but they are not sufficiently accurate to be generally applied to 1 second (30m) resolution SRTM data. Finer scale 1:25K streamline data are not generally available for the whole continent. Current work [10] is aimed at enhancing the available course resolution streamline data by inferring drainage lines in high relief areas directly from high resolution SRTM data after initial drainage enforcement has been applied by ANUDEM. Such inferred streamline data can be used as an interim supplement to support current fine scale elevation gridding efforts. There is however a compelling case for compiling a new high resolution, topologically consistent, national streamline network in the light of new high resolution noisy elevation data sets that require appropriately coordinated data smoothing and drainage enforcement to realize their full potential.

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