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Measuring Distance “As the Horse Runs”: Cross-Scale Comparison of Terrain-Based Metrics

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1. Introduction

Distance metrics play significant roles in spatial modeling tasks, such as flood inundation (Tucker and Hancock 2010), stream extraction (Stanislawski *et al.* 2015), power line routing (Kiessling *et al.* 2003) and analysis of surface pollutants such as nitrogen (Harms *et al.* 2009). Avalanche risk is based on slope, aspect, and curvature, all directly computed from distance metrics (Gutiérrez 2012). Distance metrics anchor variogram analysis, kernel estimation, and spatial interpolation (Cressie 1993). Several approaches are employed to measure distance. Planar metrics measure straight line distance between two points (“as the crow flies”) and are simple and intuitive, but suffer from uncertainties. Planar metrics assume that Digital Elevation Model (DEM) pixels are rigid and flat, as tiny facets of ceramic tile approximating a continuous terrain surface. In truth, terrain can bend, twist and undulate within each pixel.

Work with Light Detection and Ranging (lidar) data or High Resolution Topography to achieve precise measurements present challenges, as filtering can eliminate or distort significant features (Passalacqua *et al.* 2015). The current availability of lidar data is far from comprehensive in developed nations, and non-existent in many rural and undeveloped regions. Notwithstanding computational advances, distance estimation on DEMs has never been systematically assessed, due to assumptions that improvements are so small that surface adjustment is unwarranted. For individual pixels inaccuracies may be small, but additive effects can propagate dramatically, especially in regional models (e.g., disaster evacuation) or global models (e.g., sea level rise) where pixels span dozens to hundreds of kilometers (User *et al.* 2003). Such models are increasingly common, lending compelling reasons to understand shortcomings in the use of planar distance metrics. Researchers have studied curvature-based terrain modeling. Jenny *et al.* (2011) use curvature to generate hierarchical terrain models. Schneider (2001) creates a ‘plausibility’ metric for DEM-extracted structure lines. d’Oleire-Oltmanns *et al.* (2014) adopt object-based image processing as an alternative to working with DEMs; acknowledging the pre-processing involved in converting terrain into an object model is computationally intensive, and likely infeasible for some applications.

This paper compares planar distance with *surface adjusted distance*, evolving from distance “as the crow flies” to distance “as the horse runs”. Several methods are compared for DEMs spanning a range of resolutions for the study area and validated against a 3 meter (m) lidar data benchmark. Error magnitudes vary with pixel size and with the method of surface adjustment. The rate of error increase may also vary with landscape type (terrain roughness, precipitation regimes and land settlement patterns). Cross-scale analysis for a single study area is reported here. Additional areas will be presented at the conference.

2. Data and Study Area

The study area is 7,885.94 square kilometers (sq km), located in western North Carolina, (35.798 degrees N and 81.473 degrees W) spanning the Pisgah National Forest. Its location at

the southern edge of the Appalachian mountain range is a humid, hilly landscape, averaging 51 inches (129.5 cm) annual precipitation, with elevations ranging from 209 to 1602 meters (m). Distances are measured on 10, 30, 100, 1000, and 5000m resolution DEMs and compared with the 3m lidar benchmark data. The first three were downloaded from Geospatial Data Gateway (<https://gdg.sc.egov.usda.gov/>). The source for 100m and 1000m DEMs was Shuttle Radar Topography Mission (SRTM) (http://dds.cr.usgs.gov/srtm/version2_1/). The 5000m DEM was resampled from 100m data, and provided courtesy of USGS. DEMs are in NAD1983 UTM Zone 17N.

3. Methods

Five straight-line transects were registered on each DEM ranging in length from 39.58 km to 107.26 km as measured on the 3m lidar data (Figure 1). Each transect was sampled at 3m intervals to create a set of test points for comparing the various distance metrics (Figure 2a).

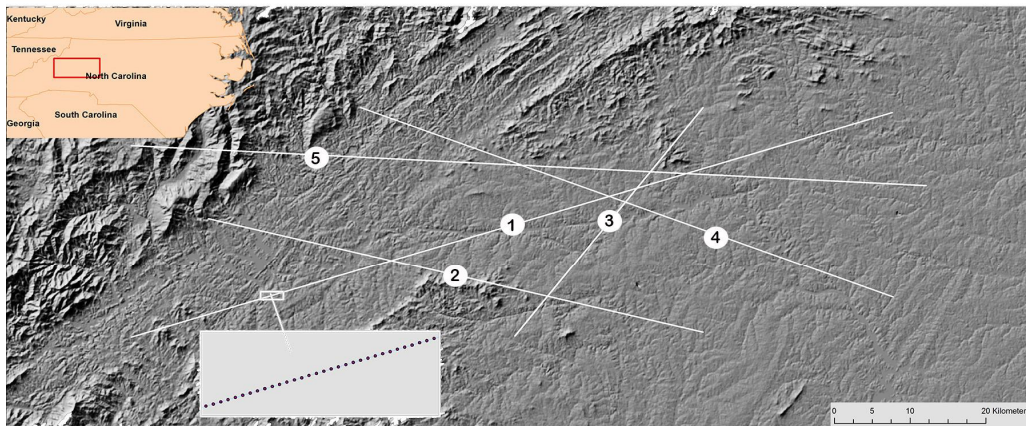


Figure 1. 3m LiDAR DEM with five transect lines overlaid. Transect lengths (in kilometers) used for validation are as follows: #1: 103.31; #2: 68.00; #3: 39.58; #4: 75.50; and #5: 107.37. Gray rectangle enlarges a section of one transect to show point samples taken at 3m spacing.

The tested methods all incorporate elevation, but differ in contextual information about surrounding pixels to gain a progression of surface adjustment. For example, Pixel-to-Pixel distance traverses sampled points in sequence along each transect. A 3D Euclidean calculation sums distances between sampled points but ignores adjacent pixels (Figure 2b). Four additional tested methods utilize elevation and spatial context. These are:

- *Closest Centroid* distance assigns the elevation at the pixel centroid to any point along the selected path that falls within that pixel (Figure 2c) and will be used to measure lengths on the lidar benchmark to validate transect distances at coarser resolutions.
- *TIN* distance is an ArcGIS® command partitions the DEM and interpolates elevations for points within each triangular facet from the three local vertices.
- *Natural Neighbor* distance (ArcGIS® command) partitions Thiessen polygons. Sampled transect points seed a second layer of Thiessen polygons. The proportion of overlap between the two layers weights interpolation of the elevations of all Thiessen neighbors.
- *Weighted Average* distance uses the average elevation of the pixel containing the point and the eight surrounding pixels, weighted by the distance to corresponding pixel centroids (Figure 2d).

Three additional methods fit local polynomials with varying degrees to progressively incorporate elevation, slope and curvature (full surface adjustment) into the distance metric. Bilinear distance fits a first order polynomial to four adjacent pixels. Biquadratic fits a second order equation to eight pixels. Bicubic distance fits a third order polynomial to sixteen surrounding pixels. Figures 2e-2g show example configurations.

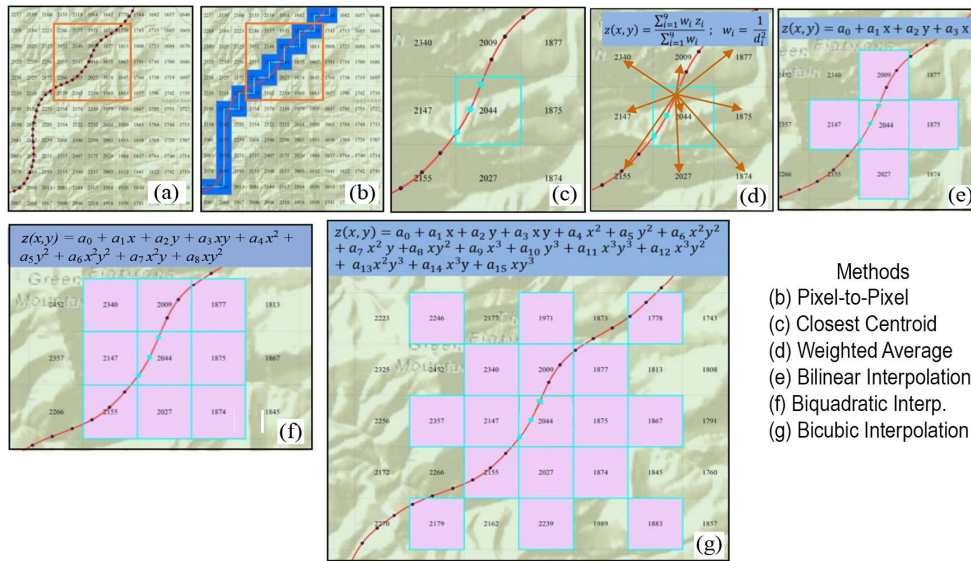


Figure 2. (a) 3m samples along transect; (b)-(g) distance computation methods. Orange vectors (d) show distance to adjacent centroids for sampled point lying at their intersection. Orange boxes (a)-(b) show areas enlarged in other panels. Elevations for magenta pixels (e)-(g) included in polynomial computations.

3. Results

All methods deviate from the benchmark, with Pixel-to-Pixel and Closest Centroid showing highest magnitude errors and consistent over-estimation for all transects at 10, 30 and 100m resolutions. Surprisingly, Arc[®] TIN and Arc[®] Natural Neighbor show nearly identical residuals for most transects across all resolutions, for reasons that are not clear. Due to space limitations, detailed distances are not reported here. Figure 3 plots absolute residuals by transect for four methods whose results are closer to the benchmark. Residuals show a general trend of increase at coarser resolutions, as additional sample points fall within a single DEM pixel. This is most pronounced for the two longest transects (#1 and #5). Residuals progress at different rates for each transect because of the varied character of terrain that each one spans. The 5th transect shows the most extreme error pattern because it crosses both rough and smooth terrain. These imply that transect length and terrain type are important factors needing further testing.

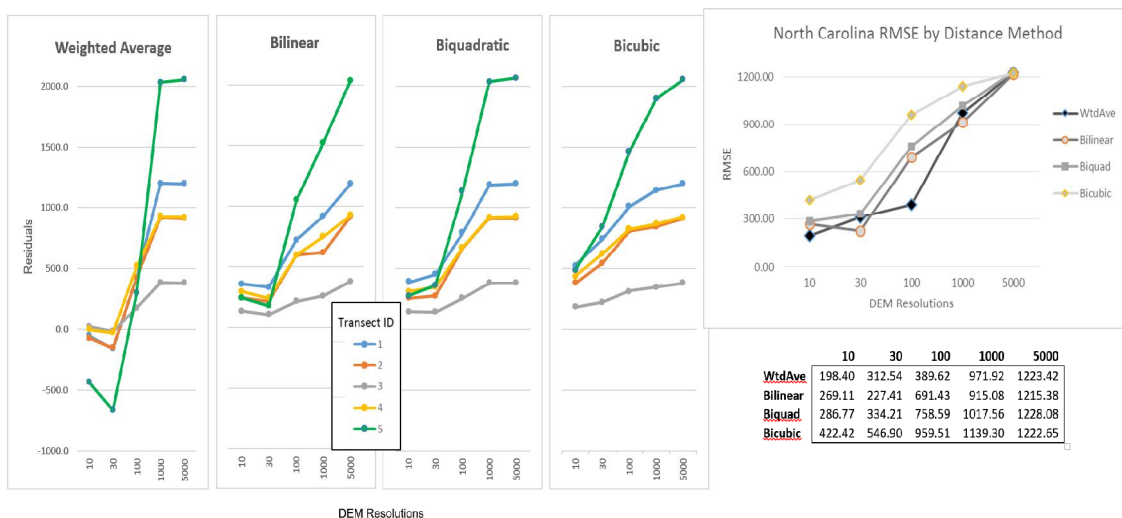


Figure 3. Residuals Analysis. Residual (lidar minus test DEM distance) and RMSE plots in meters.

Figure 3 also shows RMSE values for the four selected distance methods, with lowest RMSEs for either Weighted Average or Bilinear polynomial at each DEM resolution. However, the Weighted Average seems to be the least precise method of the four, furnishing a larger range of residual values, as well as mixing over- with under-estimation.

4. Discussion

Chronic mis-estimation resulting from planar distance metrics impacts models that rely on terrain for science, planning and decision support. One goal of this work is to determine if surface adjustment can obviate the need to work at lidar resolutions, given the scarcity of lidar data in rural areas and developing regions. This research demonstrates that surface adjustment generates terrain-based distance measurements that approach results for finer resolution data, with some caveats. Results depend on DEM resolution and method of surface adjustment. The choice of point sample spacing is likely scale dependent. At coarser resolutions a multitude of point samples fall within a single DEM pixel: for some distance methods (e.g., Closest Centroid) redundant samples can distort transect distances. Thinning point samples proportionate to test resolutions is an option under investigation. Resampling the 500m DEM also distorted measurements, and should be avoided for tasks requiring precise distance. Results also depend on terrain homogeneity. Transect #5 that crosses rough to smooth terrain exhibits a unique error pattern relative to those crossing more uniform terrain, and this warrants examination of heterogeneous landscapes as well as considering a larger sample of transects, which would permit statistical validation. Polynomials prove reliable, but the improvement from bicubic equations seems barely worth the added complexity when the bilinear performs similarly, and the weighted average equally well at coarse resolutions. Ongoing research explores whether findings hold true in other landscapes.

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