What Should a Bare Earth Digital Terrain Model (DTM) Portray?

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Abstract—**National mapping agencies in North American and western Europe have released free lidar point clouds with densities of 2-23 points/m², and derived terrain grids. Geomorphometric processing uses a bare earth digital terrain model (DTM), which can be acquired from mapping agencies or created from the point cloud to better control its characteristics. Free software provides tools for noise removal, ground classification, surface generation, void filling, surface smoothing, and hydraulic conditioning. Tests with three ground classification algorithms, and four surface generation algorithms show that they produced very similar results. The main issues for geomorphometric operations on DTMs involve whether the highest and lowest ground points should be in the DTM if they are not on a grid node, how water, buildings, and roads should be treated, if using a DTM of lower resolution will effectively filter out noise and allow much faster processing, and if lower resolution DTMs should be created directly from the point cloud or by processing a higher resolution DTM.**

I. Introduction

Lidar elevation data, both as point clouds and derived grids, has become a standard mapping product for a growing number of national mapping agencies (Table I) with rapidly increasing coverage. Widespread use of this data will revolutionize geomorphometric studies which have relied on DSMs like SRTM and ASTER with 30 m spacing where buildings and vegetation have been hard to remove. Lidar will allow easy generation of a bare earth DTM, but will require rethinking the desired characteristics of a DTM, and the scale at which we want to perform the analysis. Classifying landforms has been done at the scale of SRTM or ever coarser resolution DEMs [1,2]. We could now perform that work on lidar topography for some smaller countries, or states in the United States, and it is worth thinking about how the DTM should be prepared for those efforts.

II. DEMs and DTMs

A. Types of DEM

Terminology regarding DEMs can be confusing, and a full discussion is beyond what this short paper can cover. I use digital elevation model (DEM) as a traditional and generic term [3] (like the ubiquitous SRTM DEM) [3], which can embrace multiple specific models. The digital surface model (DSM) is the highest return for every cell in the grid, and provides the best representation of the terrain for visualization. The non-vegetated surface (NVS) has the lowest return in each cell, removing vegetation but not buildings, and provides the best estimates for mobility since buildings will hinder mobility much more than most vegetation. This is easier to produce than the DTM. The digital terrain model (DTM) shows the bare earth, with buildings and vegetation removed. It represents an un-natural surface showing what the ground might look like after bulldozing the buildings, and might also remove bridges and culverts. The canopy height model (CHM) depicts the height of the vegetation from the ground to top of the canopy, but must be generated with map algebra as the difference between the DSM and DTM.

All national mapping agencies produce DTMs (Table 1), and some also create DSMs. These definitions follow those from the UK, but not the US, and users should always clearly specify the use of the terms DEM, DSM, and DTM. This suggests a realization by at least some agencies that one type of DEM cannot meet all needs including visualization, hydrologic mapping, geormophometric computations, and others. The underlying point cloud, available for all the countries in Table 1 can generate DEMs to meet particular needs.

B. Steps in DTM Creation

Chen and others [4] presented an exhaustive review of DTM generation, and concluded that no single method works in all terrain types. Their work, and the process used by OpenTopography [5], suggests that DTM generation involves up to 6 steps using a lidar point cloud. Free tools can be combined to perform these operations in sequence [6, 7, 8, 9, 10].

Noise removal flags or removes isolated points below the ground surface, or above features of interest. National mapping agencies generally perform this on their point clouds. **Ground classification** uses local relationships of points to infer what the points represent. Mapping agencies provide ground classification, generally with an unspecified or proprietary algorithm from the contractor who actually produced the data. A number of free programs will classify ground points, but none will distinguish water, trees, and buildings. **Surface generation**

can use a triangulated irregular network (TIN), inverse distance weighting (IDW), drop in the bucket, or nearest neighbor algorithm. **Void filling** replaces water, buildings, or coverage gaps if these remain after surface generation. **Surface smoothing** using digital filters can remove noise from clutter or excessive detail. **Hydrologic conditioning** can fills pits and adjusts elevations so that every pixel has a distinct flow path prior to use for surface water flow if the DTMs prioritizes hydrologic flow paths over depiction of the terrain.

TABLE I. NATIONAL MAPPING AGENCY LIDAR DATA AVAILABILITY

Country	Typical Cloud Density (pts/m^2)	Grids Available	Grid spacing (m)	Data Projection	Classification Categories	RGB Imagery
Norway	23.4	DSM,DTM	1	UTM	Ground, vegetation, buildings	No
Netherlands	19.7	DSM,DTM	0.5	Amersfoort	Ground, buildings	No
Denmark	9.5	DSM,DTM	0.4	UTM	Ground, vegetation, buildings	No
UK	5	DSM,DTM	1	UK OS	Ground, vegetation	No
Slovenia	4.5	DTM	1	Slovenia 96	Ground, vegetation, buildings	No
Finland	2.6	DTM	2	UTM	Ground, vegetation	No
United States	2.2	DTM	1	UTM	Ground	No
Spain	0.6	DTM	5	UTM	Ground, vegetation, buildings	Yes

C. Flaws in current DTMs

Current DTMs remove most but not all buildings, but show a clear trace of building outlines. Even in rural areas, roads leave prominent scars. DTMs created with TIN interpolation can have prominent triangular facets, especially over water. While these might just be visual imperfections (Fig.1), they will affect geomorphometric computations using the DTM.

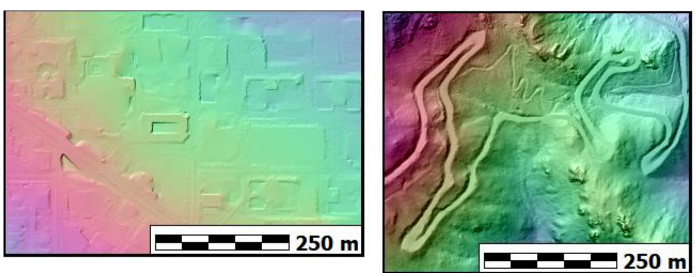

Figure 1. Flaws in USGS 1 m lidar derived DTM covering Boulder, Colorado.

III. EFFECTS ON DTM GENERATION

Two independent leaf-off lidar point collections (Table II) cover a small area in eastern Pennsylvania near Chadds Ford. The USGS DTM, created with one of the point clouds, will be used as control; its processing produces complete coverage at the cost of potentially inaccurate assumptions. The default DTM algorithm used for comparison performs a drop in the bucket gridding with the lowest return among the ground-classified points in each cell of the grid, and then performs an inverse distance weighting interpolation out to 2 grid cells to fill small holes.

TABLE II. LIDAR POINT CLOUDS ANALYZED

Provider	Date	Total Point density (pts/m^2)	Ground point density (pts/m^2)	Project
Open Topography (NCALM, TerraScan)	April 2010	16.8	5.2	Christina River Basin Critial Zone
USGS (Woolpert contract)	Dec 2014-Jan 2015	5.2	1.2	MD/PA Sandy Supplemental Lidar

A. Effect of Original Point Cloud

Figure 2 shows a small portion of the USGS 1 m DTM, and DTMs created from the two point clouds. The voids in the DTM occur in the water bodies, and the buildings, where the USGS DTM shows the results of additional processing.

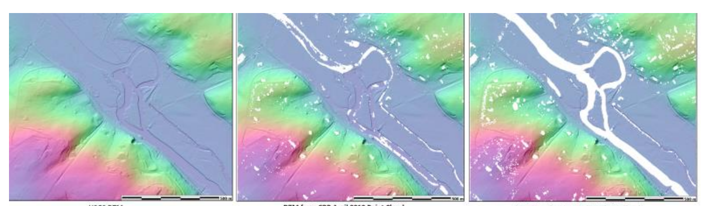

Figure 2. DTMs from different point clouds. Voids in white.

Statistics computed for the SW quadrant of the map, to avoid the flat valley floor which is missing significant data for the two DTMs created from the point clouds, have very similar characteristics except for except for slope skewness and kurtosis.

The USGS DTM has gentler slopes resulting from the flat building pads.

B. Effect of Ground Classification algorithms

Five different point classification algorithms were applied to the CRB point cloud: Fusion, MCC-lidar, two from WhiteBox, and the TerraScan classification in the point cloud. Figure 4 shows two of the grids compared to the USGS DTM. Except for the voids left by the buildings, the maps appear very similar. Statistics from the grids are very similar except the DTM created from the Fusion point classification which includes a number of extreme points not classified as ground by the other algorithms. Fig. 4 maps the differences from the grids, compared to the USGS DTM. Differences are very small, except along the edges of steep slopes and pits.

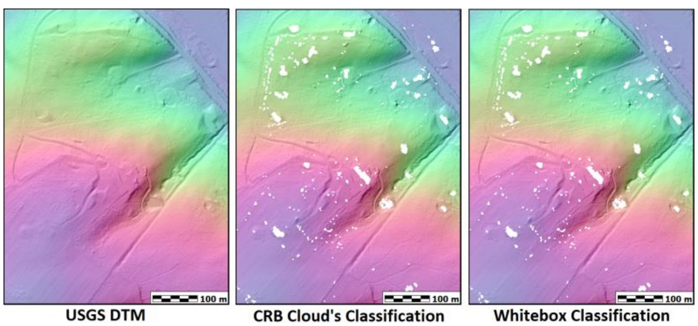

Figure 3. DTMs created with two different point classification algorithms compared to the USGS DTM.

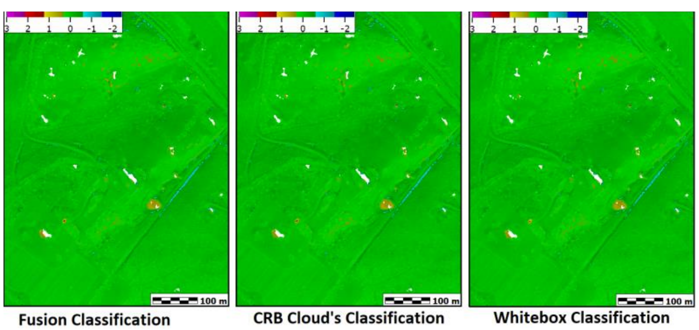

Figure 4. Difference between USGS DTM and DTMs derived from using different ground classification algorithms. Lower USGS DTM is positive.

C. Effect of Surface Interpolation Algorithm

Figure 5 shows DTMs created by four different algorithms. They are visually very similar, except for the Fusion TIN which fills all holes. Slope and elevation moments calculated from the DTMs are also similar except for slope skewness and kurtosis.

D. Effect of DTM Resolution

Point clouds with resolutions over 2 ground points/m² acquired without snow or leaf coverage can produce DSMs and DTMs with 1 m or better spacing, which will provide detailed base maps and visualizations. The level of detail, or noise, may be excessive for many applications, particularly geomorphometry, and coarser grids may be appropriate. One solution [11] uses a Gaussian pyramid, with smoothing and scaling. An alternative would be to create multiple scales of DTM directly from the point cloud, which can be done in a single pass through the data. Figure 6 contrasts the two methods, showing slope maps computed at 5 different resolutions. As the grid size increases, the number of gaps from buildings and water decreases, and small irregularities on the terrain surface disappear.

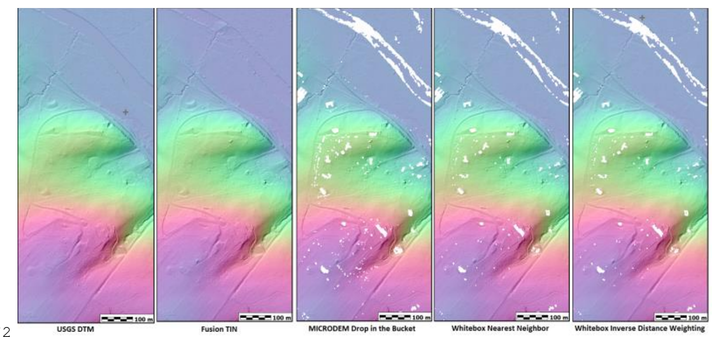

Figure 5. DTMs derived with differing interpolation algorithms.

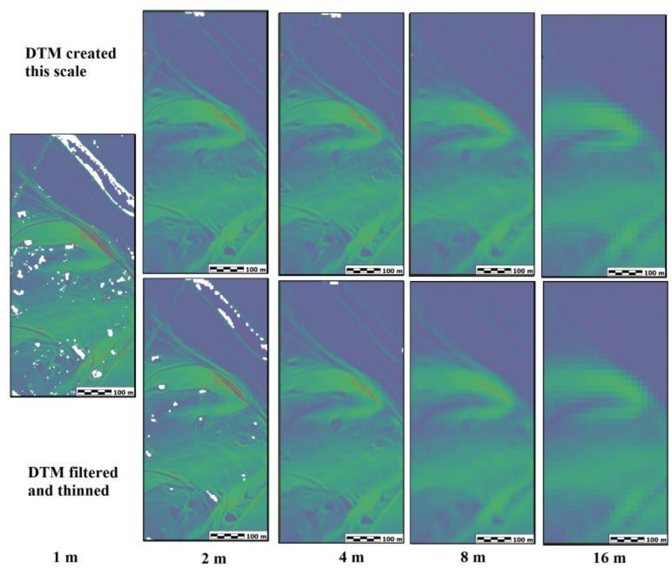

Figure 6. Effect of DTM grid size on computed slope maps, comparing two methods of creating the pyramid of grids.

IV. Conclusion: Impact for Geomorphometry

Multiple free algorithms take a lidar point clouds, classify ground points, and create a DTM surface, and produce very similar results.

Buildings, roads, and water present challenges for geomorphometry. Processing by national mapping agencies produces very nice looking water surfaces, but for computations would we prefer to see the underwater elevations, use the flat regions, or restrict analysis to the land area only? Water might best be left as voids, or represented with an additional mask that could be applied before making computations. Buildings produce artificial flat pads and rectangular patterns, and keeping them as voids or an accompanying mask has some attraction. Whether holes or flat pads provides a better depiction, as either presents an artificial representation of the terrain, might be a matter of personal taste depending on the use of the DTM. The NVS avoids this by prominently displaying the buildings, but would not be suitable for most geomorphometric work.

At what scale can we see features in that landscape that we want to use in terrain classifications? The common recommendation to filter the DEM before deriving curvature or landform classification suggests that we could use a coarser DEM, because the coarser DEM smooths the terrain. For a lidar DTM, coarser grids limit the impact of buildings, water, and roads. Geomorphometric work with DTMs will likely want grids with larger spacing than the underlying lidar point clouds can produce, to remove excessive noise and detail. The challenge will not be interpolating among widely spaced points using TINs, IDW, or kriging, but in selecting an elevation to represent each grid cell. The selection could be done with the point cloud, or operating on a detailed DTM and modifying it. Working with the point cloud, we could (1) take the minimum or maximum, to preserve ridges and valleys, even if they must be slightly displaced to line on a grid point; (2) take the mean of the points in the grid cell; or (3) take the point closest to the center of the grid cell. All of these options can be efficiently programmed, and other choices could also be justified.

DTMs produced by national mapping agencies follow very specific procedures [12] which produce consistent products which are generally visually appealing. Some agencies recognize the additional need for a DSM, but even a single DTM is unlikely to meet the needs of all users. If the original point cloud is freely available, as is increasingly common, users can create a custom DTM or DTMs that deal with water, buildings, and roads to support the desired operations. The procedure can also create multiple resolutions to better understand the geomorphometric characteristics of the landscape.

Acknowledgment

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