A Progressive Black Top Hat Transformation Algorithm for Estimating Valley Volumes

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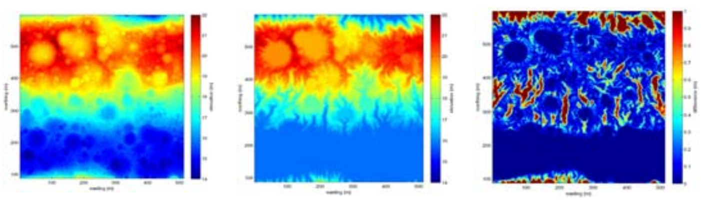
1. Introduction

The amount of valley incision and valley volume are important parameters in geomorphology and hydrology research, because they are related to the amount of erosion (and thus the volume of sediments) and the amount of water needed to create the valley. This is not only the case for terrestrial research but also for planetary research such as figuring out how much water was on Mars. Inspired by the Progressive TIN Densification algorithm (Axelsson, 2000) and the Simple Morphological Filter (Pingel et al., 2013) used in LiDAR data processing to separate bare-Earth surface and above ground features and the Black Top Hat Transformation algorithm (Soille, 2004) in image processing to extract dark features on a varied background, we present a new Progressive Black Top Hat Transformation algorithm to estimate valley volume more accurately.

2. Test Data

To test/develop the algorithms, we used a simulated surface of Mars [Figure 1(B)], which is the result of rainfall and runoff erosion of an initial cratered landscape [Figure 1(A)] (Howard, 2007). The "true" volume of erosion can be easily derived by calculating the difference between the initial surface [Figure 1(A)] and final surface [Figure 1(B)]. The result is Figure 1(C).



(A) (B) (C)

Figure 1 (A) Initial topography of a cratered landscape simulating Mars condition before fluvial erosion (B) Result of rainfall runoff erosion using Howard's MARSSIM model (Howard, 2007); (C) Difference between (A) and (B), scaled to between 0 and 1, highlighting the valleys.

3. Algorithms

3.1 Progressive TIN Densification Algorithm (Axelsson's algorithm)

Axelsson's Algorithm was first developed to parse 3D LiDAR point cloud data to separate bare earth and above ground objects (such as buildings, trees, etc). It starts with a sparse Triangular Irregular Network (TIN) derived from neighborhood minima, and then iteratively adds points that meet the following criteria: (a) the angles that a point forms with the closest triangle facet must be below a data-derived threshold (see α, β, γ in Figure 2), and (b) a point must be within a minimum distance of the nearest triangle node (see d in Figure 2). The iterative process ends when no more points can be added according to the above criteria (Axelsson, 2000).

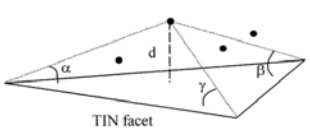


Figure 2 Diagram illustrating angles and distance used in Progressive TIN Densification Algorithm (Figure from Axelsson, 2000)

3.2 Black Top Hat Transformation

The Black Top Hat (BTH) transformation is an image processing technique originally used to extract dark features on a variable background (Soille, 2004) and has been successfully applied to extract valley depth and/or volume (Rodriguez et al., 2002; Luo, 2010) based on DEM data. BTH works by creating a pre-incision surface from the present DEM and subtracting the present DEM from the pre-incision DEM. The pre-incision surface is constructed by first finding maximum within a moving window (called dilation) and then the minimum of the maximum (called closing). The process of BTH transformation is illustrated in Figure 3 for a 2D profile. The free parameters are the moving window size λ and the threshold value for noise *t*.

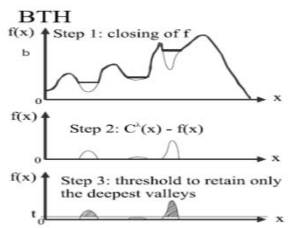


Figure 3. Schematic diagram showing steps of BTH transformation with a 2-D profile example. Here *f(x)* represents elevation at location *x*; $C^{\lambda}(x)$ is the closing of *f(x)*, which represents the pre-incision elevation, with a moving window of size *λ*; *t* is the threshold to remove noise and retain only the deepest valleys. Figure from Rodriguez et al. (2002).

3.3 Progressive Black Top Hat Transformation

The single window size used in BTH method may result in an underestimate of valley volume because smaller tributaries may not be included. Here we propose a progressive BTH (PBTH) transformation algorithm, which is similar to BTH but is iteratively applied with the window sizes progressively increased so that smaller features such as tributaries will also be included. A slope based threshold was introduced to automatically adjust the threshold values for different window sizes: $t = \lambda s$, where s is the slope factor (= dz/dx) and λ is the window size.

4. Results

4.1 Applying the three algorithms to test data

The results of applying the three algorithms outlined above to the test data are shown in Figure 4 and Table 1. For the Axelsson's algorthm, we inverted the topography so that the valley becomes positive features that can be separated from the "bare-earth TIN" and volume calculated. For BTH method, we used window size λ = 9 pixels and slope factor s = 0.02. For PBTH, λ = 3, 4, 5, 6, 7, 8, 9 pixels and s = 0.02.

From the valley masks (Figure 4), it is clear that results from all three algorithms are generally consistent with the "truth". From the volume estimate (Table 1), all three methods underestimate the volume. PBTH method has the highest relative accuracy (~90%) and highest Kappa value (0.72).

Table 1 Comparison of volume estimate by different methods

Algorithm	Volume Estimate (m^3)	Relative accuracy (%)	Cohen's Kappa
Axelsson	16,275.00	77.15	0.7033
Black Top Hat	14,935.31	70.80	0.6411
Progressive Black Top Hat	18,788.36	89.07	0.7217
Difference ("truth") (>0.2m)	21,094.66	100 .0	1.0000

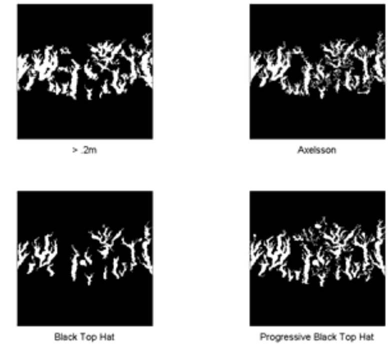


Figure 4 Masks of valleys: (A) Initial surface – eroded surface thresholded at 0.2 m. This is used as "truth"; (B) Result from Axelson's Algorithm; (C) Result from BTH method (λ = 9 pixels and s = 0.02); (D) Result from PBTH method (λ = 3, 4, 5, 6, 7, 8, 9 pixels and s = 0.02)

4.2 Applying BTH and PBTH to Ma'adim Vallis, Mars.

The results of applying BTH and PBTH to Ma'adim Vallis, Mars are show in Figure 5 and 6. Similar to the test data, PBTH method captures more details of the valley and volume estimate are larger than BTH method. The volume estimates appear to converge as the (maximum) window sizes increase.

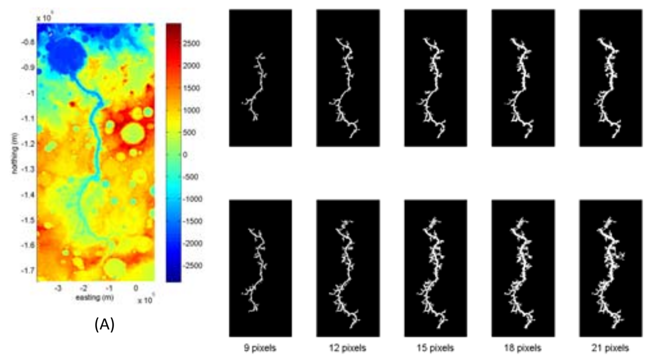


Figure 5(A) MOLA DEM of Ma'adim Vallis, Mars. (B) Top row, BTH method at various window sizes (note: only a single window size is applied); Bottom row, PBTH method at various window sizes up to the maximum labeled.

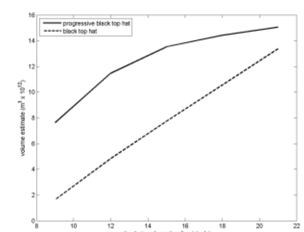


Figure 6 Comparison of volume estimate using BTH and PBTH method.

5. Summary and Future work

All three methods produce results generally consistent with the "truth" in the test data. The PBTH method is the best by using progressively larger window sizes. Future work will focus on methods to automatically determine the maximum window size and threshold value based on the data. The ultimate goal is to estimate the volume of valley network excavation on a global scale for Mars.