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Micro-Terrain and Canopy Feature Extraction by Breakline and Differencing Analysis of Gridded Elevation Models

Identifying Terrain Model Discontinuities with Application to Off-Road Mobility Modeling

S. Bruce Blundell

March 2021

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Abstract

Elevation models derived from high-resolution airborne lidar scanners provide an added dimension for identification and extraction of micro-terrain features characterized by topographic discontinuities or breaklines. Gridded digital surface models created from first-return lidar pulses are often combined with lidar-derived bare-earth models to extract vegetation features by model differencing. However, vegetative canopy can also be extracted from the digital surface model alone through breakline analysis by taking advantage of the fine-scale changes in slope that are detectable in high-resolution elevation models of canopy. The identification and mapping of canopy cover and micro-terrain features in areas of sparse vegetation is demonstrated with an elevation model for a region of western Montana, using algorithms for breaklines, elevation differencing, slope, terrain ruggedness, and breakline gradient direction. These algorithms were created at the U.S. Army Engineer Research Center – Geospatial Research Laboratory (ERDC-GRL) and can be accessed through an in-house tool constructed in the ENVI/IDL environment. After breakline processing, products from these algorithms are brought into a Geographic Information System as analytical layers and applied to a mobility routing model, demonstrating the effect of breaklines as obstacles in the calculation of optimal, off-road routes. Elevation model breakline analysis can serve as significant added value to micro-terrain feature and canopy mapping, obstacle identification, and route planning.

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Preface

This study was conducted for the U.S. Army Engineer Research and Development Center, Geospatial Research Laboratory (ERDC-GRL) under PE 633463, Project AU1, Task: Enhanced Terrain Processing – Demonstration. The project manager was Dr. Jean Nelson and the technical monitor was Ms. Nicole Wayant.

The work was performed by the Data and Signature Analysis Branch (TR-S) of the Topography Imagery and Geospatial Research Division (TR), ERDC-GRL. At the time of publication, Ms. Jennifer L. Smith was Chief, TR-S; Ms. Martha Kiene was Division Chief, TR; and Mr. Ritchie Rodebaugh was the Technical Director for the Geospatial Research and Engineering (GRE) business area. The Deputy Director of ERDC-GRL was Ms. Valerie L. Carney and the Director was Mr. Gary Blohm.

COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

A fundamental task of geographic information analysis is to create representations of the earth's surface, which includes the patterns and distribution of features on the surface. Many terrain features can be mapped as spatially referenced point, linear, or polygonal objects, with one or more associated attributes providing additional pertinent information about the object. Elevation above a known base level represents a continuously varying parameter across horizontal space that can serve as a feature attribute. Such a continuous surface can be digitally modeled as a field of elevation samples with referenced locations.

Two common approaches in topographic modeling are Triangular Irregular Networks (TINs) and gridded surfaces such as Digital Elevation Models (DEMs). A TIN model is an irregular array of points whose locations come from individual samples of surface elevation or from vertices of known linear features (Maune 2001). A gridded model is a horizontal array of uniformly spaced cells, referenced and aligned to the x and y axes of a geographic coordinate system. Each cell is attributed with a representative surface elevation value determined by sampling proximal source elevation data points. The horizontal resolution of such a model is represented by the grid spacing. The tools, associated algorithms, and display functions for topographic model analysis described in this work depend on gridded elevation models as required input data.

Field techniques for the collection of topographic information have undergone rapid change. Early classical surveying techniques gave way to aerial stereo photography, followed by spaceborne sensor platforms, for the collection of elevation data over broad areas. Modern airborne lidar (or LiDAR) scanners now efficiently provide this function by determination of range to the terrain surface from the timing of high-frequency laser light pulses. The resulting high-resolution point clouds can be efficiently converted into gridded elevation data for digital analysis. The data are carefully georeferenced with continuous capture of Global Positioning System (GPS) positioning data and internal collection geometry. Resulting models can provide geodetic accuracy of terrain structure at sub-meter resolutions (Carter et al. 2007).

Airborne lidar remote sensing systems generate rapid, near-infrared laser pulses to acquire sequential range measurements over the terrain, creating voluminous point clouds of reflective returns with associated elevation values. These distances are related to a geoid model from the recorded position and attitude of the aircraft, giving the geographic position and elevation of each pulse return.

A key advantage of airborne lidar is the potential collection of multiple pulse returns at each ground location, which yields information about vertically superposed reflective surfaces. Returns from the point cloud can be interpolated into a set of regular gridded matrices. The first return allows for the creation of a Digital Surface Model (DSM) of first-surface elevations that include tree canopy and artificial structures above the bare terrain. Additional higher-return pulses coming from surfaces at or near the ground, under canopy and around building footprints, are used to generate a bare-earth model that closely approximates the underlying terrain. Bare-earth algorithms are designed to remove buildings and other structures from the model by classifying them as non-ground returns (Fowler 2001). This type of model is often referred to as a Digital Terrain Model (DTM). To create a bare-earth DTM, post-processing must be performed to filter the point cloud or set of multiple-return matrices into ground and non-ground returns. In this work, DSMs and DTMs are types or examples of the more generic DEM concept.

The availability of high-resolution digital elevation model data with a horizontal resolution of about 1 meter (m) (or less) has revolutionized the analysis of landscapes and the natural and artificial features on them. Features can change over time and elevation data can be collected and exploited repeatedly in order to understand dynamic processes that sculpt the terrain. At times, earth processes can cause rapid change, and their effects can be better understood through elevation model analysis. Razak et al. (2013) used DTMs derived from airborne laser scanning data to map landslides under dense vegetation in a tropical forest. Tarolli et al. (2012) employed high-resolution topographic data to study features related to shallow landslide processes and bank erosion in mountainous terrain. Thresholds for recognizing features were based on a statistical analysis of landform curvature variability. Chang et al. (2016) identified and correlated topographic factors for landslide susceptibility, optimizing them through DEM analysis for better landslide prediction.

At a DEM grid spacing of approximately 1 m or less, micro-terrain features, such as gullies and minor escarpments, are often characterized by breakline discontinuities in the terrain model. Breaklines, or breaks-in-slope, are

represented by sudden changes in slope over short horizontal distances. They can be identified and extracted for analysis and creation of secondary terrain products. Bakula and Kurczynski (2013) extracted structural lines representing ridges and drainage as vectors from digital terrain models. These were used to create hybrid-structured terrain models for more efficient hydraulic modeling. Martin et al. (2011) designed a model to extract anthropogenic linear structures from DTMs separately from geomorphological linear features. Roads were separated from geological lineaments by their slope, curvature, and shape properties. Bonetto et al. (2015) created a tool to extract geological lineaments from DTMs, such as valleys, ridges, and breaks-in-slope, based on principal curvature values.

Relief patterns of terrain can play a key role in landscape process dynamics, such as erosion, deposition, and ecosystem function (Hoechstetter et al. 2008). These patterns, expressed as areal features, may be characterized by calculation of a roughness or ruggedness parameter applied to each cell in a gridded elevation model. Surface roughness may be defined as the topographic expression of a terrain surface, varying with location and horizontal scale. Several different parameters have been used to quantitatively model roughness, such as the root-mean-square height, root-mean-square deviation, and root-mean-square slope (Shepard et al. 2001). Frankel and Dolan (2007) proposed a method based on the standard deviation of slope about every terrain model cell. Korzeniowska and Korup (2016) developed a curvature-based method for computing surface roughness from lidar-derived DTMs to map gullies on Santa Cruz Island, CA. Riley et al. (1999) created a terrain ruggedness map of the state of Montana from U.S. Geological Survey (USGS) DEM data with a cell size of 1 km². Ruggedness was calculated for each cell by summing the squares of elevation residuals for its eight neighboring cells.

This report summarizes ongoing research at the U.S. Army Engineer Research and Development Center – Geospatial Research Laboratory (ERDC-GRL) in new approaches to the analysis of high-resolution DEMs in breakline algorithm development, return differencing of gridded elevation models, and the creation of a dimensionless ruggedness parameter. This development work, as well as other algorithms for elevation model analysis, have been incorporated into an in-house research tool called the *DEM Breakline and Differencing Analysis Tool*. This tool presents a convenient user interface for gridded elevation model processing and display of results, with user control of various parameters to enable the extraction of desired terrain features.

To demonstrate the utility of these algorithms and the tools developed to exploit them, a scenario in off-road or cross-country mobility routing in rugged terrain is presented in finding a least-cost route in the face of breaklines as obstacles. Other terrain analysis applications are suggested from this work, such as extraction of canopy cover, identification of linear micro-terrain features, breakline gradient direction trend analysis, and ruggedness classes of extended features in diverse landscapes.

1.2 Overview

The *DEM Breakline and Differencing Analysis Tool* (hereafter referred to as the Breakline Tool) was developed at ERDC-GRL in the Environment for Visualizing Images/Interactive Data Language (ENVI/IDL) image processing environment developed by the Harris Corporation. The Breakline Tool's main function is analyzing DEMs to determine breaks-in-slope (discontinuities) on a cell-by-cell basis. Elevation model cell subsets are identified and selected for display by the application of upper and lower bounds or thresholds. The cell subsets are presented as color-mapped overlays over a background image. In addition to the *breakline* overlay, other tool functions include overlays for *model differencing*, *slope*, *ruggedness*, and *breakline gradient direction*.

The Breakline Tool is presented to the user as a Graphical User Interface (GUI) with a variety of controllable parameters and settings for each type of output function. Required input to the Breakline Tool consists of a gridded DSM stored as a GeoTIFF (Tagged Image File Format) file (normally, but not necessarily created from a lidar-derived first surface model), a bare-earth model in GeoTIFF format, and a reference TIFF image coincident with the elevation models and used for background display. If a lidar data collection is the source data for the model, and a bare-earth model is not available, a DEM based on the last return data can substitute for the bare-earth model. The elevation values of such a DEM will be based on lidar pulse energy reflected from deeper in the canopy and may serve as an acceptable approximation of the under-canopy ground surface.

Slope discontinuities extracted and displayed by the Breakline Tool for individual model cells are often grouped into curvilinear objects that represent micro-terrain features. Examples of micro-terrain features include gullies, channels, small scarps, boulder fields, berms, mounds, minor excavations, or any fine-scale terrain irregularity characterized by a

sudden change in slope. Such features are found in the DEM by calculating a breakline value with numerical techniques applied to elevation values about each model cell. The Breakline Tool is used to display an overlay of color-mapped breakline values over a reference image created from the input DEM. By selecting various computation and display parameters, the breakline overlay shows the locations of features associated with elevation discontinuities.

A basic slope overlay capability is included in the Breakline Tool where its values are calculated by a numerical technique similar to that for the breakline values. This overlay provides a slope analysis function for characterizing elevation-dependent features such as hill slopes or roof geometry.

The Breakline Tool also contains an elevation model differencing algorithm for calculating an output difference overlay. This overlay is created by subtracting bare-earth model cell values from the corresponding cells in the DSM. The resulting model is sometimes referred to as a “canopy height” model as the difference elevations are a good approximation of tree heights above the surrounding terrain (Popescu and Wynne 2004). Buildings and other structures not appearing in the bare-earth model are also represented in the elevation difference model. If a lidar last return-based DEM is used instead of a bare-earth model, buildings and structures will be absent in the difference model because there will be essentially no elevation differences between the DSM and the last return-based DEM for roof surfaces.

Vegetated areas may also be extracted by the Breakline Tool and displayed in the breakline overlay by taking advantage of the densely packed discontinuities that occur in the DEM representation of canopy. This technique only requires the DSM or first-surface model and is usually more effective than differencing for canopy extraction. Canopy identified by this technique may be due to trees, woody shrub vegetation, or cropland. The density of the vegetation may range from dense regions of closed tree or crop canopy to scattered individual plants. Low-density vegetation will appear in the breakline overlay if supported by the horizontal resolution of the gridded elevation model.

In addition to creating breakline, slope, and elevation difference overlays of model cell subsets, two additional overlays are available. One displays a unique dimensionless terrain ruggedness parameter developed for the

Breakline Tool; the other shows the breakline gradient direction (the direction of maximum change) of individual breakline cells.

The ruggedness overlay is a color-mapped rendering of elevation model ruggedness on a cell-by-cell basis. It is calculated using an algorithm that incorporates each model cell's slope value, its breakline value, and elevation values in the local cell neighborhood. The gradient direction overlay shows the azimuthal direction, with respect to the elevation model grid axes, of the maximum breakline value (the maximum spatial rate of change in slope, or "gradient vector") for all model cells identified in the breakline overlay. These are divided into a limited set of direction classes and color-mapped for overlay display. Visual analysis of the breakline gradient direction overlay allows the potential discovery of direction trending in sets of breakline features.

Although any gridded digital elevation model in the GeoTIFF format will suffice, the Breakline Tool is primarily designed to work with gridded DEMs created by systems such as Buckeye, a deployable airborne image and lidar collection capability in use by the U.S. Armed Forces. Such systems provide the horizontal resolution (on the order of 1 m or less) necessary to extract fine-scale terrain features.

1.3 Objectives

This work directly supports the Enhanced Terrain Processing (ETP) research effort at the ERDC-GRL. ETP is a task performed under the Tactical Geospatial Information Capabilities (TGIC) project. The goal of ETP is to improve the processing of tactical geospatial data in order to generate feature data more quickly and with higher accuracy. At present, the Army lacks up-to-date tactical geospatial data and associated terrain products and relies on disparate community databases and software tools with limited processing ability. ETP was created to provide accurate, timely and actionable geospatial data and products for Army operations. ETP teams are generating tools in the following areas: image pre-processing for satellite sources of high-resolution imagery; binary maps from multispectral imagery for canopy cover/non-forest areas, land/water, and bare soil/non-bare soil; land cover classification from high-resolution imagery; breakline and associated topographic analysis of high-fidelity elevation models; output of global daily soil moisture and soil strength at 10-100 meter resolution; and identification of optimal locations for wet gap crossing operations.

This report was prepared in support of the ETP breakline analysis team. Its purpose is to fully describe ongoing GRL research into the development of a suite of algorithms to enable breakline extraction and associated analysis from gridded elevation models, and to provide a practical example of their use in a real-world setting. Under ETP, these algorithms will be enhanced and transitioned to other data processing environments to support the goals of ETP and its parent project TGIC.

2 Algorithm Development

The elevation model analysis functions previously introduced are accomplished by a series of algorithms developed in-house for convenient use in the user environment of the Breakline Tool. They are the basis for creating overlay displays for breaklines, elevation difference, slope, terrain ruggedness, and breakline gradient direction. These algorithms are fully described in the following sections.

2.1 Breakline algorithm

In the context of an elevation model, a breakline, or break-in-slope feature, is identified by a sudden change in slope across a relatively short horizontal distance. On a classical flat map, this is equivalent to a sudden compression of contour lines that appear to be organized into a linear feature. For a DEM, these sudden changes in slope are found by calculating the directed second derivative of elevation in a limited set of directions for each grid cell. The largest absolute value from the set of directed second derivatives becomes the breakline value for that DEM cell. The units for the breakline values are inverse distance.

To find the breakline value, algorithms were developed in ENVI/IDL to calculate an estimation of the unknown continuous function represented by successive elevation value samples along a line from a grid cell in a particular direction. The algorithms are based on a modified numerical cubic spline interpolation technique (Blundell 2006) and are implemented by the Breakline Tool. This results in a limited set of directed second derivative estimations for that grid cell, one for each of several directions defined on the matrix (Figure 1). From this set of second derivative values, the maximum absolute value is found. This value, its original sign (+/-), and its associated direction are then saved in matrix array layers for each grid cell.

In order to calculate each directed second derivative, a strategy must be developed to select a linear sequence of grid cell elevation value samples centered on the grid cell for which a breakline value is required. The method used here is to identify a sequence of five grid cells in a given direction about the center cell. A total of eight directions are identified in the model matrix emanating from the center grid cell. The grid cell identification process for an arbitrary grid cell location is shown in

Figure 1. The gridded matrix directions indicated (0, 26.6, 45, 63.4, 90, 116.6, 135, and 153.4 degrees) are determined by the trigonometric relationship between the center cell and the other four samples in a given sequence.

Figure 1. DEM matrix positions for numerical breakline value calculation with a 9x9 kernel.

Figure 1 shows gridded matrix locations for cell elevation values to be used in the breakline calculation for the center cell, which is represented by *S*. A series of eight directions from the center cell are represented from 0 to 180 degrees. For each direction, the other four cells required are represented by *S+1*, *S+2* (from 0 up to, but not including, 180 degrees), and *S-1*, *S-2* (from 180 up to, but not including, 360 degrees). Breakline calculations are only required for the directions shown in Figure 1; the reverse directions beyond 180° are implicit for each 5-cell sequence.

These 5-cell linear sequences (*S-2*, *S-1*, *S*, *S+1*, *S+2*) are depicted in Figure 1 for a 9x9 computation kernel window (the default kernel size in the Breakline Tool). For a 9x9 kernel, the successive matrix positions from the center cell are identified at every other DEM grid cell location in the *i* and *j* orthogonal directions (90° and 0°, respectively). The distance

between these cells is shown as $2D$ in Figure 1, assuming a DEM ground sample distance of D .

The ground distance between adjacent elevation matrix samples, or ΔS_θ , is a function of the size of the computation kernel, the direction θ and the DEM ground sample distance D . It is a key parameter used in the breakline value computations, described in the following section. As shown in Figure 1, for the 9x9 kernel, $2D$ is the minimum value for ΔS_θ , occurring along the i, j orthogonal directions.

The Breakline Tool allows the user to select kernel sizes other than the default size 9x9. Although not shown here, these other available choices are 5x5, 17x17, and 33x33. For these other kernels, elevation values are sampled for successive S cell locations along the i, j orthogonal directions from adjacent cells, from every 4th cell, and every 8th cell, respectively. This scheme avoids the need to interpolate between grid cell elevation values when taking samples for the 5-cell linear sequences. The minimum value for ΔS_θ for the full range then becomes D , $2D$, $4D$, and $8D$ (for kernel sizes 5x5, 9x9, 17x17, and 33x33, respectively). As the kernel size increases, the horizontal resolution of calculated changes in slope decreases. The best strategy is to choose a kernel size that graphically identifies breaklines as components of individual features without sacrificing detail within each feature of interest.

The ground distance between successive S center cell positions in a particular direction, normalized by ground sample distance, is given by $\Delta S_\theta / D$. Table 1 provides values for $\Delta S_\theta / D$ for all eight sampling directions and for the full range of computation kernel options. As an example, for the 9x9 kernel, the distance between successive sample cells in a 5-cell sequence in direction $\theta = 45^\circ$ (Figure 1) is $\Delta S_\theta = [(2D)^2 + (2D)^2]^{1/2} = [(8D)^2]^{1/2} = 2\sqrt{2} D$. In units of D , this distance becomes $2\sqrt{2}$ (Table 1).

For the 5x5 kernel, which takes elevation samples from adjacent cells distance D apart, the kernel geometry does not allow for a 5-cell linear sequence for directions other than 0, 45, 90, and 135 degrees without interpolating between values. Therefore, in this case, the maximum breakline value must be found using four directions instead of eight.

Table 1. $\Delta S_{\theta}/D$ values by direction (θ) and window size.

θ	5x5	9x9	17x17	33x33
0°	1	2	4	8
$\tan^{-1} \frac{1}{2} = 26.6^{\circ}$	---	$\sqrt{5}$	$2\sqrt{5}$	$4\sqrt{5}$
$\tan^{-1} 1 = 45^{\circ}$	$\sqrt{2}$	$2\sqrt{2}$	$4\sqrt{2}$	$8\sqrt{2}$
$\tan^{-1} 2 = 63.4^{\circ}$	---	$\sqrt{5}$	$2\sqrt{5}$	$4\sqrt{5}$
90°	1	2	4	8
$\tan^{-1} -\frac{1}{2} = 116.6^{\circ}$	---	$\sqrt{5}$	$2\sqrt{5}$	$4\sqrt{5}$
$\tan^{-1} -1 = 135^{\circ}$	$\sqrt{2}$	$2\sqrt{2}$	$4\sqrt{2}$	$8\sqrt{2}$
$\tan^{-1} -2 = 153.4^{\circ}$	---	$\sqrt{5}$	$2\sqrt{5}$	$4\sqrt{5}$

2.1.1 Breakline computation strategy

In order to compute the breakline value for each model cell, a modified form of cubic spline interpolation is employed. For a function that may contain sudden local changes, such as terrain elevation, the spline is often a very good approximation of the function's behavior. In this technique, a piecewise cubic function is fitted to a set of data points. The function consists of a set of third-order polynomials that pass through the data points. Smoothness at the data points is maintained for the entire piecewise function.

The general purpose of the spline technique is to interpolate a set of data points with a smooth curvilinear function. During this process, expressions are derived for the interior data points in the sequence that contain estimates of the second derivative at those interior locations of the piecewise spline function. For a linear sequence of five elevation model grid cells, these expressions can be solved simultaneously for the second derivative of elevation at the center of the sequence. This is the breakline value for grid position S in Figure 1. At this point, the spline process is terminated as interpolation between the grid cells is not required. A new grid cell sequence is then defined, and the spline process re-started. Further details of this computation strategy are provided below.

Using the grid cell sampling scheme described above, cubic spline interpolation is applied to each sampled sequence of five elevation points, including the elevation of the central cell, to generate the breakline values for each direction. For cubic splines, third order connecting polynomials are derived for each interval in each 5-point elevation point series, given assumptions about the function values and its derivatives at each point (Chapra and Canale 2002). These polynomials contain the second

derivatives at the ends of each interval. If they are then differentiated with the condition that the first derivatives at the three interior points must be continuous, an expression results containing only derivatives of the second order. These derivatives can be evaluated by applying the expression to the three interior points in the series in the following way.

For the five-point series $S-2$, $S-1$, S , $S+1$, and $S+2$ defined in a particular direction θ in Figure 1, an expression can be formed for each of the three interior points $S-1$, S , and $S+1$, based on the cubic spline assumption that the first derivative at the interior points must be equal. Although not explicitly derived here, this expression appears as

$$E''_{S-1,\theta} + 4E''_{S,\theta} + E''_{S+1,\theta} = 6(E_{S+1,\theta} - 2E_{S,\theta} + E_{S-1,\theta}) / \Delta S_{\theta}^2 \quad (1)$$

where $E_{S,\theta}$ is the elevation value at matrix position $S = S(i,j)$ for which the second derivative $E''_{S,\theta}$ is required in direction θ from position S . The second derivatives $E''_{S-1,\theta}$ and $E''_{S+1,\theta}$ refer to neighboring sampled cells on either side of S . ΔS_{θ} is the horizontal distance between successive elevation matrix samples and is a function of θ and the sensor ground sample distance D . The quantities $E_{S+1,\theta}$ and $E_{S-1,\theta}$ are elevation values at sampled matrix positions on either side of position S associated with direction θ . Figure 2 depicts an example of an elevation profile from a gridded elevation model with the series of five matrix positions $S-2$, $S-1$, S , $S+1$, and $S+2$.

Figure 2. Example elevation profile sample sequence for cubic spline interpolation.

After Equation 1 is formed for any elevation model cell S , two more equations are formed for the two neighboring interior points, $S-1$ and $S+1$. For the $S-1$ interior point, its neighboring sampled cells are $S-2$ and S ; for the $S+1$ interior point, its neighboring sampled cells are S and $S+2$. These additional equations for points $S-1$ and $S+1$ are in the same form as Equation 1 for the central interior point S , and appear respectively as

$$E''_{S-2,\theta} + 4E''_{S-1,\theta} + E''_{S,\theta} = 6(E_{S-2,\theta} - 2E_{S-1,\theta} + E_{S,\theta}) / \Delta S_{\theta}^2 \quad (2)$$

$$E''_{S,\theta} + 4E''_{S+1,\theta} + E''_{S+2,\theta} = 6(E_{S,\theta} - 2E_{S+1,\theta} + E_{S+2,\theta}) / \Delta S_{\theta}^2 \quad (3)$$

The system of three equations (1), (2), and (3) contain 5 unknowns, the set of second derivatives at each of the 5 points in the sequence. However, by employing the so-called natural cubic spline assumption that the second derivatives at the two end points $S-2$ and $S+2$ are zero, three unknowns remain in the set of three equations. The set of equations then becomes

$$E''_{S-1,\theta} + 4E''_{S,\theta} + E''_{S+1,\theta} = 6(E_{S-1,\theta} - 2E_{S,\theta} + E_{S+1,\theta}) / \Delta S_{\theta}^2 \quad (4)$$

$$4E''_{S-1,\theta} + E''_{S,\theta} = 6(E_{S-2,\theta} - 2E_{S-1,\theta} + E_{S,\theta}) / \Delta S_{\theta}^2 \quad (5)$$

$$E''_{S,\theta} + 4E''_{S+1,\theta} = 6(E_{S,\theta} - 2E_{S+1,\theta} + E_{S+2,\theta}) / \Delta S_{\theta}^2 \quad (6)$$

Equations 4, 5, and 6 represent the second derivatives for the interior points $S-1$, S , and $S+1$ for the five-point series. The three equations must now be solved simultaneously for $E''_{S,\theta}$, which is the breakline value for the center cell S of the 5-cell sequence in direction θ . Solutions for the second derivatives for the neighboring points $S-1$, $S+1$ are not required and are not saved. Direction θ is then incremented to its next value, and the process begins again. For computation kernel sizes of 9x9 and higher, the maximum absolute value of the cubic-spline-derived breakline value is saved from the set of eight directional computations for the central grid cell. As previously described, for a 5x5 kernel, only four directions are available due to the kernel geometry and sampling scheme.

In order to solve Equations 4, 5, and 6, the Thomas algorithm (Chapra and Canale 2002) is employed. This decomposition technique, related to Gaussian elimination, is an efficient method for solving systems of linear algebraic equations. The Thomas algorithm can be used to solve a tridiagonal system with n unknowns. In such a system, the coefficients can be arranged in a tridiagonal matrix, or one that has non-zero elements along the main diagonal and the diagonals immediately above and below it, with zeroes everywhere else. In this case, a solution is required for the system of equations represented by

$$A X = B \quad (7)$$

where A is a 3x3 tridiagonal matrix of coefficients that depend only on sampling distance ΔS_θ , X is a solution vector for the three unknowns, and B is a vector of constants.

These matrices are:

$$A = \begin{bmatrix} 4 \Delta S_\theta & \Delta S_\theta & 0 \\ \Delta S_\theta & 4 \Delta S_\theta & \Delta S_\theta \\ 0 & \Delta S_\theta & 4 \Delta S_\theta \end{bmatrix} \quad X = \begin{bmatrix} E''_{S-1,\theta} \\ E''_{S,\theta} \\ E''_{S+1,\theta} \end{bmatrix}$$

$$B = \begin{bmatrix} 6(E_{S,\theta} - 2E_{S-1,\theta} + E_{S-2,\theta}) / \Delta S_\theta \\ 6(E_{S+1,\theta} - 2E_{S,\theta} + E_{S-1,\theta}) / \Delta S_\theta \\ 6(E_{S+2,\theta} - 2E_{S+1,\theta} + E_{S,\theta}) / \Delta S_\theta \end{bmatrix}$$

Application of the Thomas algorithm to Equation 7 solves for vector X and provides second derivative solutions for the three interior sample points, although only the central value for position S is needed. The result of these calculations is a matrix of maximum breakline values represented by $E''_{S,\theta}$ for each grid cell in the input DEM.

In the Breakline Tool, no distinction is made between breakline values resulting from an increase or decrease in slope in the vicinity of each grid cell. As a result, negative breakline values are not presented to the user. Therefore, the absolute value is taken of each breakline value in the output matrix. Upper and lower thresholds can then be applied to the range of breakline values, with the understanding that the sharpness of the breakline increases from zero in the positive direction. These thresholds create model subsets that can be displayed as overlays over a shaded relief image of the DEM. Careful selection of thresholds can result in the extraction of features in the model, such as micro-terrain or areas of vegetative canopy.

The Breakline Tool allows for a user-selectable number of color-coded classes of breakline values for display within the chosen threshold bounds. To prepare the breakline overlay, class boundaries are determined by calculating a so-called *equal-area* solution for the range of breakline values between upper and lower thresholds. This is an iterative process that allows the class boundaries to be adjusted in order to place the same number of displayed breakline cells in each class. For many areas of actual terrain, as breakline values increase, they are represented by fewer and fewer numbers of grid cells in the digital model. An equal-area approach to determining color-coded class bounds provides a more uniform representation of the range of breakline values depicted in the overlay.

2.1.2 Application to lidar-derived DSM

To illustrate the use of the breakline overlay, the algorithm was applied to a first-return DSM created from an airborne lidar dataset collected over an area of southwestern Montana using an Airborne Laser Terrain Mapper scanning system manufactured by Optech, Inc. and mounted on a DeHavilland DHC-7 aircraft. The approximate location of the overflight area is shown on Figure 3. The data was collected in 2003 and was provided by the U.S. Army Geospatial Center.

Figure 3. Geographic location of Montana airborne lidar dataset.

The study area is a region of high, rugged country with discontinuous coniferous forest in mountainous terrain. Elevations are greater than 2,400 m above sea level. Forest cover in this region is coniferous and largely represented by five species: subalpine fir, lodgepole pine, whitebark pine, Engelmann spruce, and Douglas fir (DeBlander 2001). The region is influenced by the geology of the Yellowstone area, and is

drained by streams following joints or cracks in the granitic bedrock (Fritz 1994). Figure 4 shows a shaded relief image of a portion of the DSM dominated by canopy, covering an area of 2.5 km² with a horizontal grid resolution of 1 meter. North is up in this and succeeding figures.

Visual examination of terrain elevation profiles representing vertical cross-sections of individual micro-terrain features demonstrate correlation of breaklines with grid cell patterns of above-threshold breakline values. An example of a micro-terrain feature in the Montana DSM identified in this way by a sudden change in slope by the breakline algorithm is shown in Figure 5. On the left in the figure, a micro-terrain discontinuity is depicted in a red overlay, showing two parallel linear components. A cross-section profile was extracted at the position of the green line. This profile is shown on the right without vertical exaggeration, revealing a 6-meter high escarpment with break points approximately 10 m apart bounding an area with a fairly constant slope of about 30°. These break points, extended along the horizontal, correlate with the two parallel red lines in the overlay.

The portion of the profile between the break points where the change in slope is minimal corresponds to the non-red strip between the upper and lower breaklines in the DSM.

Figure 4. Montana first-return DSM of canopy area.

Figure 5. Example micro-terrain feature (left) and cross-section profile (right).

In addition to micro-terrain features, careful selection of thresholds in the Breakline Tool can create an accurate canopy overlay from the breakline overlay. For the Montana DSM in Figure 4, an upper threshold was taken as the maximum breakline value in the model. Using a computation kernel size of 5x5, trial-and-error experimentation was used to choose the lower threshold by comparing the color-mapped overlay to the underlying shaded relief representation of the canopy areas. Only one color-coded class was selected to provide a uniform appearance. Results are shown in Figure 6. The lower breakline threshold is 3.0/meter, providing an overlay that optimally represents the canopy. If the threshold is reduced further, non-vegetated topographic breaklines begin to appear in the overlay.

Figure 6. Breakline overlay optimized for canopy extraction.

2.2 Elevation difference algorithm

Another key function of the Breakline Tool is the calculation of vertical heights of features above the underlying terrain. This is done on a cell-by-cell basis by subtracting a bare-earth or DTM closely approximating the terrain surface from a DSM showing the highest surfaces of all features. Upper and lower thresholds can then be applied to this difference model, resulting in overlays showing above-ground features. These features normally consist primarily of vegetation and artificial structures that have been carefully removed during the bare-earth model generation process.

If the DSM under consideration contains tree canopy, the upper threshold should be chosen to contain the highest tree in the model. In an area without tall buildings or other structures, this threshold may be the largest elevation difference found. The choice of lower threshold may require more care. If set too low, the resulting overlay may include non-canopy cells with small elevation differences. In addition, a substantial number of difference cells with negative values close to zero can sometimes occur due to the limits of accuracy in model generation. This can also happen when a DSM contains small depressions in the terrain surface that are not fully captured in a bare-earth model due to the smoothing process that takes place during bare-earth model generation.

Figure 7 shows a histogram of difference cells with a bin size of 0.125 m for the Montana model depicted in Figure 4. The central spike in the figure represents many cells in heavily populated bins clustered close to zero with both negative and positive values. A break point in the histogram curve is also indicated with a value of 0.25 m. This value was chosen as the lower difference threshold for a difference overlay depicting canopy. This break point serves as the boundary between small spurious elevation differences and the long positive “tail” of histogram bins representing real differences due to canopy structure. Other break points may appear in the histogram representing extended regions of vegetation or groups of structures at similar above-ground heights.

The Breakline Tool allows for a user-selectable number of color-coded classes of elevation difference for display. Unlike the equal area solution for the breakline overlay, an *equal class width* solution is calculated to determine class boundaries for the thresholded range of elevation difference values. The class boundaries depend on the range and on the

chosen number of classes, resulting in equal class widths. The number of elevation difference cells are allowed to vary within each class.

Figure 7. Elevation difference histogram for the Montana model.

A difference overlay for the Montana data is shown in Figure 8. Only one class, color-mapped in red, was chosen to represent the canopy. The red cells in the overlay represent 25% of the total cells in the model. The corresponding value for Figure 6 is 59% and, from examination of the shaded relief image in Figure 4, the increase in captured canopy cells in the breakline overlay is apparent. With careful thresholding, the breakline algorithm can be more effective than the difference algorithm in extracting canopy cover.

Figure 8. Difference overlay optimized for canopy extraction.

2.3 Slope algorithm

The slope algorithm calculates slope values for all cells in the DEM. It uses a numerical differentiation technique that takes advantage of Taylor's theorem, which states that a smooth function can be approximated by a polynomial expression of discrete functional values. This polynomial is known as the Taylor series and allows the prediction of a functional value at one point in terms of the functional value and its derivatives at another point. If a vertical plane is passed through a continuous surface model of terrain, its intersection with the model represents a smooth univariate elevation function in terms of horizontal distance. This function can be approximated by the Taylor series and used to estimate slope from a gridded elevation model.

The Taylor series expansion for a function $f(x)$ is given by

$$f(x_{i+1}) = f(x_i) + f'(x_i)(x_{i+1} - x_i) + \frac{f''(x_i)}{2!}(x_{i+1} - x_i)^2 + \frac{f^{(3)}(x_i)}{3!}(x_{i+1} - x_i)^3 + (8)$$

where x_i is a point for which the functional value is known and x_{i+1} is a nearby point whose functional value is to be estimated. The Taylor series contains an infinite number of terms, but only the first four that include the third derivative are shown here.

Slope is the first derivative of elevation. It is represented by the tangent of the angle subtended by the local change in elevation over a short horizontal distance, or “rise over run.” A Taylor series approximation of the elevation function contains this derivative and can be solved to yield a slope value. The accuracy of the slope estimate increases as more terms in the series are included in the approximation. These solutions are known as *divided-difference* formulas for numerical differentiation. Three forms of divided-difference formulas can be constructed by manipulation of the Taylor series: *backward*, *forward*, and *centered*, depending on which points, and their functional values, are chosen for computation in the vicinity of the point for which the slope approximation is required (Chapra and Canale 2002).

Using the notation employed in Equation 1 for elevation values and the horizontal distance between successive samples, the first four terms of the Taylor series in Equation 8 can be rearranged to create a forward difference approximation of the first derivative. This form is called forward difference because it uses data points at the S and $S+1$ locations shown in Figure 1:

$$E'_{S,\theta} \cong (E_{S+1,\theta} - E_{S,\theta} - E''_{S,\theta} \Delta S_{\theta}^2/2 - E^{(3)}_{S,\theta} \Delta S_{\theta}^3/6) / \Delta S_{\theta} \quad (9)$$

Similarly, the backward difference approximation of the first derivative, using points at the S and $S-1$ locations, is

$$E'_{S,\theta} \cong (E_{S,\theta} - E_{S-1,\theta} + E''_{S,\theta} \Delta S_{\theta}^2/2 - E^{(3)}_{S,\theta} \Delta S_{\theta}^3/6) / \Delta S_{\theta} \quad (10)$$

By adding Equations 9 and 10 and combining terms, an expression for the centered difference approximation for the first derivative, using points at the $S-1$ and $S+1$ locations is obtained:

$$E'_{S,\theta} \cong (E_{S+1,\theta} - E_{S-1,\theta}) / 2\Delta S_{\theta} - (E^{(3)}_{S,\theta} \Delta S_{\theta}^2) / 6 \quad (11)$$

In the slope algorithm, the second and third derivative terms in the Taylor series are included in the computation for slope to increase the accuracy of the approximation. The centered difference approach is used, because it is more accurate than the forward and backward forms and because it readily conforms to a 5-point sequence of elevation grid values centered about any cell for which the slope is required. In this way, the centered difference slope algorithm takes advantage of the DEM grid interrogation

process used for breakline value computation by the cubic spline interpolation method.

In order to use Equation 11 for calculating a slope value for each central cell in any 5-point sequence, the third derivative $E^{(3)}_{S,\theta}$ must be evaluated. This is done by combining Taylor series estimates of the forward and backward forms of the second derivative to form an expression for the third derivative in terms of $S+2$, $S+1$, $S-1$, and $S-2$ locations. Although not derived here, this expression for $E^{(3)}_{S,\theta}$ is then substituted in Equation 11 to yield

$$E'_{S,\theta} \cong [-E_{S+2,\theta} + 8E_{S+1,\theta} - 8E_{S-1,\theta} + E_{S-2,\theta}] / 12 \Delta S_{\theta} \quad (12)$$

Equation 12 is the centered difference formula used to calculate a slope estimate for each elevation model cell in terms of known elevation grid values in a linear sequence with direction θ . As in the breakline algorithm, the slope value is computed for each cell in several directions using the sampling scheme in Figure 1. From these values, the maximum slope is saved for that cell.

In the Breakline Tool, the user chooses lower and upper thresholds of slope for display. The slope values between these thresholds are divided into a selectable number of color-mapped classes for overlay display. An equal class width solution is calculated to determine class boundaries for the thresholded range of slope values. The class boundaries depend on the range and on the chosen number of classes, resulting in equal class widths. The number of slope cells selected for display can vary within each class.

2.4 Ruggedness algorithm

The Breakline Tool provides a terrain ruggedness overlay capability using an algorithm that takes advantage of the breakline and slope parameters previously calculated during initial DEM processing. The algorithm also incorporates an elevation deviation-based computation derived from cells in the local neighborhood. For each cell, the geometric mean of these three values is calculated to provide a unique parameter called the Breakline Ruggedness Index (BRI). The BRI values are then separated into classes and color-mapped for display.

To characterize the elevation changes in the local neighborhood about each model cell, a measure of deviation is computed for elevation values in

the computation kernel that was centered on the cell for calculation of the breakline value. However, instead of the usual practice of taking residuals from the mean, residuals are taken from the central elevation value in the kernel. These are squared, summed, and divided by the number of kernel cells used. Finally, the square root of this quantity is taken to provide a final value for elevation deviation in the vicinity of each cell.

The number of residuals taken depends on the size of the breakline computation kernel used in initial DEM processing. For a 5x5 kernel, 16 cells, 4 per each of 4 directions, are used to compute the BRI. For kernel sizes of 9x9, 17x17, and 33x33, 32 kernel cells, or 4 per each of 8 directions, are used. If the elevation deviation as described above is represented by E_{DEV} , the BRI calculation for any given model cell S is given by

$$BRI = [(E''_{S,\theta}) (E'_{S,\theta}) (E_{DEV})]^{1/3} \quad (13)$$

The geometric mean calculation for BRI is thus the cubed root of the product of breakline value, slope value and elevation deviation. BRI values are always positive. The index was designed to represent not only the elevation-based roughness in a cell's immediate neighborhood, but the slope and the degree of slope discontinuity at its location as well.

The units for the breakline value are inverse distance. Slope has no dimension, and the elevation deviation has units of distance. As a result, the BRI is dimensionless. This means that no dimensional conversion is necessary when comparing BRI values across DEMs based on different distance units (e.g. meters to feet).

The BRI overlay is best applied to extended areas in order to reveal features with a uniform degree of ruggedness, such as a boulder field or disturbed land. The cell neighborhood used for elevation deviation is the same kernel used to compute the breakline value, so in a sense, the BRI is scaled to the user's settings and requirements for terrain discontinuity mapping.

The Breakline Tool allows for a user-selectable number of color-coded classes of ruggedness values for display. As with the breakline overlay, an equal-area iterative solution is calculated to determine class boundaries for the entire range of ruggedness values. The class boundaries are

adjusted to allow for the same number of displayed ruggedness cells in each class.

2.5 Breakline gradient direction algorithm

The breakline gradient direction algorithm employed by the Breakline Tool collects the azimuthal direction information of the maximum breakline value for each DEM cell and prepares it for display. Each cell can be considered as having a breakline gradient vector, in which the magnitude of the vector is the breakline value computed by the breakline algorithm. The gradient direction algorithm performs no additional computations but merely identifies those cells with breakline values between upper and lower thresholds selected by the user and assigns directions to them to prepare for a color-mapped overlay display. If the 5x5 kernel was used for breakline computations, only four gradient directions are used due to limitations of kernel geometry; for the larger kernels, eight directions are available.

Figure 9 shows a color classification scheme for gradient direction boundaries overlaid onto the breakline cell sampling grid for a 9x9 kernel.

Figure 9. Color-coded directional classes for a 9x9 kernel geometry.

As previously described, the Breakline Tool does not distinguish between breakline values resulting from an increase or decrease in slope in the vicinity of each grid cell; the absolute value is taken of all values. As a result, for each 5-cell sequence in Figure 9, the forward and reverse directions are assigned the same color.

The gradient direction algorithm was applied to a region of the Montana dataset showing open rocky terrain adjoining and to the south of the area shown in Figure 4. A shaded relief image of this open area is shown in Figure 10.

Figure 10. Montana first-return DSM of rugged open terrain area.

Instead of depicting canopy, breakline thresholds were chosen in this case to show micro-terrain features. Figure 11 shows breaklines associated with two groups of escarpments trending in different directions, one group trending generally north-south and the other east-west. When one or more breaklines that identify a particular feature have little or no directional variation, the feature will have a dominant color in the gradient direction overlay.

To better illustrate the trending of directional features in Figure 11, a histogram of the extracted micro-terrain cells by the set of eight gradient directions is shown in Figure 12. The distribution appears to be bimodal, with one group of cells centered about 90-270 degrees (yellow) and the other group centered about 0-180 degrees (blue). These two groups represent micro-terrain features trending approximately N-S and E-W, respectively. Figure 13 depicts an area in the lower right portion of Figure 11, with features represented in the color scheme shown in the histogram. Micro-terrain feature cells trending E-W (in blue) comprise 53% of the total number of micro-terrain cells in Figure 11; the corresponding figure for the cells trending N-S (in yellow) is 37%.

Figure 11. Breakline gradient direction overlay optimized for micro-terrain features.

Figure 12. Histogram of breakline gradient direction overlay micro-terrain cells.

Figure 13. Breakline gradient direction overlay subset showing feature trending.

Spatially correlated gradient directions for groups of micro-terrain features may be useful for geologic trend analysis for fault scarps or outcropping patterns of resistant beds. The direction overlay may also have application in depicting breakline trends associated with artificial terrain features such as ditches, channels, or berms.

3 Off-Road Mobility Modeling with Breakline-Derived Micro-Terrain Features

3.1 Mobility model set-up

Micro-terrain features identified through breakline analysis can add value to route-finding algorithms that consider slope and obstacles on the terrain as barriers to off-road mobility. In this exercise in mobility modeling, output overlays from the Breakline Tool were input as analytical layers in a Geographic Information System (GIS). ArcGIS, a desktop suite of tools maintained by the Environmental Systems Research Institute (ESRI), was employed for this purpose. A route-finding tool in ArcGIS was used to compare computed routes for an off-road vehicle with and without micro-terrain features across the rugged terrain shown in Figure 10. Breakline and canopy overlays were created in the Breakline Tool as input layers to the DSM in ArcGIS. Within ArcGIS, additional layers of slope, roads, buildings, and watercourses were created and combined with the breakline and canopy layers as potential obstructions for cross-country route finding.

The Breakline Tool layers are shown combined into a single display in Figure 14. Breakline overlay results using different kernel sizes were generated and visually compared. As kernel size increases for given upper and lower thresholds, the spatial frequency and density of color-mapped breakline cells tend to increase. In this case, a computation kernel window size of 17x17 was chosen for the best graphical representation of micro-terrain features while retaining sufficient spatial detail.

Figure 14. Micro-terrain (red) and canopy (green) features over DSM shaded relief.

A route analysis application in ArcGIS was processed with and without the micro-terrain feature layer to assess the usefulness of this data with respect to cross-country mobility. Derived routes are the result of a least-cost path analysis between a chosen origin and destination within the model. The different terrain layers were weighted based on an estimate of the effect or cost that each layer has on mobility. River channel, stream, buildings, and canopy raster layers were weighted as completely (100%) impassable.

Both slope and micro-terrain layers were derived from the bare-earth DTM. The features in the micro-terrain or breakline layer were also weighted as impassable for the route analysis in which they were included. Slope was considered to have a variable effect on mobility and was weighted according to the scheme in Table 2. The minimum and maximum slope for the model in Figure 10 were determined by the slope algorithm to be 0 and 86 degrees, respectively. Along the derived routes both with and without micro-terrain, the slope generally did not exceed 20 degrees.

Table 2. Slope weights for route analysis.

<i>Slope (deg.)</i>	<i>Weight (%)</i>	<i>Slope (deg.)</i>	<i>Weight (%)</i>	<i>Slope (deg.)</i>	<i>Weight (%)</i>	<i>Slope (deg.)</i>	<i>Weight (%)</i>
0 – 3	0	17 – 18	36	28 – 29	58	39 – 40	80
3 – 5	5	18 – 19	38	29 – 30	60	40 – 41	82
5 – 7	10	19 – 20	40	30 – 31	62	41 – 42	84
7 – 10	20	20 – 21	42	31 – 32	64	42 – 43	86
10 – 11	22	21 – 22	44	32 – 33	66	43 – 44	88
11 – 12	24	22 – 23	46	33 – 34	68	44 – 45	90
12 – 13	26	23 – 24	48	34 – 35	70	45 – 46	92
13 – 14	28	24 – 25	50	35 – 36	72	46 – 47	94
14 – 15	30	25 – 26	52	36 – 37	74	47 – 48	96
15 – 16	32	26 – 27	54	37 – 38	76	48 – 49	98
16 – 17	34	27 – 28	56	38 – 39	78	49 – 86	100

3.2 Route-finding results and discussion

Figure 15 shows derived routes generated with and without the micro-terrain features included in the least-cost path calculation. Origin and destination points were chosen on opposite sides of the DSM to force traversal over a significant portion of the rugged terrain. A bridge over the north-south flowing river channel in the eastern portion of the study area and another over the north-south flowing stream to the west allowed for traversal across these features. Improved and unimproved roads were also delineated in ArcGIS and assigned a weight of 0% as they were not considered a hindrance to mobility. The distance along each route was treated as a feature attribute. Transit time was found by querying the least-cost path analysis layer at the destination point. From route distance and transit time, average route speed was derived.

Figure 15. Effect of micro-terrain features on calculated least-cost routes.

In Figure 15, hydrology (blue), improved roads (maroon), unimproved roads (black), and buildings (orange) are also shown. Both routes were forced to cross the bridge located in the lower right due to the impassable river feature. Calculated distances and average speeds are shown in Table 3. Maximum speed along each route was designated as 48 km per hour.

Table 3. Distance and average speed for calculated routes.

ROUTE	Distance traveled (km)	Average speed (km/hr)
With micro-terrain	2.38	39.40
Without micro-terrain	2.34	40.46

The lack of disparity in distance and average speed may be explained by the short distance traversed as well as the least-cost path routine's efficiency in finding gaps through and between the impassable but disjointed features of micro-terrain and canopy. Calculated average speed may also be overly optimistic in that it does not consider a driver's caution in approaching these features as well as the time taken to determine possible alternate routes while underway.

The calculated route generated with the micro-terrain features was noticeably altered relative to that generated without micro-terrain. Although the distance traveled and average speeds were not markedly different, results suggest that routes determined without consideration of micro-terrain features may have an adverse effect on logistical planning for operations involving off-road mobility in rugged terrain.

4 Summary and Conclusions

High-resolution elevation models have shown to be effective in terrain modeling and analysis of surface features and canopy. In gridded form, these models allow for the computation and delineation of breaklines in the model where changes in slope occur rapidly over short distances. These breaklines add value to feature extraction and the understanding of terrain morphology and are associated with micro-terrain features characterized by terrain elevation discontinuities. They can also inform cross-country mobility models that calculate least-cost off-road routes while avoiding obstacles.

This report summarizes ongoing research at ERDC-GRL in the application of numerical methods to high-resolution DEMs to extract breaklines, perform model differencing, calculate slope and terrain ruggedness, and capture and map the vector component of breakline gradients. Algorithms to perform these functions are employed in an in-house ENVI/IDL tool called the *DEM Breakline and Differencing Analysis Tool*, or “Breakline Tool.” This tool allows for significant user control of processing parameters and creates overlay displays of extracted features with shaded relief images of input DEMs. Various functions of the Breakline Tool are demonstrated in the processing of DEMs created from airborne lidar data, representing a rugged region of western Montana.

The display of thresholded breakline values over a shaded relief model image can reveal micro-terrain features such as small escarpments, gullies, and channels. Breaklines coincide with linear expressions of sudden changes in slope. They are also particularly efficient in the extraction of extended areas of canopy due to the abrupt changes in canopy surface elevation values in gridded DSMs that are created from first-surface airborne lidar returns.

Breakline and slope values extracted by the Breakline Tool are used in the calculation of a unique ruggedness parameter on a cell-by-cell basis called the BRI. The BRI algorithm also incorporates a measure of neighborhood elevation variance and is a dimensionless quantity. BRI values can be mapped as classes of terrain ruggedness over extended areas.

When elevation models are generated from airborne lidar scanner data, multiple returns can allow for bare-earth models that approximate the

ground surface underneath vegetation as well as man-made structures. Model differencing combined with careful thresholding of the difference model can reveal these features.

An off-road mobility modeling exercise was performed for the Montana DEM data using a least-cost route-finding algorithm in ArcGIS. Along with the DEM, breakline and canopy overlay data were input into the Arc environment as obstacles. Other feature data, including buildings, watercourses, and roads, were created in Arc to add realism to the model. Slope information was generated, classed into steepness bins, and weighted accordingly. Routes were calculated with and without the breakline overlay data while holding other features constant. Results showed a significant difference in calculated least-cost routes due to avoidance of micro-terrain features as obstacles.

Terrain feature extraction and route-finding algorithms are informed by the additional dimension gained through elevation modeling. The numerical methods described in this report are effective tools for geospatial analysis and mobility modeling and can enhance military planning and search-and-rescue or other emergency operations.

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Acronyms and Abbreviations

Acronym	Meaning
BRI	Breakline Ruggedness Index
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
ENVI	Environment for Visualizing Images
ERDC	Engineer Research and Development Center
ESRI	Environmental Systems Research Institute
ETP	Enhanced Terrain Processing
GIS	Geographic Information System
GPS	Geospatial Positioning System
GRL	Geospatial Research Laboratory
GUI	Graphical User Interface
IDL	Interactive Data Language
LiDAR	Light Detection and Ranging
TGIC	Tactical Geospatial Information Capabilities
TIFF	Tagged Image File Format
TIN	Triangular Irregular Network
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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14. ABSTRACT Elevation models derived from high-resolution airborne lidar scanners provide an added dimension for identification and extraction of micro-terrain features characterized by topographic discontinuities or breaklines. Gridded digital surface models created from first-return lidar pulses are often combined with lidar-derived bare-earth models to extract vegetation features by model differencing. However, vegetative canopy can also be extracted from the digital surface model alone through breakline analysis by taking advantage of the fine-scale changes in slope that are detectable in high-resolution elevation models of canopy. The identification and mapping of canopy cover and micro-terrain features in areas of sparse vegetation is demonstrated with an elevation model for a region of western Montana, using algorithms for breaklines, elevation differencing, slope, terrain ruggedness, and breakline gradient direction. These algorithms were created at the U.S. Army Engineer Research Center – Geospatial Research Laboratory (ERDC-GRL) and can be accessed through an in-house tool constructed in the ENVI/IDL environment. After breakline processing, products from these algorithms are brought into a Geographic Information System as analytical layers and applied to a mobility routing model, demonstrating the effect of breaklines as obstacles in the calculation of optimal, off-road routes. Elevation model breakline analysis can serve as significant added value to micro-terrain feature and canopy mapping, obstacle identification, and route planning.					
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