ANNOTATED BIBLIOGRAPHY

FILTERING

Axelsson, P. 1999. Processing of laser scanner data – algorithms and applications. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54:138-147.

Presents methods and algorithms for filtering laser scanner data based on elevation values. Classification is based on user defined slope thresholds; Minimum Description Length criterion. Recommends incorporating number of returns and reflectance values to improve filter performance.

Axelsson, P. 2000. DEM generation from laser scanner data using adaptive TIN models. *International Archives of Photogrammetry and Remote Sensing*, Vol. 35, Part B4/1:236-241.

Introduces a filtering algorithm based on densifying a Triangular Irregualr Network (TIN).

Bretar, F., C. Chesnier, M. Roux, and M. Pierrot-Desilligny. 2004. Terrain modeling and airborne laser data classification using multiple pass filtering. In *Proceedings of the 20th ISPRS Congress, International Archives of Photogrammetry and Remote Sensing*, Vol. 35, PartB:314-319.

Presents an approach based on a multiple pass classification process on a regular grid. The classification divides laser points in three main classes: ground, low non-ground, and non-ground. The initial estimation is the input for a deformable model algorithm.

Chen, Q., P. Gong, D.D. Baldcchi, and G. Xie. 2007. Filtering airborne laser scanning data with morphological methods. *Photogrammetric Engineering & Remote Sensing,* 73(2):175-185.

Present a progressive morphological filter adaptive to local slope.

Evans, J.S and A.T. Hudak. 2007. A multiscale curvature algorithm for classifying discrete return LiDAR in forested environments. *IEEE Transactions on Geoscience and Remote Sensing*, 45(4):1029-1038.

Present an automated method to classify LiDAR points as ground or non-ground using an iterative multi-scale algorithm. The method was applied to data representing a heavily forested area with complex terrain.

Haugerud, R.A. and D.J. Harding. 2001. Some algorithms for virtual deforestation (VDF) of lidar topographic survey data. *International Archives of Photogrammetry and Remote Sensing*, Vol. 34, Part3/W4:211-217.

The authors investigate a despike algorithm that classifies return as ground and non-ground on the basis of the geometry of the surface in the neighborhood of each return. The laser-return is represented as TIN constructed from discrete returns. The despike algorithm can work with first, last, or multiple returns; this paper used only last return. Breaklines can be included in the surface model.

Kraus, K. and N. Pfeifer. 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 53:193-203.

The authors introduce a filtering and interpolation method to classify lidar data points into terrain and off-terrain points. The algorithm is based on linear prediction.

Kraus, K. and N. Pfeifer. 2001. Advanced DTM generation from lidar data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 34, Part3/W4:23-30.

The authors present modification to a previously developed algorithm. In addition, methods are described to derive 3D breaklines from the lidar point cloud.

Liu, X. 2008. Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography*, 32(1):31-49.

A review LiDAR filtering methods, interpolation, and issues around resolution and DEM generation.

Liu, X. 2008. Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography*, 32(1):31-49.

A review LiDAR filtering methods, interpolation, and issues around resolution and DEM generation.

Meng, X., N. Currit. And K. Zhao. 2010. Ground filtering algorithms for airborne LiDAR data: a review of critical issues. *Remote Sensing*, 2:833-860.

A review LiDAR filtering methods and discussion of critical issues for the development and application of LiDAR ground filtering algorithms.

Roggero, M. 2001. Airborne laser scanning: clustering in raw data. *International Archives of Photogrammetry and Remote Sensing*, Vol. 34, Part3/W4:227-232.

Describes an algorithm to identify and then classify LiDAR points as ground points. A ground surface is approximated using local regression criterion. LiDAR points are classified as ground on the basis of vertical distance from the approximated surface meeting threshold criterion.

Silvan-Cardenas, J.L. and L. Wang. 2006. A multi-resolution approach for filtering LiDAR altimetry data. *ISPRS Journal of Photogrammetry & Remote Sensing*, 61(1):11-11.

A model-based approach is described in which multi-scale gradient of the surface is computed and used to adaptively erode gridded LiDAR data with the multi-scale Hermite transform (MHT).

Sithole, G. 2001. Filtering of laser altimetry data using a slope adaptive filter. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 34, Part3/W4:203-210.

Describes modifications to an existing slope-based filtering algorithm to overcome limitations on slope thresholds.

Sithole, G. and G. Vossleman. 2003. Comparison of filter algorithms. *International Archives of Photogrammetry and Remote Sensing*, Vol. 34, Part3/W13:71-78.

A review of LiDAR filtering algorithms.

Sithole G. and G. Vosselman. 2004. Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59:85-101.

A review of LiDAR filtering algorithms.

Sithole G. and G. Vosselman. 2005. Filtering of airborne laser scanner data based on segmented point clouds. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 36, Part3/W19:66-71.

The paper presents an approach to filtering point clouds using scan line segmentation with multiple orientations. The segment-based classification preserves discontinuities in the bare Earth surface but the detection of vegetation in sloped terrain is problematic.

Wack, R. and A. Wimmer. 2001. Digital terrain models from airborne laser scanner data – a grid based approach. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 34 Part3B:293-296.

Presents a filtering approach based on the rasterization of data points. Th algorithm consist of a hierarchical approach combined with a weighting function. The weighting function considers terrain shape in conjunction with point distribution within a raster element

Vosselman, G. 2000. Slope based filtering of laser altimetry data. *International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences*, Vol. 33 Part B3/2, 935-942.

Presents a filtering method based on height differences. Acceptable height difference between two points is defined as a function of the distance between the points.

Zaksek, K. and N. Pfeifer. 2006. An improved morphological filter for selecting relief points from a LiDAR point cloud in steep area with dense vegetation. *IEEE Transactions on Geoscience and Remote Sensing*, 41(4):872-882.

A morphological filtering approach is presented that uses the first return of a LiDAR pulse as a factor in selecting ground points. The assumption is that geomorphology can be predicted from vegetation. The elevation difference between approximated surface of the first and last returns is used as a threshold.

Zhang, K., S. Chen, D. Whitman, M.Shyu, J. Yan and C. Zhang. 2003. A progressive morphological filter for removing nonground measurements from airborne LIDAR data. *IEEE Transactions on Geoscience and Remote Sensing*, 41(4):872-882.

The authors developed a progressive morphological filter that uses variable opening operations and elevation difference thresholds.

Zhang, K. and D. Whitman. 2005. Comparison of three algorithms for filtering airborne LIDAR data. *Photogrammetric Engineering & Remote Sensing*, 71(3):313-324.

The authors compare the elevation threshold with expanding window (ETEW), maximum local slope (MLS), and progressive morphological (PM) filters for removing non-ground points from airborne laser scanning data.

FILTER ENHANCEMENT

Bretar, F. and N. Chehata. 2007. Digital terrain model on vegetated areas: joint use of airborne lidar data and optical images. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 36, Part3(W49A):19-24.

The authors combine lidar intensity data and optical images to generate a Hybrid Normalized Difference Vegetation Index (HNDVI). The vegetation mask is used in adapting the window size of a morphological-based filtering algorithm.

Goepfert, J, U. Soergel, and A. Brzank. 2008. Integration of intensity information and echo distribution in the filtering process of LIDAR data in vegetated areas. In *Proceedings of Silvilaser 2008: 8th International Conference on LiDAR Applications in Forest Assessment and Inventory*, September 17-19, Edinburgh, UK.

Introduces an algorithm that incorporates intensity information and distribution of multiple echoes into an adaptive weight and iterative filtering process.

Jutzi, B. and H. Gross. 2009. Normalization of lidar intensity data based on range and surface incidence angle. *International Archives of Photogrammetry and Remote Sensing*, Vol. 33, Part3/W8:213-218.

Demonstrates that intensity values for the same material/surface yields different values and normalization improves results where intensity is used for segmentation or classification.

Liu, Y, Z. Li, R. Hayward, R. Walker, and H. Jin. 2009. Classification of airborne LIDAR intensity data using statistical analysis and Hough Transform with application to power line corridors. In *Proceedings of Digital Image Computing: Techniques and Applications, 2009 (DICTA '09)*, December 1-3, Melbourne, Australia.

The authors classified ground and non-ground points in a LIDAR point cloud with statistical measures skewness and kurtosis of the intensity data values.

Mandlburger, G. and C. Briese. 2007. Using airborne laser scanning for improved hydraulic models. In *International Congress on Modeling and Simulation (MODSIM07)*, December, Christchurch, New Zealand.

The authors use the full waveform of backscattered signal to assign a-priori point weights based on echo width.

Nardinocchi, C. G. Forlani, and P. Zingaretti. 2003. Classification and filtering of laser data. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 34, Part3/W13:, Dresden, Germany.

The authors use image segmentation to classify LiDAR data as terrain, buildings, and vegetation using height differences only. The classification is refined (e.g., classify noise and data gaps) and a final local analysis is preformed on each grid cell to lable raw data points inferred by the classification.

Raber, G.T., J. R. Jensen, S. R. Schill, and K. Schuckman. 2002. Creation of digital terrain models using an adaptive lidar vegetation point removal process. *Photogrammetric Engineering & Remote Sensing*, 68(12):1307-1315.

An existing vegetation point removal algorithm is used, adjusting the parameters based on presence of vegetation land cover types. Vegetation is classified from the lidar dataset.

Schickler, W. and A. Thorpe. 2001. Surface estimation based on lidar. In *Proceedings of the American Society of Photogrammetry & Remote Sensing Annual Conference*, April 23-27, St. Louis, Missouri, USA.

An approach to estimate bald-earth surfaces from LIDAR data by including independently measured breaklines and surface categories derived from statistics on individual LIDAR points, curvature, and slope.

Wang, C. and N. F. Glenn. 2009. Integrating LiDAR intensity and elevation data for terrain characterization in a forested area. *IEEE Geoscience and Remote Sensing Letters*, 6(3):463-466.

The authors present a new methodology to identify ground points based on vegetation classification derived from LiDAR intensity and Gaussian distribution of LiDAR elevations.

GENERALIZATION

Berenbrock, C. 2006. A genetic algorithm to reduce stream channel cross section data. *Journal of the American Water Resources Association*, 42(2):387-394.

Describes application of genetic algorithm to reduce stream channel cross section data for use in 1-D hydraulic flow and sediment transport models. Compares the process to the "standard procedure" used by Barton et al. (2004).

Berenbrock, C. 2010. Decimation of river geometry datasets using genetic algorithms for use in surface-water models. In *Proceedings of the 2nd Joint Federal Interagency Conference (9th Federal Interagency Sedimentation Conference and 4th Federal Interagency Hydrologic Modeling Conference)*, June 29 – July 1, Las Vegas, Nevada, USA

Describes application of genetic algorithm to the decimation of LiDAR and bathymetric data. Compares the process to theautomatic point selection procedure developed by Chen and Guevara (1987) and LATTICETIN, an implementation ArcInfo to generate a triangulated irregular network (TIN) from a regularized grid (DEM).

Kersting, J and A.P.B Kersting. 2005. LiDAR points filtering using ArcGIS' 3D and Spatial Analyst. In *Proceedings of the 25th ESRI User Conference, July 25 -27, San Diego, California, USA*

Present an algorithm aimed at reducing the number of points in a TIN. The algorithm is implemented in C+ using ArcObjects and ArcGIS extenstions 3D and Spatial Analyst.

Mandlburger, G., C. Hauer, H. Habersack, and N. Pfiefer. 2009. Optimisation of LiDAR derived terrain models for river flow modelling. *Hydrology and Earth System Sciences*, 13(8):1453-1466.

A TIN refinement approach to reduce the number of data points in a surface model is presented that uses a filtered DTM as opposed to the original point cloud. Starting from a few known terrain points new points are added based on certain distances from the triangulated surface.

INTERPOLATION

Agarwal, P.K., L. Arge, and A. Danner. 2006. From Point Cloud to Grid DEM: A Scalable Approach. In: *Proceedings of the 12th International Symposium on Spatial Data Handling*, 825-844.

Presents a scalable algorithm for a grid digital elevation model from datasets acquired by LiDAR.

Cebecauer, T., J. Hofierka, and M. Suri. 2002. Processing digital terrain models by regularized spline with tension: tuning interpolation parameters for different input datasets. In *Proceedings of the Open Sources GIS – GRASS users conference*, September 11-13, Trento, Italy.

The authors identified common problems in applying regularized spline with tension smoothing (RST) interpolation method on a variety of terrains.

Gallay, M., C. Lloyd, and J.McKinley. 2012. Optimal interpolation of airborne laser scanner data for fine-scale DEM validation purposes. In *Proceedings of Symposium GIS Ostrava 2012 – Surface models for geosciences*, January 23-25, Ostrava, Czech Republic.

The authors tested inverse weighting (IDW) and regularized spline with tension smoothing (RST).

Guo, Q, W. Li, H. Yu, and O. Alvarez. 2010. Effects of topographic variability and lidar sampling density on several DEM interpolation methods. *Photogrammetric Engineering & Remote Sensing*, 76(6):1-12.

The authors quantify the effects of topography and data density on DEM accuracy derived from natural neighbor (NN), inverse distance weighted (IDW), triangulated irregular network (TIN), spline, ordinary kriging (OK), and universal kriging (UK).

Mitasova, H., L. Mitas, and R.S. Harmon. 2005. Simultaneous spline approximation and topographic analysis for lidar elevation data in open source GIS. *IEEE Geoscience and Remote Sensing Letters*, 2(4):375-379.

The authors investigate the application of the spline approximation to smooth surface and reduce noise in lidar-based digital elevation models. Topographic parameters (slope and curvature) are simultaneously computed to extract dune crests.

BREAKLINE DETECTION

Berkhahn, V., K. Kaapke, S. Rath, and E .Pasche. 2005. A hydrid meshing scheme based on terrain feature identification. In *Proceedings of 14th International Meshing Roundtable*, September 11-14, San Diego, California, USA.

Presents an approach of generating b-spline surfaces as an analysis grid to identify breaklines and introduces the idea to use an interpolation scheme to generate smooth breaklines.

Berkhahn, V. and S. Mai. 2006. Detection of terrain features embedded in a pre-processor for topographic data. In *Proceedings of 7th International Conference on Hydroinformatics*, July 17, Nice, France.

Presents case study of terrain feature detection based on slope analysis to identify breaklines. Slope analysis is performed on a regular grid digital terrain model (DTM) to generate breakpoints. An interpolation scheme is applied to generate breakline points. The breakline points are interpolated to create breaklines.

Briese, C. G. Mandlburger, C. Ressl, and H. Brockmann. 2009. Automatic breakline determination for the generation of a DTM along the river main. *International Archives of Photogrammetry and Remote Sensing*, Vol. 34, Part 3/W8:236-241.

Presents a fully automated procedure for extracting breaklines from LIDAR data using ground return point cloud. Contract the approach to deriving breaklines from regular grids and raster-based operations previously reported semi-automated procedures (Briese 2004a, 2004b).

Rath, S. and E. Pasche. 2004. Hydrodynamic floodplain modeling based on high-resolution lidar measurements. In *Proceedings of 6th International Conference on Hydroinformatics*, 1:1-8.

The authors asses various procedures for automatic extraction of breaklines from an elevation grid.

DATA QUALITY AND ERROR ASSESSMENT

Aguilar, F.J., F. Aguera, M.A. Aguilar, and F. Carvjal. 2005. Effects of terrain morphology, sampling density, and interpolation methods on grid DEM accuracy. *Photogrammetric Engineering & Remote Sensing*, 71(7):805-816.

The paper explores the effects of terrain morphology, sampling density and interpolation methods for scattered sample data data on the accuracy of interpolated heights in grid DEMs. The objective was to identify empirical relationships between interpolation RMSE and variables such as terrain ruggedness, sampling density, and interpolation method.

Aguilar, F.J., J.P. Mills, J. Delgado, M.A. Aguilar, J.G. Negreiros, and J.L. Perez. 2010. Modeling vertical error in LiDAR-derived digital elevation models. *ISPRS Journal of Photogrammetric and Remote Sensing*, 65:103-110.

The paper present a methodology for modeling error in LiDAR-derived DEMs. The objective was to develop an empirical basis for the selection of point density in order to optimize survey effort.

Bowen Z. and R.G. Waltermire. 2002. Evaluation of light detection and ranging (LIDAR) for measuring river corridor topography. *Journal of the American Water Resource Association*, 38(1):33-41.

Evaluates the accuracy of a LiDAR dataset in representing topography along a stream corridor relative to various terrain components and cover types.

Liu, X., Z. Zhang, J. Peterson, and C. Chandra. 2007. The effect of LiDAR data density on DEM accuracy. In *Proceedings of the International Congress on Modelling and Simulation (MODSIM07)*, December, Christchurch, New Zealand.

The study explored effects of LiDAR point density on DEM accuracy.

Raber, G.T., J.R. Jensen, M. E. Hodgson, J.A. Tullis, B.A. Davis, and J. Brglund. 2007. Impact of lidar nominal post-spacing on DEM accuracy and flood zone delineation. *Photogrammetric Engineering & Remote Sensing*, 73(7):793-804.

The study explored effects of LiDAR point density on DEM accuracy relative to HEC-RAS modeling results.

Software and Tools

Brovelli, M.A. and S. Lucca. 2011. Filtering LIDAR with GRASS: overview of the method and comparisons with Terrascan. *Italian Journal of Remote Sensing*, 43(2):93-105.

Describes the LiDAR point cloud filtering algorithm implemented in GRASS, draws comparison with algorithms developed by Axelsson (1999) and implemented in Terrascan, a proprietary software.

Chen, Q. 2007. Airborne lidar data processing and information extraction. *Photogrammetric Engineering & Remote Sensing*, 73(2):109-112.

Describes the development and capabilities of Tiffs: Toolbox for LiDAR Data Filtering and Forest Studies, a software for processing LiDAR data to extract bare earth and forest structure information.

Cvijentinovic, Z., D. Mihajlovic, M. Vojinovic, and M. Mitrovic. 2011. Terrain surface modeling using triangular spline patches. In *Proceedings of the International Conference and XXIV Meeting of Serbian Surveyors,* June 24-26, Kladovo-Djerdap upon Danube, Serbia.

The authors describe TIN processing using Surfling software.

Isenburg, M., Y. Liu, J. Shewchuk, J. Snoeyink, and T. Thirion. 2011. Generating raster DEM from masspoints via TIN streaming. In *Proceedings of 4th International Conference on Geographic Information Science*, September, 20-23, 2006, Munster, Germany.

Describes tools for processing mass points into digital elevation models.

Kim, H.S., J.R. Arrowsmith, C. J. Crosby, E. Jaeger-Frank, V. Nandigam, A. Memon, J. Conner, S.B. Baden, and C. Baru. 2006. An efficient implementation of local binning algorithm for digital elevation model generation of LiDAR/ALSM datasets. *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract g53C-0921, 2006.

Describes an algorthim that uses elevation information from points within a user-specified search radius and outputs a grid with minimum, maximum, mean, and inverse distance weighted mean of local points, and number of points within the search radius. The DEM products are complementary to outputs of the regularized spline with tension interpolation algorithm.

Korzeniowska, K. and M. Lacka. 2011. Generating DEM from lidar data – comparison of available software tools. *Archives of Photogrammetry, Cartography and Remote Sensing*, 22:271-284.

The authors assess algorithms implemented in various software tools used to classify LIDAR data. Software assessed includes: Terrasolid (TerraScan), TLID, SAGA GIS,Canopy Fuel Estimator (CFE).

Liu, H., L. Wang, D.J. Sherman, Q. Wu, and H. Su. 2011. Algorithmic foundation and software tools for extracting shoreline features from remote sensing imagery and LiDAR data. *Journal of Geographic Information System*, 3:99-199.

The authors describe algorithms and software routines for extracting shoreline features from imagery and LiDAR data. The algorithms are implemented using C++ programming language and available functions in ArcGIS.

McGaughey, R.J. 2012. FUSION/LDV: Software for LiDAR Data Analysis and Visualization. *United States Department of Agriculture, Forest Service, Pacific Northwest Research Station*, 166 pages.

FUSION user manual.

Mitchell, J.J., N.F. Glenn, T.T. Sankey, D.R. Derryberry, M.O. Anderson, and R.C. Hruska. 2011. Small-footprint lidar estimations of sagebrush canopy characteristics. *Photogrammetric Engineering & Remote Sensing*, 77(5):1-10.

The authors describe the application of BCAL Lidar Tools extension.

NOAA. 2009. Refinement of Topographic Lidar to Create a Bare Earth Surface. *National Oceanic and Atmospheric Administration, Coastal Service Center*, pp.13.

The software program ALDPAT is described. ALDPAT implements a variety of automated filtering methods (Elevation Threshold with Expand Filter Window (ETEW), Progressive Morphology (PM) Filter, 2D Morphological filters, Maximum Loacl Slope (MLS), Iterative Polynomial Fitting (IPF), and Adaptive TIN (ATIN)) along with manual point extraction tools.

Romano, M.E. 2004. Innovation in lidar processing technology. *Photogrammetric Engineering & Remote Sensing*, 70(11):12011206.

Describes the development and capabilities of Merrick Advanced Remote Sensing (MARS) software application.

Soininen, A. 2011. TerraScan User's Guide.

TerraSolid's TerraScan user guide.

Tinkham, W. T., H. Huang, A.M.S. Smith, R. Shrestha, J. J. Falkowski, A. T. Hudak, T.E. Link, N. F. Glenn, and D. G. Marks. 2011. Generating raster DEM from masspoints via TIN streaming. *Remote Sensing*, 3(3):638-649.

Investigates and compares the accuracy of the Boise Center Aerospace Laboratory LiDAR (BCAL) algorithms and the Multiscale Curvature Classification LiDAE algorithm developed at the Moscow Forestry Sciences Laboratory of the USFS Rocky Mountain Research Station.

TU Vienna, IPF, and INPHO. 2010. SCOP ++ Manual. *Vienna University of Technology - Institute of Photogrammetry and Remote Sensing and INPHO GmbH*, 377 pages.

SCOP ++ user manual.

Zhang, K. and Z. Cui. 2007. Airborne LiDAR Data Processing and Analysis Tools, ALDPAT 1.0. *National Center for Airborne Laser Mapping, International Hurricane Research Center, Department of Envrionmental Studies, Florida International University*, 81 pages.

ALDPAT user manual.