LIDARSCAPES AND OBIA

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ABSTRACT

Object based image analysis (OBIA) may has evolved as a new paradigm in remote sensing and image processing. In this paper, we study some fundamental issues arising from the creation, handling, storage, and use of geographic information in an OBIA environment with a particular focus on LiDAR data. The research starts with a critical analysis of the multiplicity of scales in regard to 'across-scale metrics'. It builds on the achievements a) from the 'OBIA community' and b) on the state of the art in GIS regarding discrete objects and fields. The paper investigates how objects are derived in various existing approaches and discusses the consequences of the object delineation methodologies and generalization effects.

KEYWORDS: LiDARscapes, Object Based Image Analysis, OBIA, object extraction, point cloud modeling.

INTRODUCTION

Airborne LiDAR is probably the most significant technology introduced in mainstream topographic mapping in the last decade. It provides a direct method for 3D data collection and is highly accurate (Shan and Toth, 2008). LiDAR data became very popular and in the past few years, extremely available product. We can find a whole variety of point clouds generated by LiDAR being used on a daily basis around the world, from ground surface estimation (Emqvist, 2002), Digital Terrain Model creation (Raber et al., 2002) to modern automatic building extraction (Sohn and Dowman, 2007).

A plethora of approaches exist which aim to delineate and/or classify objects from LiDAR data. In this study we focus on airborne LiDAR although there is no significant conceptual difference to the analysis of terrestrial LiDAR data.

Many studies concentrated on the delineation of buildings (Wang and Schenk, 2000; Rottensteiner and Jansa, 2002; Alharthy and Bethel, 2002; Miliaresis and Kokkas, 2007; Sohn and Dowman, 2007; Vu et al., 2009; Rottensteiner and Briese, 2001; Wang, 1998; Vosselman and Dijkman, 2001; Brenner, 2005; Haala and Brenner, 1999; Hofmann et al., 2002; Matikainen et al., 2003) which involves less ambivalent class descriptions or ontologies as compared to natural environments. Lang and Blaschke (2003) pointed out that the recognition of natural features is more difficult than the recognition of anthropogenic features such as houses or roads. In either case, the studies are guided by the quest for elements with some exception e.g. when exclusively deriving Digital Elevation Models. But even in the latter case buildings and vegetation need to be removed with or without intermediate object generation steps.

LiDAR data handling and attempts to derive information are overwhelmingly 'technical'. We found relatively few conceptual, methodological or theoretical foundations which are part of a generic approach which concerns ontology, semantics, geomatics/geographic information science principles and informatics on account of its simultaneous consideration of multiple scales.

Our long-term objective is to put forward a way of modelling "multi-scale objects", which will help create geo-spatial databases from which it should be possible to:

– provide a vertical and horizontal perspective of the phenomena;
– produce different inventories 'on demand';
– express the change of state (and thus the inherent process);
– allow to parameterize the specific nature of an object, i.e. its social, temporal and spatial context;
– avoid redundant information, in order to facilitate data analysis and management;
– represent a single reality in a variety of ways (depending on the accuracy and quality of information available).

The research starts with a critical analysis of the multiplicity of scales (Hay et al., 2005) in regard to 'across-scale metrics'. It builds on the achievements a) from the 'OBIA community' (see Blaschke, 2010 for an overview) and b) on the state of the art in GIS regarding discrete objects and fields (Kemp, 1997; Cova and Goodchild, 2002). LiDAR data sets are systematically delineated in an OBIA framework for testing horizontal and vertical spatial resolutions and accuracies and the consequences of these accuracies for the generation of DEMs and DSMs from the original data and consequently for volume estimations in respect to the delineation of objects. A particular research question is how to make surface properties explicit. Since some forestry and ecological applications require an explicit consideration of discontinuities in the surface we aim to understand the consequences of the object delineation methodologies and generalization effects.

METHODS

Object derivation from LiDAR data

Airborne LiDAR Scanning (ALS) has been widely used to acquire topographic information (Kraus and Pfeifer, 1998; Lohmann et al., 2000; Meng et al., 2009; Vosselman, 2000; Vosselman and Maas, 2010), and it is utilized to extract features such as buildings (Sohn and Dowman, 2007) and vegetation.

During the first decade of this Millennium many approaches focused on the filtering algorithms (Axelsson, 2000; Brovelli et al., 2002; Elmqvist, 2002; Kraus and Pfeifer, 1998; Meng et al., 2009; Raber et al., 2002; Roggero, 2001; Shan and Sampath, 2005; Silván-Cárdenas and Wang, 2006; Thuy and Tokunaga, 2004; Vosselman, 2000; Wack and Wimmer, 2002; Zhang et al., 2003). Several comparisons between algorithms were conducted (Sithole and Vosselman, 2004; Zhang and Whitman, 2005; http://www.itc.nl/isprswgIII-3/filtertest/index.html). In addition, the filtering algorithms can be classified into several groups (Sithole and Vosselman, 2004). These algorithms filter the raw ALS point cloud or operate on grid elevation generated by interpolations of points (Meng et al., 2009; Sithole and Vosselman, 2004), which can be considered as DSM (Lloyd and Atkinson, 2002). Most existing algorithms work on the assumption that the natural ground changes gradually and, as a result, that a) the height difference of neighbouring ALS points on ground is small, and b) the probability that a point accepted as a non-ground point increases with the height difference increase between two neighbour points.

In the area of building extraction and reconstruction from LiDAR points we can find a whole range of methods and approaches. Almost all of the methods use derivations of DEMs and DTMs as a first step to the building extraction approach. Miliaresis and Kokkas (2007) used LiDAR generated DEM and then geomophometric region growing segmentation combined with median filtering to identify seed cells. In this approach labelling components are connected: size filtering and object labelling, object parametric representation on the basis of slope and elevation attributes and classification. All of these elements are used to delineate building class within the study area. The authors admit that this approach is not fully automated and that it requires a certain level of user interaction for some crucial parameters which differ based on situation. Sohn and Dowman (2007) used data fusion of high-resolution satellite imagery and LiDAR data to automatically extract buildings. First they differentiate on-terrain and off-terrain points. For this they use recursive terrain fragmentation (RTF) LiDAR filter. Next, they re-classify off-terrain points into more detailed feature classes (low-rise and high-rise) by means of comparing height attributes of off-terrain points with pre-specified height threshold. A 'high-rise feature class' presents a mixture of trees and building objects. To be able to delineate buildings trees need to be excluded. The authors used IKONOS multi-spectral information to generate normalized difference vegetation index (NDVI). A High-rise feature class was then back projected into IKONOS image space, and vegetation and building labels were generated. Based on this intermediate step vegetated high-rise points were removed. Generated building blobs are then bounded with rectangle polygons and fed into the rest of the building extraction process. The rest of the process includes data and model-driven line cue generation (data-driven from IKONOS imagery and model-driven from LiDAR data), creation of Building Unit Shape (BUS) representations and, finally, a Binary Space Partitioning (BSP) algorithm from which a tree from which a BUS adjacent graph with nodes representing a BUS and arc representing connectivity between neighbouring BUSes is generated. Only BUSes which belong to building structures are merged and as a result, building outlines are reconstructed. Vu et al. (2009) proposed a multi-scale solution for building extraction from LiDAR and image data. Their approach is based on mathematical morphology using nonlinear scale-space (it performs image partition into isolevel sets at each scale and links them with the closest one in the next scale) employing area morphology to extract building features from remotely sensed elevation and spectral data. They extracted complex structures as a multi-part objects in which each part is represented on a scale depending on its size. Final building footprints are represented by the boundary of the largest part. Obtained spectral data, as in the previous mentioned case, are used to remove vegetation and possibly classify the building roof materials. The authors classify their approach as a fully automated one which can make use of both spectral and elevation data working well with any nDSM and spectral data source. Rottensteiner and Briese (2001) proposed a new method for building extraction in urban areas from high-resolution LiDAR data. In first step they interpolate a DSM and a DTM from the original data at an appropriate resolution. They use their own method to generate DTM and classify original points into terrain vs. off-terrain points (by means of using user-specific values to perform thresholding the discrepancies to the computed surface) by means of robust estimation. From this instance onward, models created are used instead of original data points. By subtracting the DTM from DSM and applying thresholds to the height differences, initial building masks are created which still contain vegetation and other objects. To eliminate these areas, local variations of the DSM normal vectors and binary morphological operators are used. Individual building regions are found by a connected component analysis. Wang (1998) developed an algorithm which recognizes simple shape buildings (I, T and L shapes). His approach uses shape information to separate buildings from all other objects based on an assumption that most buildings have simple and regular shapes and other objects do not. The shape information is generated from edges detected on the elevation image applying a Laplacian of Gaussian (LoG) edge detector. Then, a classification is performed on these edges by comparing them to I, T or L shapes. Finally, potential building shapes are joined with other information sources to definitely classify the shape. Alharthy and Bethel (2002) developed a fast low cost algorithm for extraction of 3D features in urban areas from LiDAR data only. They used a two steps approach, use of ''first minus last'' return analysis and utilizing the local statistical interpretation. ''First minus last'' method is used to determine if the object is a tree or a solid construction based on calculated height. Local statistical analysis method is used to determine surface smoothness from a root mean square error calculated for each window square and used as an attribute. If the RMSE is high then it indicates an irregular surface that can be interpreted as a tree or a rough surface. Since building roofs are smooth surfaces this method was used to remove noise and some non-building objects. DEM was extracted from filtered data and the above ground objects were obtained by subtracting DEM from filtered DSM. These non-terrain objects were thresholded to remove remaining non-penetrable objects like cars etc. In the final step primitive raster objects were used to derive vector footprint delineation and some geometric constraints which are then able to create the building polygons.

If we want to take a look at different approaches in regard to object of interest, then we should also mention the work of Weinacker et al. (2004) who tried to develop filtering, segmentation and modelling modules for LiDAR and multispectral data for automatic forest inventory system. They started with raw laser data as input and ended up with derived tree parameters for each single tree. Process included DTM/DSM filtering based on active contour theory. Filtering algorithm starts with the creation of a raster area, using pixel sizes in relation to the density of the given raw data points. Based on these constructed raster surfaces DTM/DSM filtering is done. Next step was tree tops detection from smoothed DSM by means of local maximum filtering. Starting from local maxima, a pouring algorithm is detecting the approximate tree border. Last step included tree species classification and modeling based on two different approaches: statistical one based on linear stepwise discriminant analysis and the second one based on form fitting algorithm, where an extended super quadric (ESQ) is used to fit trees either based on raw laser data or based on the DSM. Approach can be used as a fundament for a semi-automatic inventory system based both on LiDAR and multi-spectral data. Hu et al. (2004) tried to develop automatic road extraction from dense urban area by integrating processing of high resolution imagery and LiDAR data. Their method firstly detects the primitives or clues of the roads and the contextual targets both from the colour image and LiDAR data by segmentation and image analysis. Intensity and height data are used and segmented to create road areas and open areas. Iterative Hough transform and Morphologic operation is used to generate candidate objects. From optical imagery by means of pixel based classification grass land, tree areas and vehicles are detected and this data is used along with generated candidate road and parking stripes to produce verified road and parking stripes. Both of them went through topology detection and final road network is detected.

All of the approaches discussed aim to extract certain types of objects from either LiDAR data only or from LiDAR data merged with other sources of information. They may be useful in specific use-case scenarios but are not necessarily applicable beyond these scenarios (e.g. using building extraction methods for tree delineation and vice versa). It is reasonable to conclude that still a lot of work has to be done: not necessarily in terms of more algorithms, but in regard to a theoretical foundation allowing for generic adaptations to various scenarios. A general working model for 3D object extraction is needed which can be implemented in various use cases. None of the before mentioned research cases have shown such broad usability and transferability.

OBIA/GEOBIA

OBIA (often referred as GEOBIA for geographic object based image analysis) claims to overcome problems of traditional pixel-based techniques of high spatial resolution image data, by firstly defining segments rather than pixels to classify, and allowing spectral reflectance variability to be used as an attribute for discriminating features in the segmentation approach (Blaschke and Strobl, 2001; Blaschke, 2010; Johansen et al., 2010). OBIA allows inclusion of additional information to guide the classification and modelling processes. This can be external information – usually from GIS data sets – or information intrinsically evident in the image and its constituents but not necessarily achievable at the level of a single pixel. This can be as simple as the use of: object average reflectance; object reflectance standard deviation; object maximum, minimum and median reflectance values; area and shape of objects; texture of objects; location of objects in relation to other objects. It can be a complex combination of individual parameters and a 'hierarchical' view: relation of objects to 'super-objects' or the image scene characteristics.

It is repeatedly stated that image segmentation is not new but has gained new momentum when incorporated in object based image (Blaschke and Strobl, 2001; Blaschke, 2010). When performing image segmentation a complete set of image objects is created. This is usually done for one specific object scale but it is increasingly recognized that OBIA accommodates multi-scale data handling (Blaschke, 2010):

Based on our literature investigation and on preliminary tests with commercial software packages (eCognition, ENVI) and open source solutions (Interimage) as well as investigations in a GIS environment (ArcGIS) we are currently systematically testing two strategies and will report at the ASPRS conference on the statistics. Both strategies aim for multi-scale image segmentation while deriving hierarchical and interlinked set of objects and were ultimately developed as step-wise methods using initial segmentation approach of Baatz and Schaepe(2000). The strategies are preliminarily illustrated in Figure 1 and Figure 2, respectively:

Bottom-up approach to 3D object extraction from LiDAR points and

Top-down approach to 3D object extraction from LiDAR points.

Either way – bottom-up or top-down – the user can control the process by defining a target scale parameter. This target scale parameter and the way user often address it is sometimes criticized. The recent development of tools (Drăguţ et al., 2010) which support the definition of such scales through statistical analysis is major step toward transparent rules.

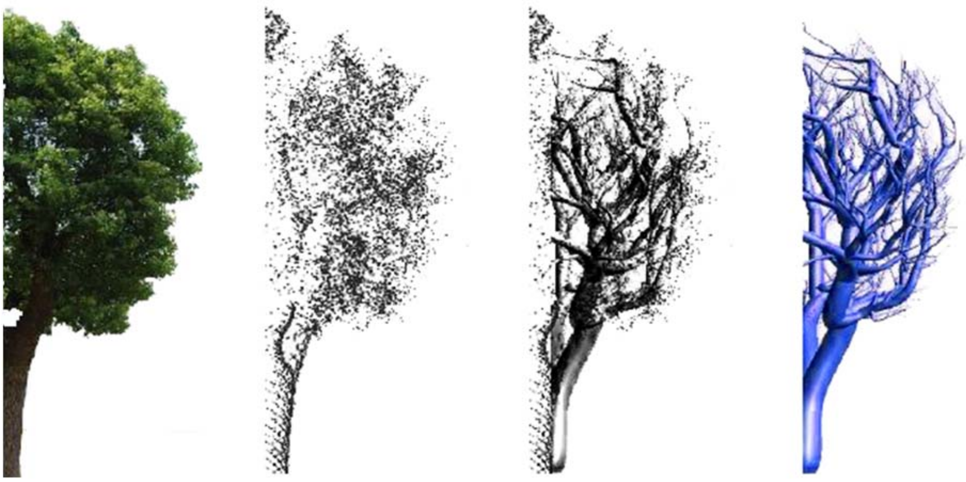

Figure 1. Bottom-up approach to 3D object extraction from a LiDAR point cloud.

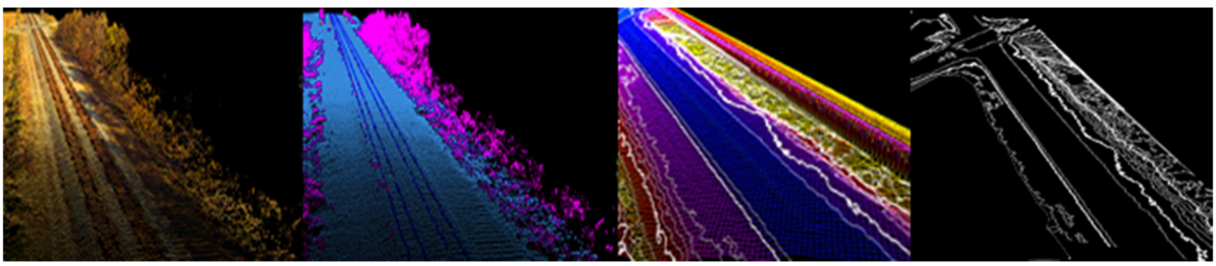

Figure 2. Top-down approach to 3D object extraction from LiDAR point cloud.

Can OBIA appropriately address the multiplicity of scales?

In (very recent) literature (Blaschke, 2010; Johansen et al., 2010) it is claimed that OBIA/GEOBIA enables a hierarchical multiple spatial scale approach when mapping, which takes advantage of characteristic nested scales of environmental features occurring across different spatial scales in all environments.

In cartography, scale refers to size on the map relative to size in the world—small-scale maps show large regions. Map scale interacts with geometry of the world and requires map generalization. In the physical sciences, such as geomorphology tackled in this research cluster, the term scale is used to indicate the size, extent, or characteristic length for physical processes (Mark, 2003). Interactions between size, shape, and function will be further explored systematically with the help of 'newer' technologies such as LiDAR or field geophysics. Using the metaphor as scale as a 'window of perception' (Marceau, 1999), cognitive aspects of scale have been highlighted (Fabrikant, 2001) and need to be incorporated in the GIScience curriculum and to the research agenda. Particular new research questions (Blaschke, 2010; Hay and Castilla, 2008; Hay and Blaschke, 2010) are focussing on multiscalar analyses and transfers (Reitsma and Bittner, 2003; Burnett and Blaschke, 2003).

CONCLUSIONS

Preliminary results demonstrate that:

OBIA-concepts (abstract models) can be applied to LiDAR point clouds to generating class hierarchies and class descriptions through an inductive analysis of object properties at a multiplicity of scales.

Recent achievements in applying OBIA to derive landforms through an integrated segmentation/ontology (Drăguţ and Eisank, 2011) could be adapted to other object categories such as trees and forest patches.

Object-centred rules were proofed to be transferable. In particular, once-created OBIA-rule-sets could be transferred to comparable data sets (images and LiDAR point clouds) with slightly changed conditions while the auto-adaptive rule sets were robust.

When screening the relevant scientific literature it may be concluded that much of the 'technical articles' are not severely based on theoretical foundations and the understanding of space. Much of the work of classic geographers and work of recent Geographic Information Science literature is not included enough and some might even have quite naturally tackled the subject in ignorance of existing theoretical work. Nevertheless, the results obtained from the sheer volume of scientific work published represents considerable progress both from the methodological point of view and from that of understanding of natural phenomena. Still, the multiplicity of scales of objects seems to be underdeveloped in geospatial literature. It thus seemed important to develop an independent approach to scale and space in order to ultimately define objects irrespectively from a first delineation.

REFERENCES

Agarwal, P., 2005. Ontological considerations in GIScience. *International Journal of Geographical Information Science,* 19:501–536.

Alharthy A., J. Bethel, 2002. Heuristic filtering and 3d feature extraction from lidar data, *ISPRS Commission III, Symposium* 2002, September 9-13, 2002.

Baatz, M. and A. Schäpe, 2000.Multiresolution segmentation: an optimization approach for high quality multi-scale image segmentation, In: Strobl, J., Blaschke, T., Griesebner, G. (Eds.), *Angewandte Geographische Informations-Verarbeitung XII*. WichmannVerlag, Karlsruhe, pp. 12–23.

Blaschke, T., 2010. Object based image analysis for remote sensing, *ISPRS International Journal of Photogrammetry and Remote Sensing,* 65(1):2-16.

Blaschke, T. and J. Strobl, 2001. What's wrong with pixels? Some recent developments interfacing remote sensing and GIS, *GIS – Zeitschrift für Geoinformationssysteme,* 14(6):12-17.

Brovelli, M.A., M. Cannata and U.M. Longoni, 2002. Managing and processing LIDAR data within GRASS, *Proceedings of the Open Source GIS-GRASS Users Conference*, Trento, Italy, 11-13 September 2002.

Burnett, C. and T. Blaschke, 2003. A multi-scale segmentation / object relationship modeling methodology for landscape analysis. *Ecological Modelling,* 168(3):233-249.

Drăguţ, L. and C. Eisank, 2011. Object representations at multiple scales from Digital Elevation Models, *Geomorphology*, 129(3-4):183-189.

Drăguţ, L., D. Tiede, S.R. Levick 2010. ESP: a tool to estimate scale parameter for multiresolution image segmentation of remotely sensed data. *International Journal of Geographical Information Science*, 24(6): 859–871.

Elmqvist, M., 2002. Ground surface estimation from airborne laser scanner data using active shape models. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences* 34 (3A):114-118.

Fabrikant, S.I. 2001. Evaluating the Usability of the Scale Metaphor for Querying Semantic Spaces, Spatial Information Theory: Foundations of Geographic Information Science, *Conference on Spatial Information Theory*, Berlin, pp. 156-171.

Fonseca, F., M. Egenhofer, P. Agouris and G. Camara, 2002. Using Ontologies for Integrated Geographic Information Systems. *Transactions in GIS* 6:231–257.

Goodchild, M.F., M. Yuan and T.J. Cova 2007. Towards a general theory of geographic representation in GIS, *International Journal of Geographical Information Science* 21(3):239–260.

Haala, N. and C. Brenner, 1999. Extraction of buildings and trees in urban environments, *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2-3), 130–137.

Hay, G.J., and G. Castilla, 2008. Geographic object-based image analysis (GEOBIA): A new name for a new discipline, In: Blaschke, T., Lang, S., Hay, G., eds. *Object Based Image Analysis*, Springer, Heidelberg, Berlin, New York, pp. 93–112.

Hay, G.J., G., Castilla, M.A. Wulder and J.R. Ruiz. 2005. An automated object-based approach for the multiscale image segmentation of forest scenes, *International Journal of Applied Earth Observation and Geoinformation*, 7:339-359.

Hay, G.J. and T. Blaschke, 2010. Foreword Special Issue: Geographic Object-Based Image Analysis (GEOBIA), *Photogrammetric Engineering and Remote Sensing,* 76(2):121-122.

Hofmann, A. Maas and H.G., A. Streilein, 2002. Knowledge-base building detection based on laser scanner data and topographic map information, *International Archives of Photogrammetry and Remote Sensing*, vol 34, part 3A, Graz, Austria, pp. 169-174.

Hu, X., V. Tao and Y. Hu, 2004, Automatic Road extraction from dense urban area by integrated processing of high resolution Imagery and LiDAR data, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XXXV(B3): 288-292.

Johansen, K., R. Bartolo and S. Phinn, 2010. SPECIAL FEATURE — Geographic Object-Based Image Analysis, *Journal of Spatial Science*, 55:1, 3-7

Kraus, K. and N. Pfeifer, 1998. Determination of terrain models in wooded areas with airborne laserscanner data. *ISPRS Journal of Photogrammetry and Remote Sensing,* 53(4):193-203.

Lang, S. and T. Blaschke, 2003. Hierarchical object representation – Comparative multi-scale mapping of anthropogenic and natural features. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. No. XXXIV-3/W8:181-186.

Lloyd, C.D. and P. M. Atkinson, 2002, Deriving DSMs from LiDAR data with kiging, *International Journal of Remote Sensing*, Vol. 23, Issue 12, 2002, pages: 2519-2524.

Lohmann, P., A. Koch and M. Schaeffer, 2000. Approaches to the filtering of laserscanner data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIII (B3):540-547.

Marceau, D., 1999. The scale issue in the social and natural sciences. *Canadian Journal of Remote Sensing,* 25(4):347–356.

Mark, D.M., 2003. Geographic Information Science: defining the field. In: Duckham, M., Goodchild, M.F., Worboys, M. (eds.), *Foundations of Geographic Information Science*. London: Taylor & Francis pp. 3–18.

Matikainen, L., J. Hyyppa and H. Hyyppa, 2003, Automatic detection of buildings from laser scanner data for map updating, *International Archives of the Photogrammetry and Remote Sensing,* vol. 34, part 3/W13, Dresden, Germany, pp. 218-224.

Meng,X., L. Wang, J.L. Silván-Cárdenas and N. Currit, 2009. A multidirectional ground filtering algorithm for airborne LIDAR. *ISPRS Journal of Photogrammetry and Remote Sensing* 64 (1), 117-124.

Miliaresis, G. and N. Kokkas, 2007. Segmentation and object based classification for the extraction of building class from LIDAR DEMs, *Computers & Geosciences*, 33:1076–1087.

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 and Remote Sensing,* 68(12):1307–1316.

Reitsma, F. and T. Bittner, 2003. Scale in object and process ontologies. In: Kuhn, W. and Worboys, M. and Timpf, S. (eds.) Spatial Information Theory. *Cognitive and Computational Foundations of Geographic Information Science. International Conference COSIT'03* Springer, Heidelberg.

Roggero, M., 2001. Airborne Laser Scanning: Clustering in Raw Data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIV (Pt. 3/W4):227–232.

Rottensteiner F. and Ch. Briese 2001. A new method for building extraction in urban areas from high-resolution lidar data, *International archives of photogrammetry, remote sensing and spatial information sciences,* volume 34, issue:3/A: 295-301.

Rottensteiner, F. and J. Jansa, 2002. Automatic extraction of buildings from LiDAR data and aerial images, *ISPRS commission IV*, Symposium 2002, July 9-12, 2002. Ottawa.

Shan, J. and Charles K. Toth, 2008. *Topographic laser ranging and scanning: principles and processing, CRC Press, New York.*
Shan, J. and A. Sampath, 2005. Urban DEM generation from raw LIDAR data: A labeling algorithm and its performance. *Photogrammetric Engineering and Remote Sensing,* 71(2):217-226.
Silván-Cárdenas, J.L. and L. Wang, 2006. A multi-resolution approach for filtering LiDAR altimetry data. *ISPRS Journal of Photogrammetry and Remote Sensing,* 61(1):11-22.
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(1-2):85-101.
Sohn, G. and I. Dowman, 2007. Data fusion of high-resolution satellite imagery and LiDAR data for automatic building extraction, *ISPRS Journal of Photogrammetry and Remote Sensing,* 62(1):43-63.
Thuy, T. and M. Tokunaga, 2004. Filtering airborne laser scanner data: a wavelet-based clustering method. *Photogrammetric Engineering and Remote Sensing,* 70(11):1267–1274.
Thuy, T., F. Yamazaki and Matsuoka M., 2009. Multi-scale solution for building extraction from LiDAR and image data, *International Journal of Applied Erath Observation and Geoinformation 11* (2009) 281-289.
Vosselman, G., 2000. Slope based filtering of laser altimetry data. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIII (B3):935-942.
Vosselman, G. and H. G. Maas, 2010. *Airborne and Terrestrial Laser Scanning.* Whittles Publising, Dunbeath.
Wack, R. and A. Wimmer, 2002. Digital terrain models from airborne laser scanner data-a grid based approach. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIV (3B):293–296.
Wang, Z. and T.Schenk, 2000. Building extraction and reconstruction from lidar data, *International Archives of Photogrammetry and Remote Sensing* XXXIII, Part B3.
Wang, Z., 1998. Extracting building information from lidar data, *International archives of photogrammetry and remote sensing*, Volume 32, number 3, section 1: 279-284.
Weinacker, H., B. Koch, U. Heyder, and R. Weinacker, 2004, Development of filtering, segmentation and modeling modules for lidar and multispectral data as a fundament of an automatic forest inventory system, *Proceedings of the ISPRS Working Group* VIII/2, 03-06 October, Freiburg, Germany, pp. 50-55.
Zhang, K., S. Chen, D. Whitman, M. Shyu, J. Yan and C. Zhang, 2003. A progressive morphological filter for removing non ground measurements from airborne LIDAR data, *IEEE Transactions on Geoscience and Remote Sensing,* 41(4):872-882.
Zhang, K. and D. Whitman, 2005. Comparison of three algorithms for filtering airborne LIDAR data. *Photogrammetric Engineering and Remote Sensing,* 71(3):313-324.