

VERTICAL ROUGHNESS MAPPING - ALS BASED CLASSIFICATION OF THE VERTICAL VEGETATION STRUCTURE IN FORESTED AREAS

C. Aubrecht^{a,*}, B. Höfle^b, M. Hollaus^c, M. Köstl^a, K. Steinnocher^a, W. Wagner^c

^a AIT Austrian Institute of Technology GmbH, Donau-City-Str. 1, A-1220 Vienna, Austria -
(christoph.aubrecht, mario.koestl, klaus.steinnocher)^a@ait.ac.at

^b Department of Geography, University of Heidelberg, Berliner Straße 48, D-69120 Heidelberg, Germany -
hoefle@uni-heidelberg.de

^c Inst. of Photogrammetry & Remote Sensing, Vienna U. of Technology, Gußhausstr. 27-29, A-1040 Vienna, Austria -
(mh, ww)^c@ipf.tuwien.ac.at

KEY WORDS: Forestry, Hazards, Mapping, Vegetation, Classification, Laser scanning

ABSTRACT:

In this paper we describe an approach to classify forested areas based on their vertical vegetation structure using Airborne Laser Scanning (ALS) data. Surface and terrain roughness are essential input parameters for modeling of natural hazards such as avalanches and floods whereas it is basically assumed that flow velocities decrease with increasing roughness. Seeing roughness as a multi-scale level concept (i.e. ranging from fine-scale soil characteristics to description of understory and lower tree level) various roughness raster products were derived from the original ALS point cloud considering specified point-distance neighborhood operators and plane fitting residuals. Aiming at simplifying the data structure for use in a standard GIS environment and providing new options for ALS data classification these raster layers describe different vertical ranges of the understory and ground vegetation (up to 3 m from ground level) in terms of overall roughness or smoothness. In a predefined 3D neighborhood the standard deviation of the detrended z-coordinates of all ALS echoes in the corresponding vertical range was computed. Output grid cell size is 1 m in order to provide consistency for further integration of high-resolution optical imagery. The roughness layers were then jointly analyzed together with a likewise ALS-based normalized Digital Surface Model (nDSM) showing the height of objects (i.e. trees) above ground. This approach, in the following described as ‘vertical roughness mapping’, enables classification of forested areas in patches of different vegetation structure (e.g. varying soil roughness, understory, density of natural cover). For validation purposes in situ reference data were collected and cross-checked with the classification results, positively confirming the general feasibility of the proposed vertical roughness mapping concept. Results can be valuable input for forest mapping and monitoring in particular with regard to natural hazard modeling (e.g. floods, avalanches).

1. INTRODUCTION

Surface and terrain roughness is an essential parameter for assessment and modeling of natural hazards such as avalanches and floods (Margreth & Funk 1999, Werner et al. 2005, Schumann et al. 2007). Basically it can be assumed that flow velocities decrease with increasing roughness (Gómez & Nearing 2005). Roughness can be seen in various scale levels, ranging from fine-scale soil characteristics to terrain features. On the micro-level soil roughness is described in a range of millimeters to centimeters. Relevant parameters in that context are land cover types such as herbaceous and grass vegetation. Relevant meso-level roughness features include objects and vegetation in a range of decimeters to meters, such as shrubs and boulders. The macro-level is determined by topography and terrain features, whereas the scale ranges from one to hundred meters (Jutzi & Stilla 2005).

In state-of-the-art avalanche modeling approaches empirically developed roughness schemes based on a set of varying land cover types are implemented (McClung 2001, Ghinoi & Chung 2005). Such land cover classification can e.g. consist of (1)

screens and boulders, (2) shrubs or mountain pines, (3) herbaceous and grass vegetation including low bushes, and (4) compact grassland or solid rock. Depending on the exposition various skid factors are derived from these surface types (see Table 1). Surface roughness is relevant for glide avalanches on micro-level as well as for snow slabs on meso- and macro-level. The estimated skid factors are introduced in snow gliding and snow pressure modeling (Höller et al. 2009). In the field of hydrology surface roughness is introduced in runoff models for detecting superficial flow velocities (Lavee et al. 1995, Rai et al. 2010). Assessment of roughness is thereby based on a coarse surface and vegetation classification. Markart et al. (2004) identified six classes ranging from very flat to very rough. Different types of vegetation can span several roughness classes. In particular this applies to forest locations, where surface roughness is depending on specific low-vegetation cover. Accordingly further parameters are needed for classification. E.g. for virgin soils the dominance of migrating plants is relevant. For grassland land use strongly affects roughness characteristics (pasturing, ski slopes, hay meadows). In moist locations the moss rate is crucial, while for areas with bushes particularly the type of plant cover is relevant.

* Corresponding author.

Land cover class	Range	Skid factor
1 Screes and boulders	>30 cm	1.2 - 1.3
2 Shrubs or mountain pines Mounds w. veg. cover Cattle treading Screes	>1 m > 50 cm 10 - 30 cm	1.6 - 1.8
3 Grass veg. incl. low bushes Fine debris mixed with veg. Small mounds w. veg. cover Grass veg. incl. superficial cattle treading	< 1 m < 10 cm < 50 cm	2.0 - 2.4
4 Compact grassland Solid rock Fine debris mixed with soil Moist sinks		2.6 - 3.2

Table 1. Skid factors assigned to land cover types featuring varying roughness (Margreth, 2007).

The current standard way of assessing surface and/or terrain roughness is using empirical methods in the field. Taking the macro-level as example, terrain features are described approximately via wavelength and amplitude of sinusoids. Roughness assessment on meso- and micro-level can be carried out by fitting ductile slats to the surface. All these methods require on-site inspections which gets extremely time-consuming and costly for large-area assessments. Remote sensing offers the advantage of an area-wide standardized survey and is expected to deliver roughness assessments in comparable accuracy.

In this paper we describe an approach to classify forested areas based on their vertical vegetation structure using ALS data. We see roughness as a multi-scale level concept, i.e. ranging from fine-scale soil characteristics to description of understory and lower tree level. Results of our ‘vertical roughness mapping’ concept can be valuable input for forest monitoring in particular with regard to natural hazard modeling.

2. STUDY AREA AND DATA

The study area covering approximately 10 square kilometers is located in the ‘Bucklige Welt’, a hilly region in the south-eastern part of Lower Austria (about 70 km south of the Vienna basin) also known as ‘land of the 1,000 hills’ (see figure 1). Widely dominated by forest of varying characteristics (i.e. deciduous, coniferous, and mixed forest) this is a typical rural area interrupted by a few small settlements (e.g. Haßbach, Kirchau, Kulm) and patches of agricultural land. In line with the overall characteristics of the ‘Bucklige Welt’ region the study site which belongs to the municipal area of Warth features hilly terrain conditions with maximal 300 meters elevation difference.

Employing a full waveform Airborne Laser Scanning (FWF-ALS) system ALS data were acquired in the framework of a commercial terrain mapping project covering the entire Federal State of Lower Austria (acquisition period: spring 2007). In spring favorable leaf-off conditions without snow cover could be guaranteed. For the presented research project 3D point clouds organized in tiles and consisting of XYZ coordinate triples (ASCII XYZ format) were delivered. Originally ALS-inherent information about scan geometry and radiometric information was not available for further analysis.

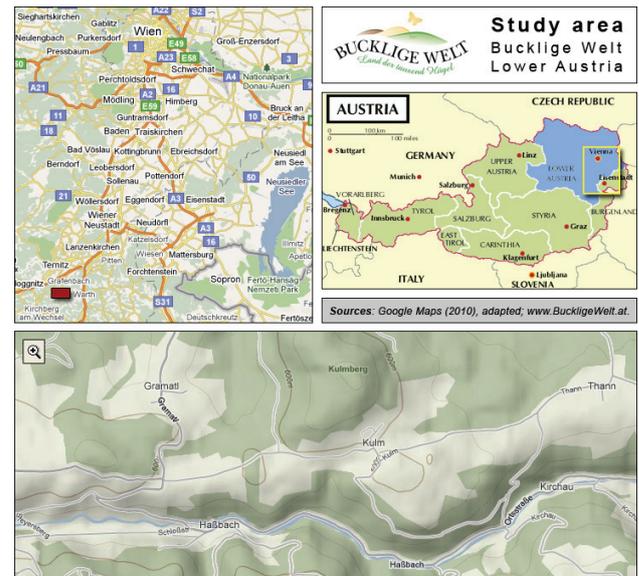


Figure 1. Study area ‘Bucklige Welt’, Lower Austria.

3. ALS BASED ROUGHNESS DESCRIPTION

This paper concentrates on products based on parameters that can be derived directly from the ALS point cloud. Only by using the 3D point cloud maximum information content is guaranteed, while preserving the highest data density and not introducing any biasing decisions on suitable target raster resolution, filter or aggregation strategies (Höfle, 2007). On the end-user side however, it is much more convenient and applicable to deal with pre-processed ‘roughness images’, i.e. featuring substantially reduced amount of data and simple raster data structure, which can be dealt with easily in standard GIS and remote sensing software packages. Computation of additional point cloud attributes and subsequent generalized raster layers requires a sophisticated software implementation, including both the mathematical definitions and intelligent management of the large amount of data which arises when working with high density laser point data.

In the following paragraphs different roughness parameters calculated on the basis of the initial ALS point cloud are described and resulting raster layer products are illustrated. In the definition of surface roughness in this context all ALS terrain points within a 0.2 m range to the ground are considered. The terrain roughness concept on the other hand just comprises objects (i.e. point clusters) close but explicitly above the terrain (>0.2 m), whereas two different vegetation story layers were analyzed for this paper: (1) very low brushwood or undergrowth from 0.2 m to 1.0 m such as bushes and shrubs, and (2) understory vegetation from 0.2 m to 3.0 m, e.g. being indicative for different tree types.

As the objective of the presented approach was to ‘look through the forest canopy’ and map the entire vertical vegetation structure (i.e. ‘roughness’ on various levels inside the woods) non-forested regions were masked out using a previously derived forest mask. This mask had been produced implementing an integrated analysis approach considering aerial imagery and ALS data (i.e. Object-based Image Analysis, OBIA).

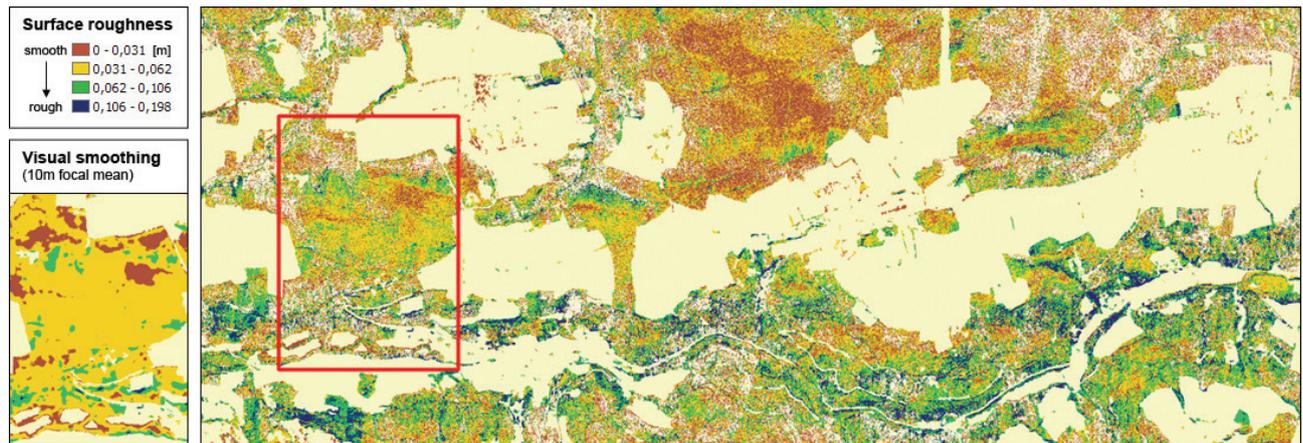


Figure 2. Surface roughness raster layer (1.0 m resolution), classified in 4 roughness categories from smooth (red) to rough (blue). Non-wooded areas are masked out (in light yellow). Detail: Smoothed visual impression through applying a focal mean operator.

3.1 Surface roughness (SR)

Surface roughness was defined as small scale height variations up to a few decimeters above ground. In mathematical terms the standard deviation of the detrended z-coordinates of all ALS terrain echoes is computed. The detrending of the ALS heights is important for slanted surfaces, where else the computed standard deviation would increase with increasing slope (i.e. height variation), even with the surface being plane. The unit of the subsequently derived SR parameter is in meters and can be compared between different flight epochs and ALS systems. Further algorithmic details can be found in Hollaus & Höfle (2010).

Figure 2 shows a derived SR raster layer featuring a terrain related variation of ± 0.2 m ($-0.2 < dz < 0.2$). All laser echoes within a 1.0 m neighborhood were considered in the plane fitting and standard deviation calculation process. The finally derived SR raster layer has a spatial resolution of 1.0 m, i.e. with the mean standard deviation value of all points falling in one predefined 1.0 m grid cell attached as attribute. Using four classes for visualization gives a good first indication on regional surface roughness variations in the study area. More than 50% of the total forested area is thus classified as having a very smooth surface (red, yellow) and around 25% show slightly higher deviations (green, blue). White pixels display 'no data' areas, i.e. areas where no information about the immediate surface is available. These can be data errors, but primarily it is due to the forest canopy being too dense thus preventing the laser beam from reaching the ground.

The detail image displayed in Figure 2 is the result of applying a focal neighborhood function to the original raster. The mean value of all cells of the input raster within a specified neighborhood is calculated and assigned to the corresponding cell location of the output raster. For the described raster a circular neighborhood (10 m radius) was chosen, i.e. all grid cells having its centers encompassed by this circle are included in the calculation. Using focal operations is a form of generalization smoothing the visual impression of the input data. It is particularly valuable for identifying hot spot regions and spatial patterns in heterogeneous raster data. It is very important to decide first how to deal with existing 'no data' values in the input data. For the displayed SR raster the option of ignoring 'no data' values in the calculation was chosen.

Another possibility would be to assign 'no data' to the output grid cell in case any of the considered neighboring cells has a 'no data' value. With just around 15% of the pixels in forested areas featuring 'no data' values it was decided to accept uncertainties entailed with ignoring those pixels and rather look at resulting generalized regional spatial patterns. It becomes clear that in the northern woods of the study area very smooth surfaces prevail while in the more heterogeneous southern parts surface in general tends to be rougher.

3.2 Terrain roughness (TR)

Terrain roughness is described as the unevenness of the terrain surface (including rocks and low vegetation) at scales of several meters. In mathematical terms this implies calculation of the standard deviation of height of non-terrain ALS echoes above terrain (normalized height) within boxes of predefined size. In contrast to the SR computation, only echoes close but above terrain (>0.2 m) are considered for the TR derivation. Two different vegetation story layers are analyzed in this context, one considering very low brushwood or undergrowth between 0.2 m and 1.0 m (e.g. bushes and shrubs; TR I; Figure 3) and the other considering understory vegetation between 0.2 m and 3.0 m (TR II; Figure 4). The second layer is particularly valuable for identifying different types of trees (e.g. large coniferous trees with few - mostly cut - branches in the lower levels or broadleaf trees with just stem and crown compared to smaller trees with branches hanging down to the ground).

Figures 3 and 4 show that these two TR parameters yield much more 'no data' values than the previously described SR parameter ($>70\%$ for TR I, $>60\%$ for TR II compared to $\sim 15\%$ for SR). Besides the same potential causes mentioned above being (1) data errors or (2) very dense tree crowns preventing the laser beam reaching the analyzed height level, no information in the ALS data can also signify empty space in reality. So, in fact even 'no data' values can provide valuable information in that context. Looking at the study site overview it is apparent that there is more TR data recorded in the southern parts of the study site. Anyhow, at this level of detail also in those areas just very little variation is detected in TR I. Values in TR II show a slightly different picture, with (1) featuring a somewhat higher information density (i.e. 37% vs. 27% for TR I) and (2) featuring more variation (i.e. mean value of 0.22 vs. 0.05 in TR I). The latter is also related to the larger vertical focus of this specific parameter ($0.2 < dz < 3.0$).

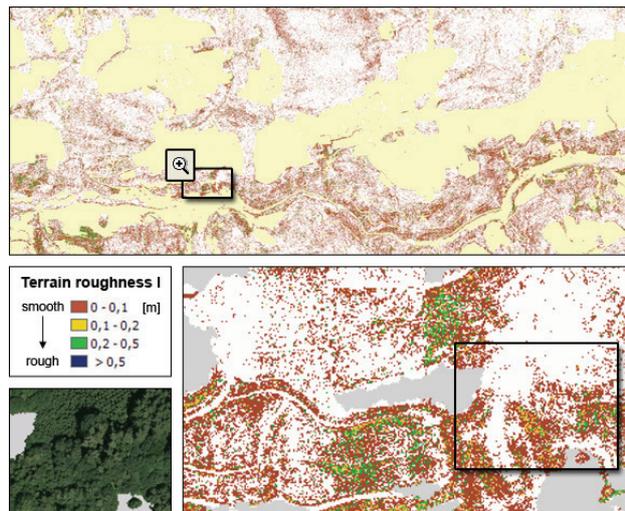


Figure 3. Terrain roughness - TR I.

Looking at the TR raster layers in more detail (details in Figures 3 and 4) local fine-scale roughness variations become visible. The spatial distribution of available information is very similar. The slightly higher data density in TR II can be an indicator of (1) vegetation being very dense in this story thus again preventing the laser beam to reach lower levels or (2) higher vegetation with branches starting somewhere around eye level, but not having any undergrowth beneath.

4. VERTICAL ROUGHNESS MAPPING – INTEGRATION OF MULTI STORY BACKSCATTER INFORMATION

After computing the ALS point cloud based roughness raster layers as described above they were jointly analyzed and combined, whereas a novel roughness classification scheme was developed, further referred to as ‘*vertical roughness*’. This novel roughness mapping concept incorporates information from various vegetation height layers using the capability of full waveform ALS, i.e. recording the entire backscatter spectrum from treetop to ground. It thus not only gives an indication of surface roughness patterns (limited to a very small height threshold above ground), but also includes information on the variance of brushwood (such as bushes and shrubs) and understory vegetation (up to 3.0 m). Results of the roughness classification were finally validated with in situ data from a field survey conducted in April 2009. The following paragraphs are dedicated to advanced classification and analysis of the ALS-derived roughness raster products. First, SR and TR layers were jointly analyzed with regard to identification of significant spatial patterns in terms of intensity and accumulation of roughness echoes. Adding yet another dimension to this integrated classification process – absolute vegetation height as illustrated by a nDSM – rounds off a novel approach of mapping roughness in wooded areas on multiple vertical levels, from now on called ‘*vertical roughness mapping (VRM)*’.

According to the basic objective of distinguishing smooth and rough surfaces, the SR raster was binary recoded with the threshold defined at $SR = 0.05$ m plus one additional ‘no data’ category. Grid cells featuring SR values larger than 0.05 were thus considered rough, while all values below that threshold were considered smooth.

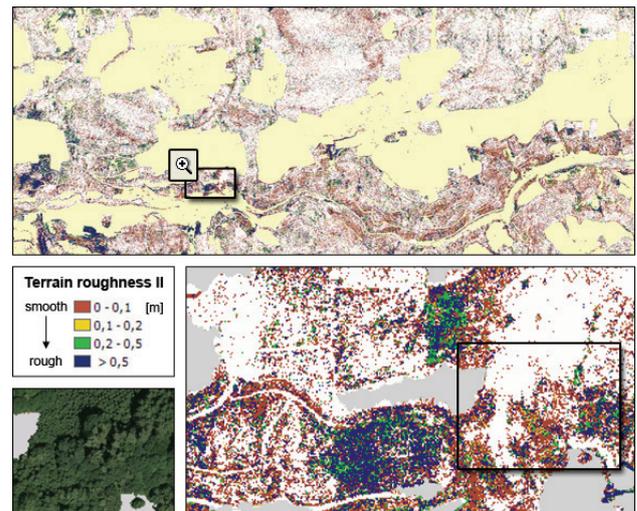


Figure 4. Terrain roughness - TR II.

Regarding the structural undergrowth information inherent in the two TR raster layers a slightly different, but yet binary classification approach was chosen. One class of pixels depicts areas where echoes are recorded in both the lower vegetation level TR I (very low brushwood or undergrowth up to 1.0 m) and the level of understory vegetation up to 3.0 m TR II. The second category includes regions where echoes were just recorded at the level of TR II, but no data exist on the lower level of TR I. Again an additional class for ‘no data’ cells was appended.

The combination of these reclassified SR and TR products ‘ $x-y$ ’ ($x \dots TR_{recl}$, $y \dots SR_{recl}$) with each layer featuring three value facets (1, 2, no data) resulted in a set of nine possible new classes (3×3 categories) describing different multi-level roughness characteristics. Most frequent classes are the categories with $x=0$ (0-0, 0-1, 0-2), i.e. having no TR data records, whereas 0-1 particularly stands out. This class covering about one third of the study area (33.4%) delineates areas with smooth surface and no recorded echoes in both levels of understory vegetation (TR I 0.2 m to 1.0 m, and TR II 0.2 m to 3.0 m).

In the previous steps information on the vertical distribution of recorded echoes within a range of 0.2 m to 3.0 m above ground was considered for VRM. In order to get an overall picture of the vertical vegetation structure another dimension was added by integrating the nDSM as third input variable, i.e. absolute height information classified in 4 story layers. The first category (‘0-x-y’) is defined as ‘vegetation up to 3.0 m’ covering about 9% of the total area. As this class boundary coincides with the upper boundary of TR II, the nDSM integration does not expand the vertical roughness information content in these areas. The biggest part of the test site’s wooded area (65.8%) is covered by trees which are between 10 m and 25 m high (category ‘2-x-y’). Integrating an additional information layer with 4 possible values to the concept results in 36 ($3 \times 3 \times 4$) classes eventually describing the full vertical vegetation structure. Figure 5 shows the new extended classification scheme – ‘*vertical roughness mapping extended (VRM^e)*’ – applied to a detail of the study area. The aerial image is given for comparison in order to provide an impression of the heterogeneous forest structure, which is already visible without even knowing how it looks like beneath the tree crown.

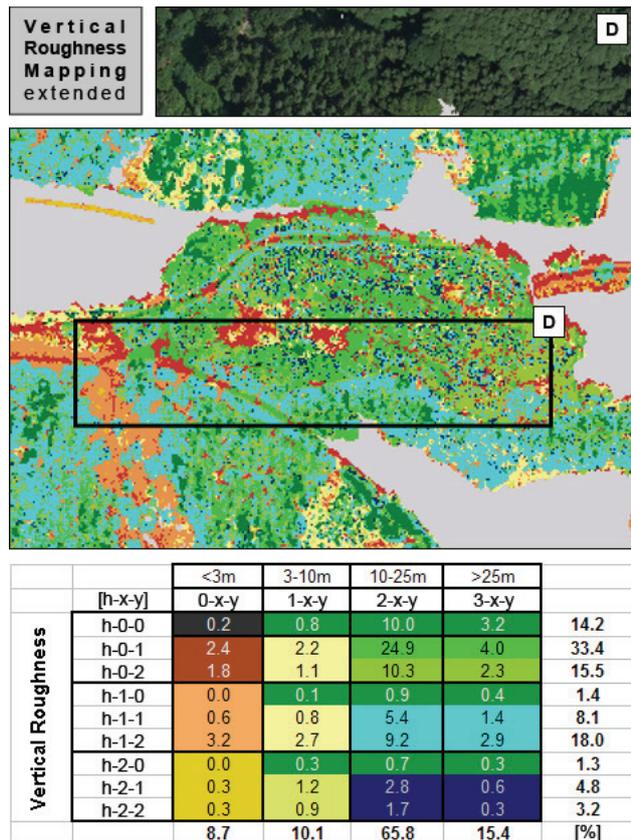


Figure 5. Vertical roughness map and classification scheme for a detail of the test site, and aerial image for comparison (D).

In fact five classes out of the 36 categories stand out each featuring more than 5% and in total covering about 60% of the test site. 22 of the remaining classes just account for less than 2% each. The by far most dominant class (25%) is ‘2-0-1’ (light green in Figure 5) featuring an overall height between 10 m and 25 m, smooth surface and no echo records regarding undergrowth. In general nearly 65% of the total forest area shows no backscatter records in the mid-vegetation level (i.e. the ‘h-0-y’ category group). In case some kind of undergrowth is present, most of the times it spans the whole vertical range between 0.2 m and 3.0 m above ground, i.e. echoes recorded in both TR I and TR II as well as ‘rough’ surface conditions (‘h-1-2’: 18%). When looking at the ‘h-1-y’ type, thus ignoring surface variation, these regions even cover 27.5% of the total study area. Classes with TR information exclusively recorded in the higher level of understory vegetation between 1.0 m and 3.0 m (i.e. the ‘h-2-y’ category) occur just very sparsely covering a total of less than 10% of the study area. Pixels assigned to these classes can mainly be attributed to large trees with branches reaching down to the 3.0 m range but not all the way down to the ground.

5. VALIDATION

For validating the results of the ALS based vertical roughness mapping in situ reference data was collected. The field survey was done on April 16, 2009 taking Haßbach (village in the southwest of the test site, see Figure 1) as starting point. Locations of reference points were stored using a Garmin eTrex GPS handheld model.

Extensive photo documentation was an essential part of the data collection allowing capturing a certain neighborhood around fixed reference point locations. A total of 24 points was collected in the course of the field survey whereas the focus was on getting a representative point set featuring different types of vegetation including scrubs and brushwood.

For this paper two selected reference points of varying characteristics will be presented in detail serving as examples for cross-validating ALS derived roughness and reality conditions. Figure 6 shows the vertical roughness map (VRM^e) for the examined area with the aerial image included for comparison and orientation reasons. For each of the two reference points (no. 463 and 464) a vertical-bar graph is presented illustrating the VRM^e pattern (class ratios) within a 10 m neighborhood (marked with red circles in the map). To illustrate reality conditions pictures from the field survey are shown in the bottom part of the figure (463: P1, 464: P2).

First, spatial roughness patterns as illustrated in the raster map and class ratio numbers are analyzed. For reference point 463 a good portion of its immediate neighborhood (63%) is classified as ‘1-1-2’ (light yellow in Figure 6), i.e. overall rather low vegetation height <10 m, recorded echoes in both terrain layers (TR I and TR II), along with ‘rough surface’. With respect to the entire study area this is a very untypical picture with ‘1-1-2’ just covering less than 3% in total. These ALS-based ratio values shown in the vertical-bar graph are confirmed by looking at the collected reference data, with photo P1 showing dense low-level deciduous vegetation with branches and leaves throughout the vertical range. Also in an additionally available reference data set (provided by the Research and Training Centre for Forests, Natural Hazards and Landscape, BFW) this region is qualitatively described as ‘young and very dense deciduous forest including undergrowth’. 21% are classified as ‘1-2-y’ (light green) while the remaining 16% are assigned to ‘0-2-y’ (orange), i.e. no recorded echoes in TR I at slightly varying overall tree height. As surface information is available anyhow (either smooth or rough) it is unlikely that too dense top-level vegetation prevented the laser beam from ‘seeing’ the lower level. As during the field campaign indeed some parts of this specific forest patch were observed not featuring any low-level brushwood the classified VRM^e information can be expected to be correct and significant.

Reference point 464 shows a completely different picture. Photo P2 in Figure 6 displays mixed and rather loose vegetation including e.g. large coniferous trees, small broadleaf bushes and leaf-covered surface. This is confirmed and even emphasized by the ALS based VRM^e. Looking at the class ratio values shown in the vertical-bar graph and at the raster layer no predominant category can be detected, but rather a heterogeneous mix of various roughness classes in the immediate neighborhood of the reference point. From bare soil (‘0-0-1’) to the largest trees (3-x-y) the entire range of roughness categories is present.

Photo documentation not necessarily delivers representative results, also because of directivity. However, during data collection attention was paid to that issue. As the field survey was carried out about two years after the ALS data had been recorded, data mismatches can be due to that temporal variation. Summing it up results are very encouraging and it seems that advanced vertical roughness mapping is possible at a certain spatial level of detail based on ALS information.

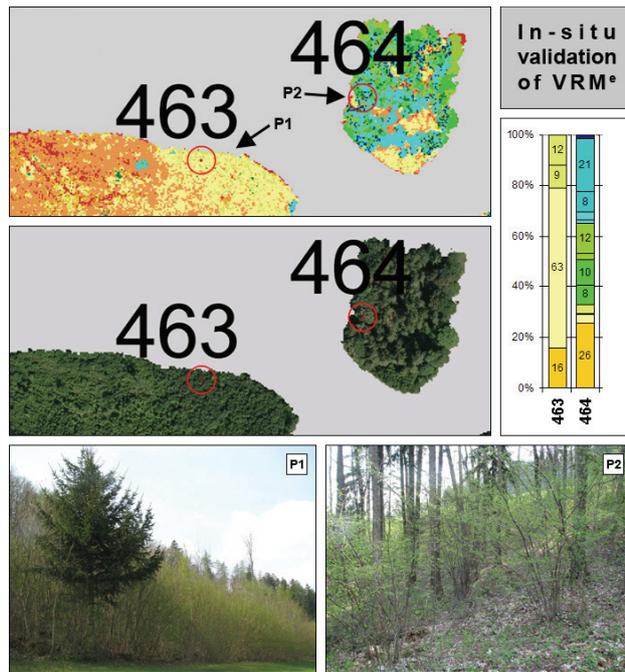


Figure 6. In situ validation of VRM^e.

6. CONCLUSION AND OUTLOOK

In this paper a novel approach of data classification and revaluation was presented with the focus on identifying ‘roughness’ on various vertical levels in wooded areas. Roughness parameters and corresponding raster layers were calculated and jointly analyzed in order to develop a novel roughness classification scheme considering the entire vertical structure of vegetation from surface to treetop. This classification procedure can be outlined as *vertical roughness mapping (VRM)*.

Results of the roughness classification were cross-validated against collected in situ reference data indicating a high level of thematic accuracy. As follow-on analysis several ways of smoothing the VRM^e raster files (i.e. information-preserving ‘intelligent’ generalization) will be tested in order to derive areal roughness hot spots useful for terrain related hazard assessments (e.g. water hazards, mass movements).

REFERENCES

- Ghini, A., Chung, C.-J., 2005. STARTER: a statistical GIS-based model for the prediction of snow avalanche susceptibility using terrain features – application to Alta Val Badia, Italian Dolomites. *Geomorphology*, 66, pp. 305-325.
- Gómez, J. A., Nearing, M. A., 2005. Runoff and sediment losses from rough and smooth soil surfaces in a laboratory experiment. *Catena*, 59, pp. 253-266.
- Hollaus, M., Höfle, B., 2010. Terrain roughness parameters from full-waveform airborne LiDAR data. ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, in press.

Höfle, B., 2007. Detection and Utilization of the Information Potential of Airborne Laser Scanning Point Cloud and Intensity Data by Developing a Management and Analysis System. *Dissertation*, Faculty of Geo- and Atmospheric Sciences, University of Innsbruck, Austria.

Höller, P., Fromm, R., Leitinger, G., 2009. Snow forces on forest plants due to creep and glide. *Forest Ecol Manag*, 257, pp. 546-552.

Jutzi, B., Stilla, U., 2005. Waveform processing of laser pulses for reconstruction of surfaces in urban areas. *International Archives of Photogrammetry and Remote Sensing*, Vol. 36, Part 8 W27 (on CD).

Lavee, H., Kutiel, P., Segev, M., Benyamini, Y., 1995. Effect of surface roughness on runoff and erosion in a Mediterranean ecosystem: the role of fire. *Geomorphology*, 11, pp. 227-234.

Margreth, S., 2007. Lawinenverbau im Anbruchgebiet. Technische Richtlinie als Vollzugshilfe. Umwelt-Vollzug Nr. 0704. Bundesamt für Umwelt, Bern, WSL Eidgenössisches Institut für Schnee- und Lawinenforschung SLF, Davos. 136 S.

Margreth, S., Funk, M., 1999. Hazard mapping for ice and combined snow/ice avalanches – two case studies from the Swiss and Italian Alps. *Cold Reg Sci Technol*, 30, pp. 159-173.

Markart, G., Kohl, B., Sotier, B., Schauer, T., Bunza, G., Stern, R., 2004. Provisorische Geländeanleitung zur Abschätzung des Oberflächenabflussbeiwertes auf alpinen Boden-/Vegetationseinheiten bei konvektiven Starkregen. BFW-Dokumentation; Schriftenreihe des Bundesamtes und Forschungszentrums für Wald, No. 3, Vienna, Austria, 88 p.

McClung, D. M., 2001. Characteristics of terrain, snow supply and forest cover for avalanche initiation caused by logging. *Ann Glaciol*, 32, pp. 223-229.

Rai, R. K., Upadhyay, A., Singh, V. P., 2010. Effect of variable roughness on runoff. *J Hydrol*, 382, pp. 115-127.

Rutzinger, M., Höfle, B., Pfeifer, N., 2007. Detection of high urban vegetation with airborne laser scanning data. *Proceedings Forestsat 2007*, Montpellier, France.

Schumann, G., Matgen, P., Hoffmann, L., Hostache, R., Pappenberger, F., Pfister, L., 2007. Deriving distributed roughness values from satellite radar data for flood inundation modeling. *J Hydrol*, 344, pp. 96-111.

Werner, M. G. F., Hunter, N. M., Bates, P. D., 2005. Identifiability of distributed floodplain roughness values in flood extent estimation. *J Hydrol*, 314, pp. 139-157.

ACKNOWLEDGMENTS

The presented research was funded by the Austrian Research Promotion Agency (FFG) in the frame of the Austrian Space Applications Programme (ASAP). The ALS data was kindly provided by the “Amt der Niederösterreichischen Landesregierung, Gruppe Baudirektion, Abteilung Vermessung und Geoinformation“.