Terrain Characterization and Vegetation Structural Analysis with Full-Waveform Airborne Laser Scanners

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Summary
Full-waveform airborne laser scanning (FWF-ALS) is an active remote sensing technique that records the entire backscattered waveform from transmitted laser pulses. By decomposing the backscatter signals into a series of echoes in a post-processing step, information about the geometric location and radiometric properties of each individual scatterer can be obtained. Even though research on small-footprint waveform data can still be considered to be only in its beginning, a number of benefits start to emerge. From a theoretical point of view, the value of FWF-ALS sensors lies in the fact that the measurement process is depicted in its entire complexity. Thus it is possible to physically model the measurements process. From a practical point of view, the combination of geometric and radiometric information offers new means for interpreting the derived 3D point cloud and for deriving vegetation and terrain information. In this contribution we discuss methods for processing full-waveform ALS data for improving the characterization of the terrain and vegetation structure. The results show that full-waveform information is particularly useful for characterizing low vegetation cover, terrain roughness, and different forest classes. Examples are drawn from study areas in eastern Austria.

1 Introduction
Airborne laser scanning (ALS) is an active remote sensing technique that uses nanosecond-long laser pulses to acquire topographic data, where the laser scanner is mounted on an airborne platform. Over vegetated areas the laser pulses may be reflected by the leaves and branches of the vegetation and the underlying terrain surface. The capability of ALS to provide ground echoes even in dense canopy forests (Kraus and Pfeifer, 1998) has lead to ALS being established as a standard method for topographic data acquisition. Discrete ALS systems are able to measure the travelling time from the first and last received echo, and from some intermediate echoes, depending on the system. Based on the group velocity of the laser pulse in the atmosphere, the range between the sensor and the backscattering object is calculated (Wagner *et al.*, 2006). In addition to the range, the position and rotation of the sensor is continuously recorded using a differential Global Positioning System (dGPS) and an Inertial Measurement Unit (IMU). Thus, the three dimensional (3D) position of each echo can be determined.

Given laser footprint sizes in the order to 0.2m to 1.0m the laser pulses may be reflected by several discrete objects, potentially yielding relatively complex backscatter signals referred to as "waveforms". By registering the full-waveform during the flight and by decomposing it into a series of echoes in a post-processing step, information about the geometric location and radiometric (scattering) properties of each individual scatterer can be obtained. These so-called full-waveform airborne laser scanners (FWF-ALS) have the benefit that, in addition to

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the range, the amplitude and the width of each individual echo are derived. As reported by Wagner *et al.* (2008) vegetation typically causes a broadening of the backscattered pulse, which allows the classification of each echo into vegetation and non-vegetation. Thus the quality of derived digital terrain models (DTM) can be improved either by removing the vegetation echoes, depending on the echo width, before the filtering process (Doneus *et al.*, 2008; Wagner *et al.*, 2008) or by using the echo width as a-priori weight in the hierarchic robust filtering (Mandlburger *et al.*, 2007). Furthermore, ALS data provide not only topographic information about the terrain surface but also about the vertical structure of forests.

2 Objectives

The overall objectives of this paper are to discuss methods for processing full-waveform ALS data for improving the characterization of the terrain and vegetation structure. The focus is to improve terrain models using the additional information provided by full-waveform ALS data. Based on precise DTMs methods are described to characterize the terrain roughness, the low vegetation cover, and the vertical structure of different forest classes. The described methods are applied for different study areas in eastern Austria and results are shown and discussed.

3 Full-Waveform Laser Scanning Data

The analyzed FWF-ALS data were acquired with a *RIEGL* LMS-Q560 that recorded the backscattered waveforms with an interval of 1ns. In post-processing the waveforms were modeled as series of Gaussian distribution functions. The applied Gaussian decomposition provides the estimated location of each echo and the scattering properties of the target i.e. the amplitude and the echo width (Wagner *et al.*, 2006). The amplitude of the echo signal provides information on the target's reflectance and cross-section. The echo width provides information on the range distribution of scatterers within the laser footprint that contribute to one echo signal and is therefore an indicator for surface roughness and the slope of the target (Ullrich *et al.*, 2007). Due to the short transmitted pulse duration of 4ns, such FWF-ALS systems produce differentiable echoes if the scattering targets are separated by at least 0.6m in range. In comparison to discrete ALS systems, where the range resolution is currently in the order of 0.6m to 1.5m (Wagner *et al*., 2006), the higher range resolution of the FWF-ALS system allows a better differentiation between terrain and near-terrain echoes.

4 Methodology

4.1 Calculation of improved topographic models

For the determination of DTMs the last reflected echoes have to be classified into terrain and off-terrain echoes. This is commonly done by applying various filtering techniques (Sithole and Vosselman, 2004), which are based on the spatial relationship of the 3D last echoes. As presented by Doneus *et al.* (2008), Wagner *et al.* (2008) and Ullrich *et al.* (2007) the integration of the additional full-waveform information i.e. the echo width, into the DTM generation leads to classified terrain points with greater confidence and consequently to an improved DTM. Furthermore, Mandlburger *et al.* (2007) and Mücke (2008) expanded the robust interpolation for classifying the ALS points into terrain and off-terrain points (Kraus and Pfeifer, 1998) with a-priori weights that were derived from the echo widths. As mentioned in Mandlburger *et al.* (2007) the use of these a-priori weights for robust interpolation allows the combination of the additional full-waveform echo attributes with the geometric criteria within the robust DTM interpolation.

4.2 Estimating terrain roughness parameters

For estimating terrain roughness parameters with a spatial scale up to a few decimeters, a high precision DTM and the 3D point cloud is required. For the current study the terrain roughness was parameterized directly using the recorded 3D echo locations depending on the vertical extent of the terrain surface. The terrain roughness parameter was determined by the standard deviation of detrended z-coordinates of ALS echoes within a local neighborhood, where only echoes with normalized heights lower than a defined threshold were used. The detrending of the ALS heights is important for slanted surfaces, where the computed standard deviation would increase with increasing slope (i.e. vertical height variations), even though the surface is plain. Thus, the terrain roughness parameter describes in addition to the unevenness of the terrain surface rocks and vegetation next to the terrain surface. Alternatively, the mean echo width for echoes next to the terrain surface can be used for roughness characterization. A further quantity to describe the surface is the backscatter cross-section, which is known from radar remote sensing including all target properties e.g. target area, reflectance and directivity (Wagner *et al.*, 2006).

4.3 Describing the vertical structure of forest

In addition to the terrain roughness parameterization, information about the vertical structure of forest is required as input for several applications, e.g. natural hazard simulation models, describing the layering of forests regarding biodiversity, or estimating the water retention capability. Since ALS can "see" through gaps in vegetation, the number of reflections (i.e. recorded echoes) is suitable to describe the vertical distribution of backscattering objects in forests. Therefore, the vertical structure of different forest classes was determined by the so-called echo ratio (*ER*) given in percent, that describes the ratio of the number of echoes in a 3D neighborhood to all vegetation echoes in the corresponding 2D neighborhood (Höfle *et al.*, 2009). The *ER* exhibits 100% for solid objects, where no significant vertical height distribution of echoes can be found. In contrast, for high vegetation the neighbors in 3D distance drastically decrease compared to the constant neighbors in 2D. For example, an *ER* of 25% means that a quarter of all laser echoes in certain 2D distance are also located near when measuring the distance in 3D. But the remaining three quarters of 2D neighbors lie either higher or lower than the "search sphere" of the given laser point. As the *ER* is a relative measure it is a robust value e.g. against varying local point densities due to the specific scanning pattern (e.g. strip overlapping areas).

5 Results

For a study area in the Vienna Woods located west of the city of Vienna the determined DTM, terrain roughness layer and echo ratio is shown in comparison to a real color orthophoto (Figure 1). Even for very dense young forests a precise DTM could be generated from the FWF-ALS data using the robust interpolation. As can be seen in Figure 1b, narrow trails, unsurfaced forest roads and ditches are clearly represented in the DTM. Based on the 3D echoes with normalized heights <1.0m the terrain roughness layer was calculated (Figure 1c). In addition to forest roads and short cut grassland, old forest stands with no understory are characterized with terrain roughness values in the range of few centimeters and indicate smooth terrain surfaces. The small white dots in the old forest stands show single tree positions where echoes were backscattered from tree stems. Furthermore, lying tree stems can be identified in the terrain roughness layer as well as in the mean echo width layer (Figure 2c). In contrast to smooth terrain surfaces dense young forests and areas covered with brambles have high terrain roughness values and point out that the height variations of the recorded echoes, that are located within a raster cell of 1x1m, are in the magnitude of several decimeters (Figure 1c). The echo ratio (Figure 1d) describes the vertical distribution of the laser echoes. High echo ratios are available if all laser echoes are backscattered from a single thin layer e.g. from forest roads, grassland or areas covered with brambles as shown in Figure 1d. For forest stands with an uniform vertical distribution of the echoes, the echo ratio values decrease and indicate a multilayered vertical forest structure.

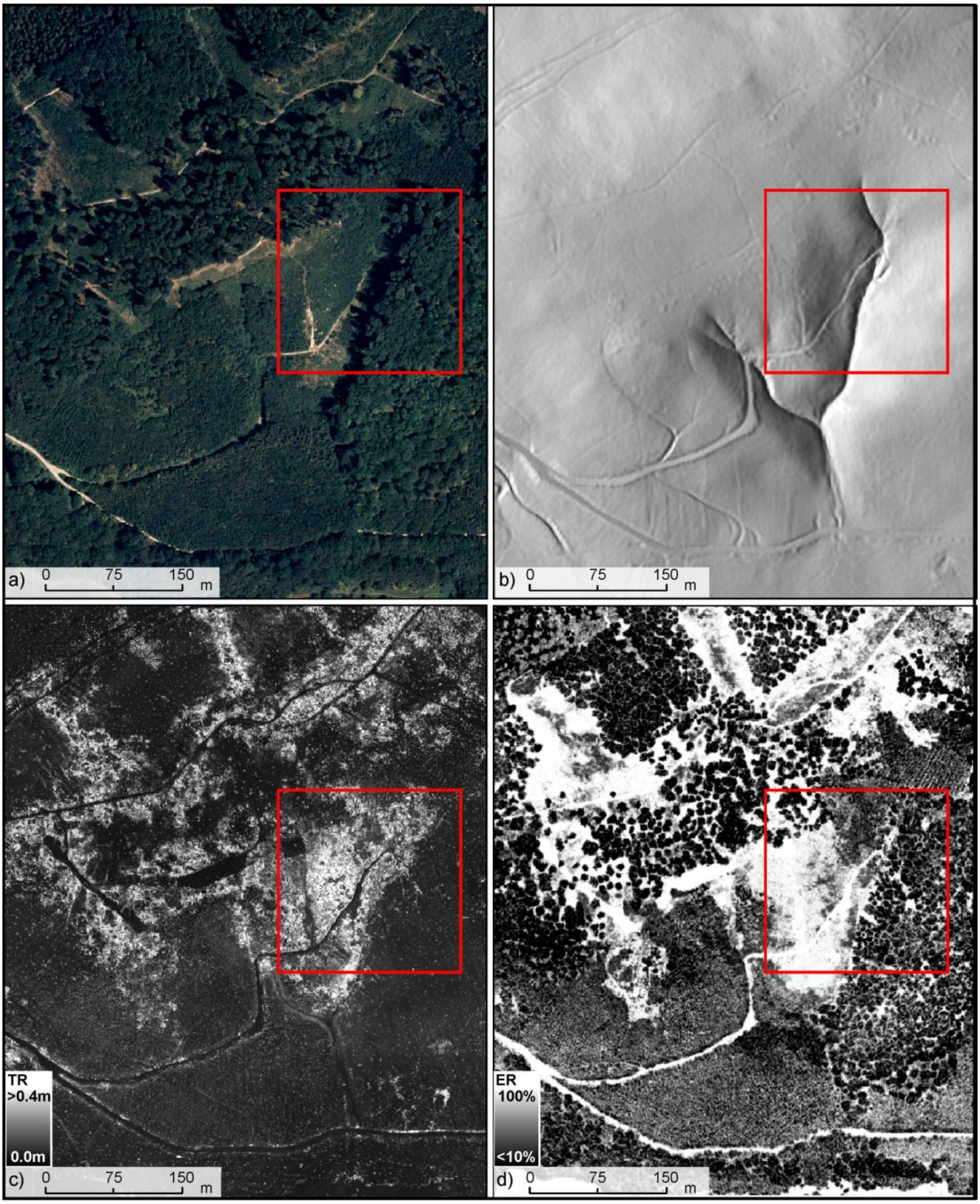

Figure 1. a) True-color orthophoto, b) shaded DTM, c) terrain roughness, d) echo ratio; the spatial resolution is 1.0m. The red square labels the subarea which is shown in Figure 2. The orthophoto and the ALS data were provided by the Stadtvermessung, City of Vienna.

The mean echo width and the mean backscatter cross-section, derived from all echoes with a normalized height <1.0m, are shown in Figure 2. Furthermore, the normalized digital surface model, computed by subtracting the DTM from the DSM, is shown in Figure 2b. The mean echo width layer characterizes the terrain roughness and is comparable to the *TR* shown in Figure 1c. Figure 2a shows the mean backscatter cross-section, where the brightest areas represent open areas (e.g. forest roads, grassland and areas that are covered with low vegetation) and dark areas mainly high vegetation.

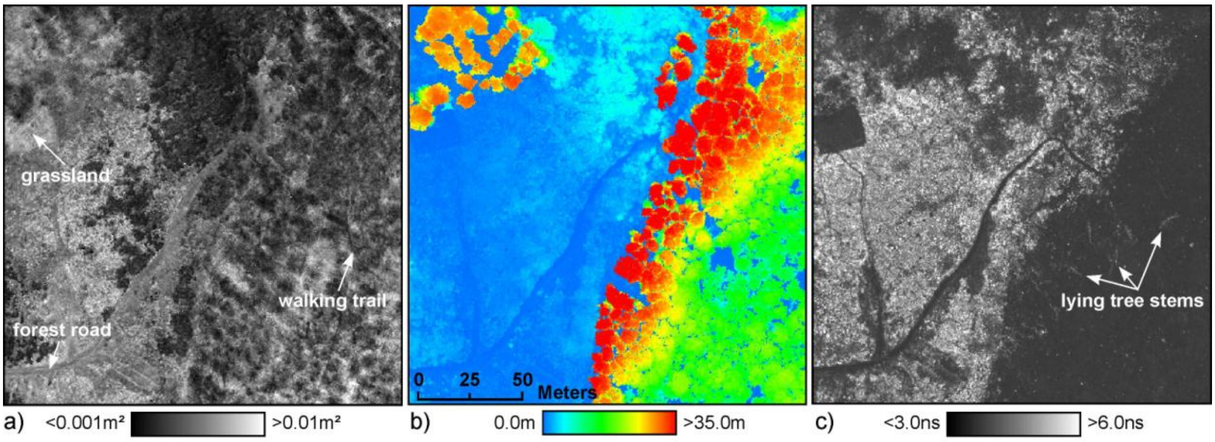

Figure 2. a) Mean backscatter cross-section, b) Normalized digital surface model computed from all first echoes and c) mean echo width of echoes with normalized heights <1.0m.

6 Discussion and Conclusion

The current study shows the potential of FWF-ALS data for terrain characterization and vegetation structural analysis. The range resolution of the used FWF-ALS system is high and therefore nearby objects with a distance of at least 0.6m can be separated, which is especially important for areas that are covered with low vegetation. Furthermore, the additional information per detected echo i.e. the echo width, improves the classification of terrain and off-terrain echoes. Consequently, a higher DTM quality can be achieved, which allows the description of the terrain roughness in more detail. The derived terrain roughness layer is a reliable parameter for describing the unevenness of the terrain surface and provides information about the height variations of the vegetation cover next to the terrain surface. As the terrain roughness is computed as the standard deviation of normalized echo heights a high laser point density is required in order to derive high resolution roughness images. Especially for lower ALS point densities, the mean echo widths of terrain echoes provide comparable information about the terrain roughness. The described echo ratio is a good indicator for the vertical distribution of echoes and can on the one hand be used to characterize the vertical forest structure and on the other hand to differentiate between buildings and vegetation as demonstrated in Höfle *et al.* (2009).

Finally, it can be stated that FWF-ALS data are well suited to quantify the terrain roughness and to characterize the vertical structure of forests. The described quantities can be used as input for e.g. forest protection planning, management and monitoring purposes, or hydrological applications.

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