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Retrieval of higher order statistical moments from full-waveform LiDAR data for tree species classification

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ABSTRACT

Tree inventories, inter alia, need information on the tree species. Previous studies aimed at distinguishing tree species based on three dimensional tree structure metrics derived from airborne laser scanning (ALS) point clouds or based on features from full-waveform (FW) laser scanning data provided by today's sensors. Classifications based on FW features mainly use echo amplitude, pulse energy (hereafter referred to as energy) and width, which are typically retrieved by waveform decomposition, often performed using the symmetric Gaussian distribution function.

However, for forested areas, the symmetry of the echo shape is potentially modified by multiple scattering and the distribution of scattering elements (e.g. leaves). We assess the potential of processing full-waveform ALS data such that the third and fourth statistical moments, i.e. the echo skewness and the echo kurtosis, can be retrieved in addition to the amplitude, energy and FWHM. We propose a waveform decomposition approach using the skew normal distribution (SND) function, which enables the modelling of skewed echoes. We investigate the difference of tree-crown aggregated SND derived FW features between seven tree species (969 individual trees) in a temperate mixed forest with the aim of detecting the most descriptive echo features. The such derived FW features are tested for species classification.

The results reveal that the largest differences across the tree species are in the mean energy of the first echoes (15 out of 21 species pairs show differences), followed by the mean amplitude of the first echoes and the mean skewness of all echoes originating from a single crown (14 out of 21 species pairs show differences against each other for both features).

The differentiation of coniferous and deciduous trees benefits from the features derived from the SND decomposition compared to the use of echo amplitude only (0.39 vs. 0.61 in Cohen's κ). As the classification accuracy of the three dominant tree species within the test site only shows a small increase (0.20 vs. 0.26 in Cohen's κ) by adding FW features, we propose the use of such features in combination with features from multispectral data for this purpose.

The SND decomposition is comparable to the Gaussian decomposition regarding the decomposition accuracy ($RMSE = 4.45$ vs. $RMSE = 3.50$) and computational cost. Hence, we propose the default use of the SND decomposition, as the SND is a more flexible function, allowing for the modelling of normally distributed echoes, as well as the fitting of skewed echoes, while no limitations regarding the direction of the skewness are introduced. We attribute the difficulties in the tree species classification to the relatively wide ranges of the crown aggregated features within one species, which for some features results in a considerable overlap of the feature ranges across the species.

1. Introduction

Tree inventories traditionally comprise measures of extent, volume, composition and condition of trees and stands (Kangas et al., 2006; Hyyppä et al., 2008; Wulder et al., 2008), but also include tree species (Hyyppä et al., 2008; Hollaus et al., 2009; Hovi et al., 2016). Tree species information is an important information, required for habitat quality assessments or to infer the susceptibility to loss, for instance (Vaughn et al., 2012).

However, ground-based field inventories are expensive, labor-intensive and thus, constrained to small areas or to a sampling approach (Torabzadeh et al., 2014a; Vauhkonen et al., 2014). Remote sensing, on the other hand, offers the possibility to provide biophysical vegetation information for large areas (Koetz et al., 2006;

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Torabzadeh et al., 2014b) and has a long tradition in ecosystem monitoring (Ustin et al., 2004; Lu, 2006; Malenovský et al., 2009; Schaepman et al., 2009). For the collection of forest inventory attributes related to tree height and canopy density, airborne laser scanning (ALS) is of particular value for information acquisition, comprising primarily a three-dimensional information dimension, namely the 3D-coordinates of the echoes. The advantage of ALS compared to optical remote sensing is its ability to penetrate the forest canopy, providing detailed three-dimensional information on the structure of the forest (Nilsson, 1996; Nelson et al., 1997; Lefsky et al., 1999). This allows for the direct extraction of inventory parameters relevant for forest management from the acquired ALS point cloud. ALS using small-footprint laser scanners is therefore used at operational level today (Wulder et al., 2013; Næsset, 2014).

In today's full-waveform (FW) laser scanners, the returning energy is digitized and recorded as a function of range. Thus, the return waveform can be considered as an additional one-dimensional information dimension, corresponding to a signal, sampled along the range distance. The shape of the backscattered waveform is determined by the characteristics of the single scatterers, namely their illuminated area, their reflectance, their orientation regarding the laser beam direction and their spatial arrangement (Wagner et al., 2006; Höfle and Pfeifer, 2007; Hovi and Korpela, 2014; Hovi et al., 2016). However, the interactions of the laser pulse with elements constituting the forest structure are complex (Romanczyk et al., 2013) and the influence of multiple scattering on the return waveform have been discussed, both for large-footprint systems (Blair and Hofton, 1999; Sun and Ranson, 2000; Ni-Meister et al., 2001) and for small-footprint systems (Morsdorf et al., 2009; Hovi and Korpela, 2014). On the other hand, the recorded waveform additionally depends on the shape of the transmitted waveform and the impulse response of the receiver (Jutzi and Stilla, 2006a), further altering the waveform shape.

1D waveform information is affected by many factors, which makes the interpretation challenging (Hovi et al., 2016). Usually, waveform processing aims at fitting known distribution functions to the waveform, i.e. performing a waveform decomposition (Hofton et al., 2000; Wagner et al., 2006; Mallet and Bretar, 2009). The Gaussian distribution function is commonly used (Hofton et al., 2000; Wagner et al., 2006; Reitberger et al., 2008), but other distributions, such as the Generalized Gaussian distribution, the Lognormal distribution (Chauve et al., 2007), the Nakagami distribution and the Burr distribution (Mallet et al., 2010) have been proposed for this task. Other approaches aim at retrieving the differential target cross-section by a deconvolution of the return waveform using the emitted (and recorded) laser pulse. This can be achieved through a Wiener-Filter deconvolution (Jutzi and Stilla, 2006b) or a B-spline deconvolution (Roncat et al., 2011).

By modelling echoes using waveform decomposition, additional echo attributes can be retrieved. Besides the echo amplitude (here: peak amplitude Wagner et al., 2008b; Mallet and Bretar, 2009; Jörg et al., 2015), these are energy (Reitberger et al., 2008; Heinzel and Koch, 2011), echo width (Wagner et al., 2006; Reitberger et al., 2008) and backscatter cross-section (Wagner et al., 2006).

In addition to structural parameters, which are derived from the 3D echo distribution within the tree crowns, the 1D echo amplitude information (Ørka et al., 2009; Korpela et al., 2010) and the echo energy (Reitberger et al., 2008; Heinzel and Koch, 2011) are typically used for tree species classification. Other studies additionally use the echo width (Reitberger et al., 2008; Lindberg et al., 2014) and the backscatter cross-section (Hollaus et al., 2009) .

Tree species classifications based on waveform attributes that are computed directly from the waveform, i.e. without performing a preliminary rigorous decomposition, showed good results, too (Yu et al., 2014; Hovi et al., 2016).

The underlying assumption for tree species classification is that the species show distinct signatures in the mentioned echo attributes. Although a wide set of tree properties with influences on the echo attributes has been revealed (e.g. Ørka et al., 2009; Korpela et al., 2010; Hovi and Korpela, 2014), the understanding of how these differences are caused and how the waveform features are modified by trees is not yet sufficiently advanced (Hovi et al., 2016).

In our study, we assess higher order statistical moments, i.e. skewness and kurtosis, of full-waveform ALS data for tree species classification. Our research objectives are:

1. implement and test an improved processing chain for return waveforms, allowing to retrieve higher order statistical moments describing the echo shape;
2. assess differentiation power of echo attributes for species classification;
3. quantify value of higher order statistical moment echo attributes for species classification.

2. Materials

2.1. Study area

The methods were tested on a 300 × 300 m plot centered at 47° 28′ 43′′ N, 8° 21′ 50′′ E (WGS84) on the southern slope of the Laegern Ridge in the northeast of Canton Aargau, Switzerland. The terrain is characterized by steep slopes ranging from 610 to 820 m above sea level. The study area is covered by an old-growth temperate mixed forest, dominated by European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*). Further details on the site are listed in Eugster et al. (2007) and Schneider et al. (2014).

2.2. LiDAR data

We used a set of small-footprint full-waveform ALS data acquired under leaf-on conditions on August 1, 2010, using a RIEGL LMS-Q680i (RIEGL Laser Measurement Systems GmbH, Horn, Austria) scanner at a wavelength of 1550 nm (Roncat, 2014). The designated mean altitude above ground was 500 m, resulting in a mean footprint diameter of 25 cm on the ground (RIEGL, 2012). The scan angle was limited to ±15°, recorded at a pulse repetition frequency (PRF) of 200 kHz. The return waveform is sampled in an interval of 1 ns.

The study area was covered by multiple flight strips. Each tree within the plot could be covered with multiple acquisition characteristics (e.g. scan angle, achieved point density).

The analysis of the recorded system waveform, resulting from the convolution of the emitted laser pulse with the receiver response function (Wagner, 2010), showed an average $FWHM_{sys}$ of 4.5 ns. We used this measure for the waveform processing, where relevant.

2.3. Tree species map

The tree species map was produced based on an ortho-mosaic of 174 geometrically rectified images which was co-registered to a canopy height model (CHM) derived from an ALS data set. The photographs were taken on October 21, 2013, using an UAV which was operated at a flight altitude of 270 m above ground. This resulted in a spatial resolution of 0.08 m × 0.08 m. For the detection of possible individual tree crowns (ITC), a semi-automatic segmentation approach was employed on the fused set combining the UAV-derived ortho-mosaic and the CHM. The extracted crowns subsequently were visually checked to avoid mixed crowns and crown polygons containing more than a single tree crown were removed. Subsequently, in-situ observations of the tree crowns were matched to the UAV-derived ITCs.

The occurrence and number of the trees per species used in the study are declared in Table 1. The composition of the forest is natural,