Attenuation correction of full-waveform airborne laser scanner data for improving the quality of volumetric forest reconstructions by simplified waveform history analysis

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Abstract. Full-waveform airborne laser scanning data yield a great amount of information for the analysis of vegetation density in forestry applications. So far, the processing of full-waveform laser scanner data in forestry applications has mostly been limited to the extraction of discrete maxima via a Gaussian decomposition. This will usually lead to a densification of the 3D point cloud between terrain model and crown model by 3-5 extra 3D points per laser pulse, plus information on echo width and amplitude. However, beyond this extraction of additional discrete 3D points, full waveform data may form a valuable basis for a fully volumetric representation of forest stands in a 3D voxel structure, wherein the voxel attributes are derived from the digitized waveform directly.
For this purpose, differential backscatter cross sections, derived from the digitized pulse echoes, have to be projected into a Cartesian voxel structure of a suitable resolution, wherein the voxel entries represent amplitudes of the cross section and can be interpreted as a local measure for the amount of pulse reflecting matter. However, the 'history' of each laser echo pulse is characterized by attenuation effects caused by reflections in higher regions of the crown. To achieve a radiometrically correct voxel space representation, the loss of signal strength caused by partial reflections on the path of a laser pulse through the canopy has to be compensated. Thereby, the correction term has to be derived from the digitized pulse echo itself. In this paper, we present an approach for a discrete correction, realized as a segment-based modification of the echo waveform amplitude. The basic idea of the procedure is to enhance the waveform intensity values in lower parts of the tree crown for portions of the pulse intensity, which have been reflected (and thus blocked) in higher parts of the crown. The paper will discuss the developed model of attenuation correction and show results from a validation both with synthetic and real world data.

Keywords: Full-waveform airborne laser scanning, attenuation correction, pulse history analysis

1. Introduction

Small-footprint full-waveform laser scanning has been increasingly used in forestry applications for some years now. This development triggers an enhanced demand for voxel based data-analysis

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methods. So far, the new approaches are mostly based on the generation of 3D raster domains derived from the extracted discrete 3D points [1]–[3]. Deriving the voxel attributes from the digitized waveform directly instead of using a densified point cloud was proposed by Persson et al. [4] and Buddenbaum et al. [5]. Lindberg et al. [6] point out that using ALS waveform data to describe the volumetric aspects of vertical vegetation structure is very promising.

We expect that these volumetric representations will facilitate the determination of parameters which could so far hardly be extracted from airborne laser scanner data, for instance vertical and horizontal forest structure, open stem area, lower tree crown delineation and classification as well as the density of understory vegetation. Moreover, a significant improvement of the precision of biomass and biodiversity parameters can be predicted. Generating volumetric forest stand representations of high geometric and radiometric quality from full-waveform airborne laser scanner data requires a series of geometric and radiometric transformations of the data into a voxel structure as well as an improved understanding of the interaction between laser pulse and pulse reflecting matter.

An important factor herein are attenuation effects caused by reflections in higher regions of the crown. So far, these effects are either not considered or only considered in a very simple way. Lindberg et al. use an iterative normalization algorithm based on the Beer-Lambert law to compensate the attenuation of the signal energy as the signal propagates through a canopy. Allouis et al. [7] correct the aggregated waveform with a logarithmic function. Furthermore, several simulation studies contribute to an improved understanding of signal-forest interactions [8]–[12].

In order to derive the biophysical structure of a forest stand from full-waveform airborne laser scanner data, advanced methods for attenuation correction are required. Finding a suitable correction method will contribute to improve the accuracy of volumetric forest reconstructions and enable forestry applications which require accurate information in the understory of a forest canopy [12]. In this paper we present an attenuation correction method based on a simplified waveform history analysis. The paper is divided into 5 parts: Part 2 treats the theoretical background, and part 3 describes the developed correction model. The results of the validation with synthetic and real world data are discussed in part 4. Finally a short conclusion is given in part 5.

2. Theory

The physical principle of full-waveform airborne laser scanning comprises the emission of laser pulses from an airborne platform, the interaction of the emitted pulse with the target, and the recording of the backscattered signal, called received waveform. On one hand, the shape of the received waveform depends on several sensor parameters (shape of the laser pulse, receiver impulse function, pulse spreading), on the other hand on the backscattering characteristics of the target [13]. The target properties, e.g. reflectivity, target size, and directionality of scattering, are summarized into one parameter: the differential backscatter cross section $\sigma(t)$. The formation of the received waveform $P_r(t)$ can be described mathematically as the result of a convolution of the emitted laser pulse $P_e(t)$ and the differential backscatter cross section [14].

$$P_r(t) = P_e(t) \otimes \sigma(t) \tag{1}$$

The most interesting quantity is the unknown backscatter cross section, which can be estimated with decomposion [15] or deconvolution [16-19] techniques. Depending on the chosen method the cross section is treated as a sum of discrete values or as a continuous variable [13]. In the latter case, the differential backscatter cross section can be projected into a Cartesian voxel structure (Figure 1). The voxel entries represent the amplitudes of the corresponding differential backscatter cross section and can be interpreted as a local measure for the amount of pulse reflecting matter.

The procedure of filling the voxel space has both geometric and radiometric aspects. The geometric aspects include an intersection of the diverging laser cone with the voxel structure and an

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interpolation procedure to obtain the actual voxel values. Before entering the waveform amplitudes into the voxel structure, these have to undergo some radiometric correction, which is the focus of this paper. There are different attenuation effects which influence the emitted waveform – on the one hand the attenuation due to atmospheric effects, on the other hand the attenuation of the signal

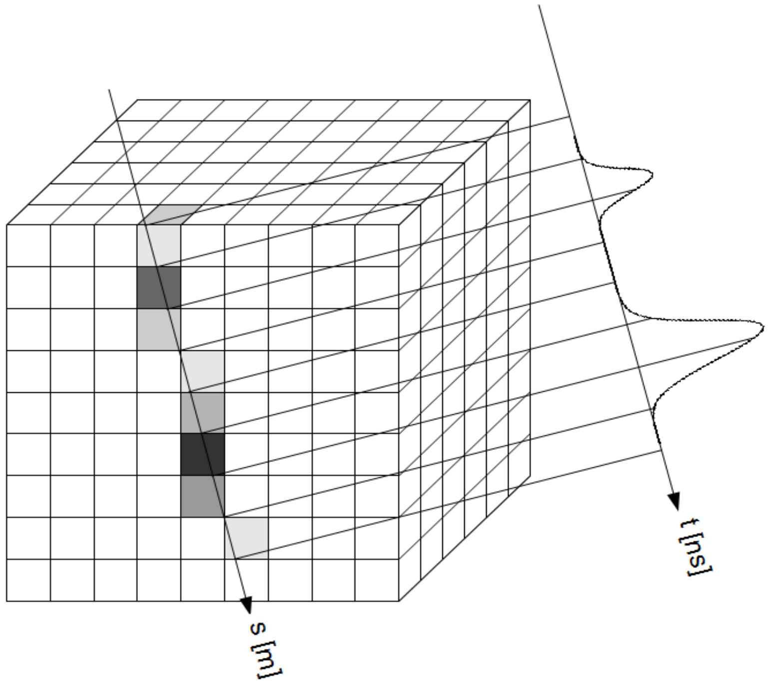

Figure 1: Cartesian voxel structure with projected differential backscatter cross section

during its propagation through the canopy. The former is treated in diverse studies [20, 21] and does not require a further discussion here. The latter issue is analyzed in the following section.

3. Method

During the propagation of the emitted laser pulse through a forest canopy, it interacts with different forest components (leaves, boughs, branches, forest floor). Depending on the material, the number of incoming photons is reduced due to reflection, transmission, absorption and scattering processes. Therefore, less photons are available for subsequent interactions. As a result, the received waveform signals within the canopy have a lower amplitude than it would be observed for an identical structure without the previous canopy structure interactions [22]. If the biophysical structure is determined from the waveform raw data, material in the lower parts of the canopy is thus underrepresented.

In their simulation study, Cawse-Nicholson et al. [12] used the Digital Imaging Remote Sensing Image Generation (DIRSIG) simulation environment to investigate the factors influencing the attenuation. DIRSIG waveform LiDAR simulation is a ray-tracing program which is able to model photon paths in a virtual scene. To simplify matters, the virtual forest structure was represented by a simple geometric model consisting of a couple of plates in several levels with predefined reflectance and transmission. Cawse-Nicholson et al. generated simulated waveforms in different experiments, performed a Gaussian decomposition to derive mean, amplitude and standard deviation for each peak, and developed a correction factor based on the results of the Gaussian decomposition.

Our correction method is similar to this approach, even though it is not based on the detailed consideration of single photons. In contrast to the theoretical approach of Cawse-Nicholson et al., we tackle the problem from a practical point of view. Our objective is to develop a correction method, which can be easily applied to real forestry data sets. Furthermore, our attenuation correction is derived from the complete recorded signal, not applying decomposition methods.

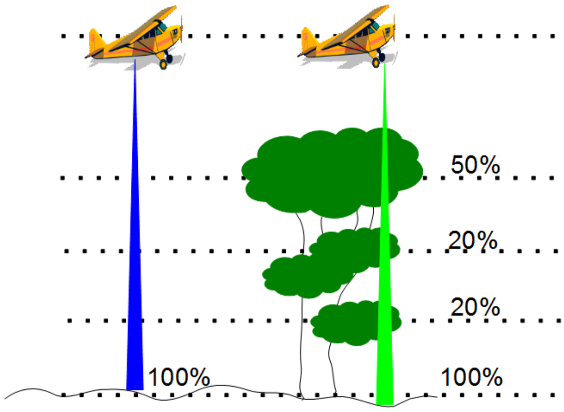

Figure 2: Synthetic example for the propagation of a laser pulse without interaction (left) and trough canopy (right)

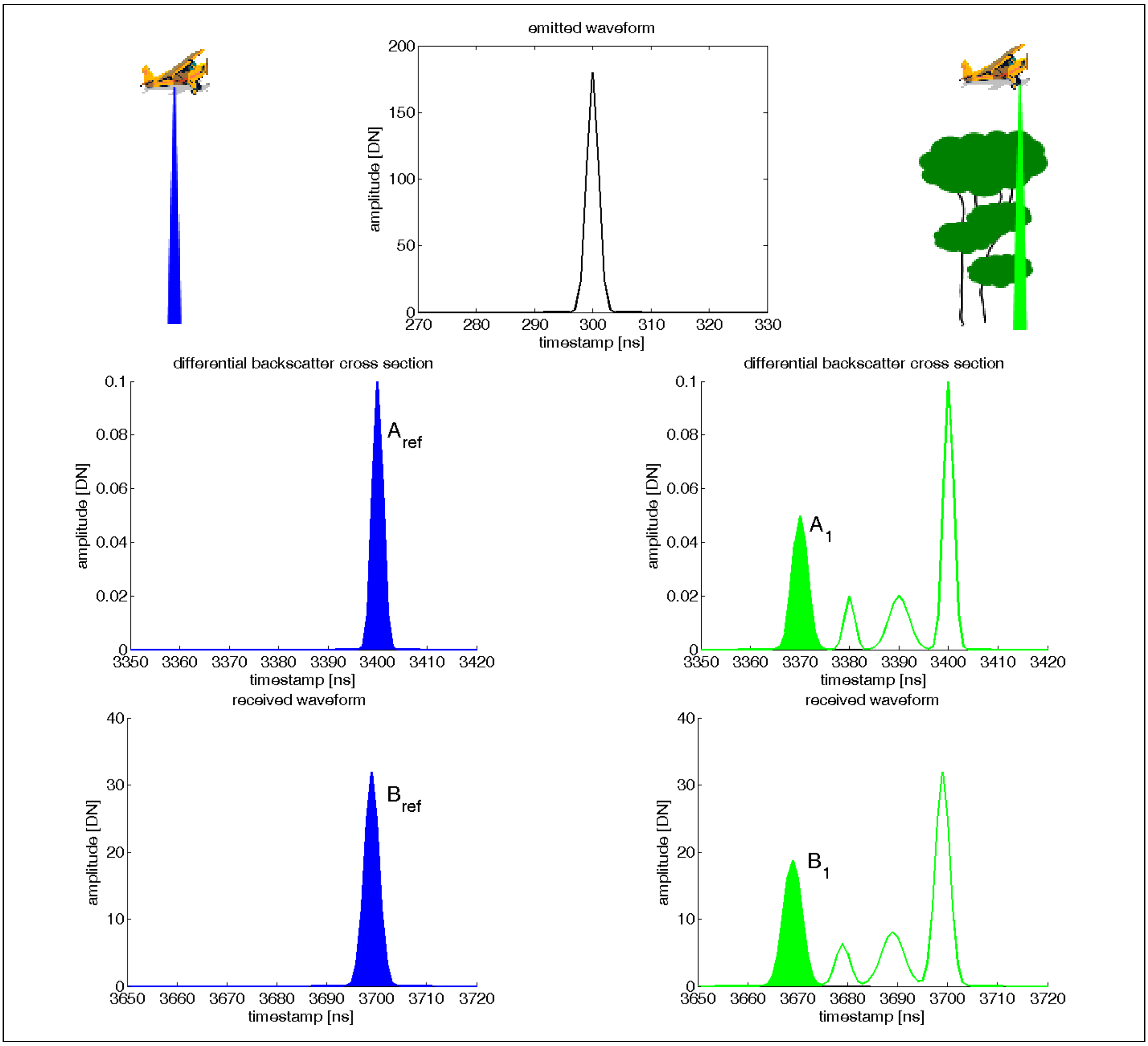

Figure 3: Synthetic emitted waveform (top), synthetic differential backscatter cross sections (middle) and received waveform (bottom) with highlighted areas under the curves (A_{ref}, B_{ref}, A_1, B_1)

3.1. Attenuation during the penetration trough the canopy

First of all we need to describe the attenuation during the propagation of the laser pulse trough the canopy with a suitable model. For this purpose, we create a synthetic example (Figure 2) consisting of two cases: the undisturbed propagation of the emitted laser pulse to the ground without any interactions (left), and the propagation through a canopy with interactions at three layers and the forest floor (right). The percentages in Figure 2 specify which proportion of the incident signal is reflected at each layer. The first case serves as reference for percentages in the second case. We designed a synthetic emitted waveform and two synthetic differential backscatter cross sections, where the spatial expansion of the tree layers is considered (Figure 3). An ideal received waveform without attenuation effects is obtained by convoluting emitted waveform and cross section (equation 1). In the next step, the attenuation is taken into account by decreasing the received waveform with a linear attenuation factor a_i calculated from the ratio between the area under the reference cross section A_{ref} (blue) and the area under the cross section for every interaction $A_1 - A_i$ (green).

$$a_i = 1 - \frac{A_i}{A_{ref}} \tag{2}$$

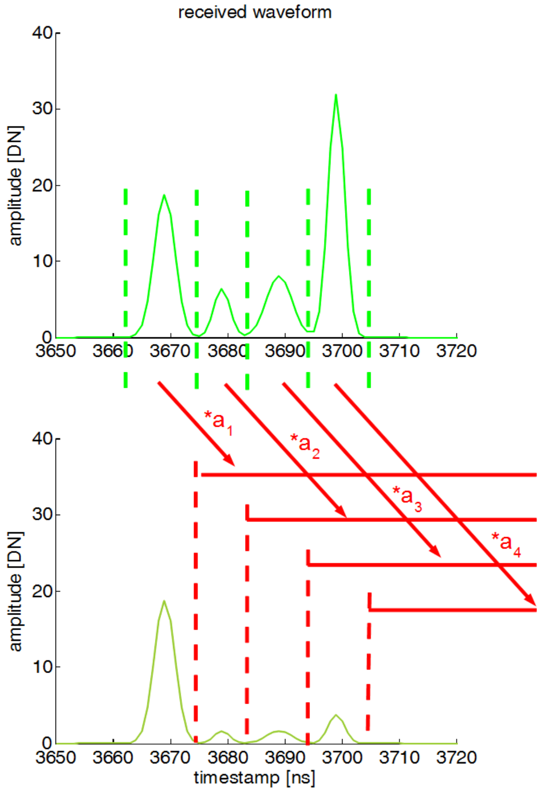

Figure 4: Received waveform after convolution (top) and waveform affected by attenuation (bottom)

3.2. Model of attenuation correction

To remove the above described attenuation effects, we developed a discrete correction method, realized as a segment-based modification of the echo waveform amplitude. The procedure is based on the increase of the waveform intensity values in lower parts of the tree crown for portions of the pulse intensity, which have been reflected in higher parts of the crown. Assuming that the attenuation of a laser pulse in the canopy fulfills the above described model, a correction factor can be developed by inverting the attenuation process. For this purpose, we calculate the portion p_i of the signal which was reflected at the first interaction by setting the area under the received waveform B_i in relation to the reference value B_{ref} (see figure 3, bottom):

$$p_i = \frac{B_i}{B_{ref_i}} \tag{3}$$

To estimate the area under the received waveform, the peaks and borders between the peaks have to be detected. This is done by a simple local minima/maxima search. Afterwards, we calculate a new reference value for the next interaction:

$$B_{ref_{i+1}} = B_{ref_i} * (1 - p_i) \tag{4}$$

The attenuation correction factor c_i is obtained as follows:

$$c_i = \frac{B_{ref_i}}{B_{ref_{i+1}}} \tag{5}$$

In this way, the attenuated received waveform can be corrected by stepwise increasing the amplitudes after each peak with the appropriate correction factor c_i. The deconvolution of emitted waveform and corrected received waveform results in the true differential backscatter cross section, which is free of attenuation effects and can be inverted to the correct biophysical structure. Our correction method is based on the (in fact only confinedly valid) assumption that all surfaces, which interact with the emitted laser pulse, have a similar reflectance. Strictly speaking, this applies only on synthetic data because the reflectance of leaves, branches and forest floor differ from each other. The results in the next section, however, show that the quality of the volumetric forest reconstruction is nevertheless considerably improved.

4. Results and Discussion

4.1. Validation with synthetic data

We generated the synthetic data as described in section 3.1. The left part of Figure 5 shows the initial received waveform resulting from the convolution of synthetic emitted waveform and synthetic differential backscatter cross section as well as the received waveform after consideration the attenuation. The results of the attenuation correction are presented in the right part of the figure. Herein, initial waveform and the corrected waveform lie in top of each other, proving that they are identical.

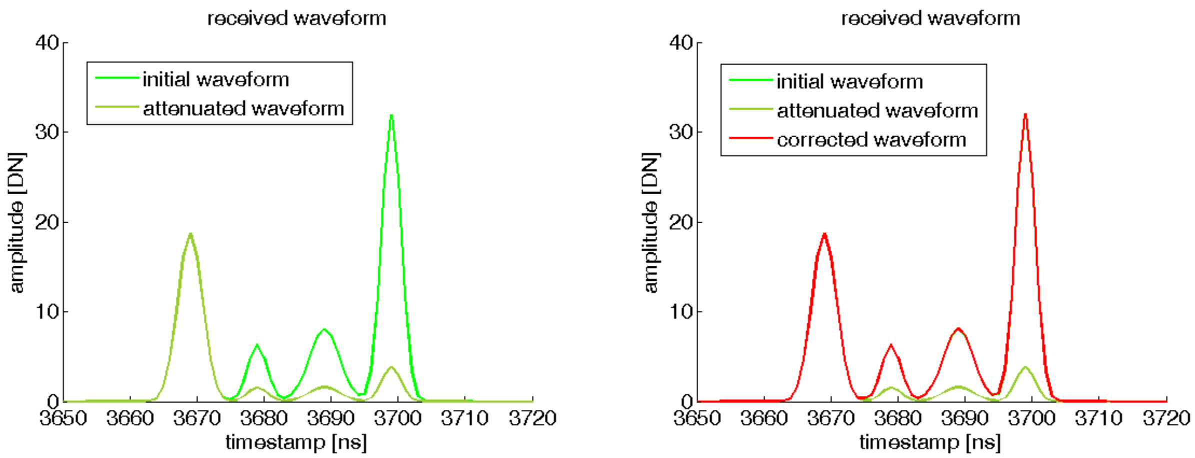

Figure 5: Initial waveform without attenuation and attenuated waveform (left), same with corrected waveform (right)

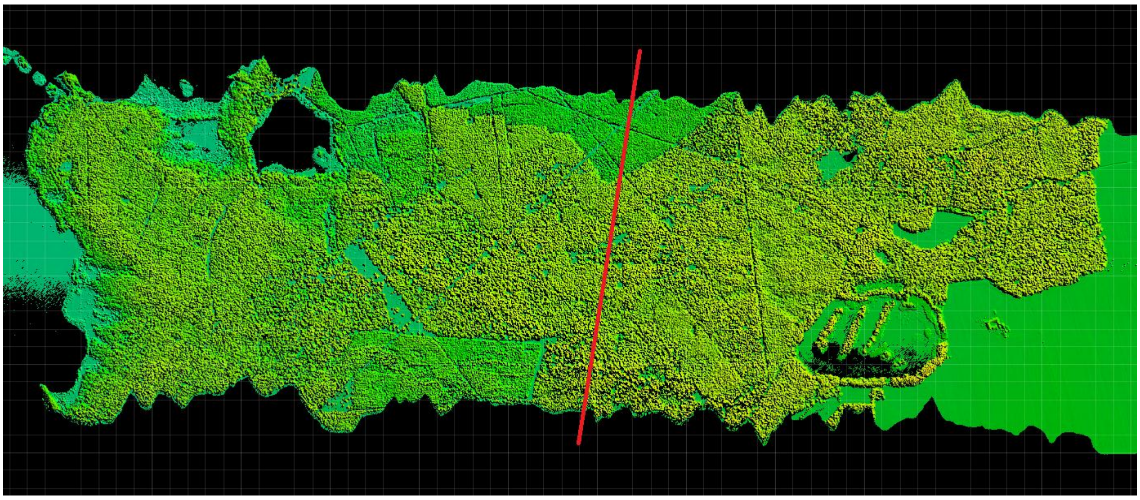

Figure 6: Top view of the investigated region generated with the software RiProcess

4.2. Validation with real world data

In addition to our synthetic data, a real world data set recorded with a Riegl LMS-Q680 scanner in March 2010 in the area of Oberlausitz in Saxony (Germany) is available. We concentrate our investigations on a mixed forest region shown in Figure 6. To calculate the attenuation correction factor (Equation 5), the reference value B_{ref} must be known. In contrast to the synthetic data, where the reference waveform results from a defined cross section (Figure 3), a suitable reference derived from the recorded data set itself is required here. According to the above described attenuation model, this reference is derived for each scan line from laser pulses penetrating to the ground without any canopy interaction (Figure 7). For this purpose, the mean value of the areas under all eligible waveforms in the nadir area of the scan line is estimated.

The comparison of the raw data and the corrected data after applying the method as shown in 3.2 shows the benefit of the developed correction method (Figure 8). As an example, the data of a section of the red marked scan line in Figure 6 is visualized as a vertical view with color coded waveforms. An improvement of the forest structure representation in the lower parts of the canopy can clearly be recognized.

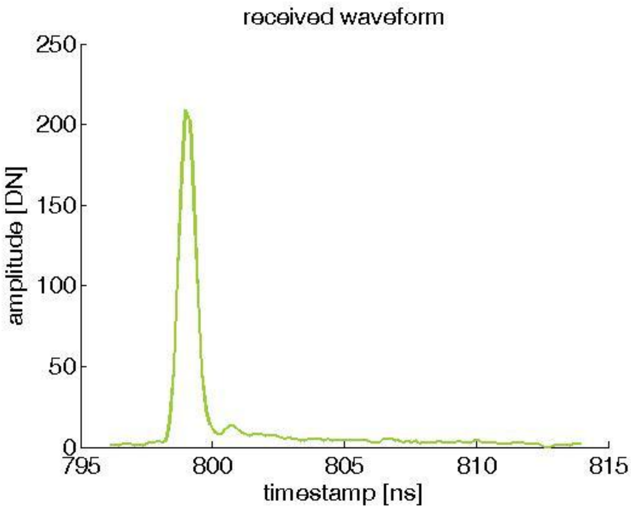

Figure 7: Example for a received waveform suitable for reference estimation

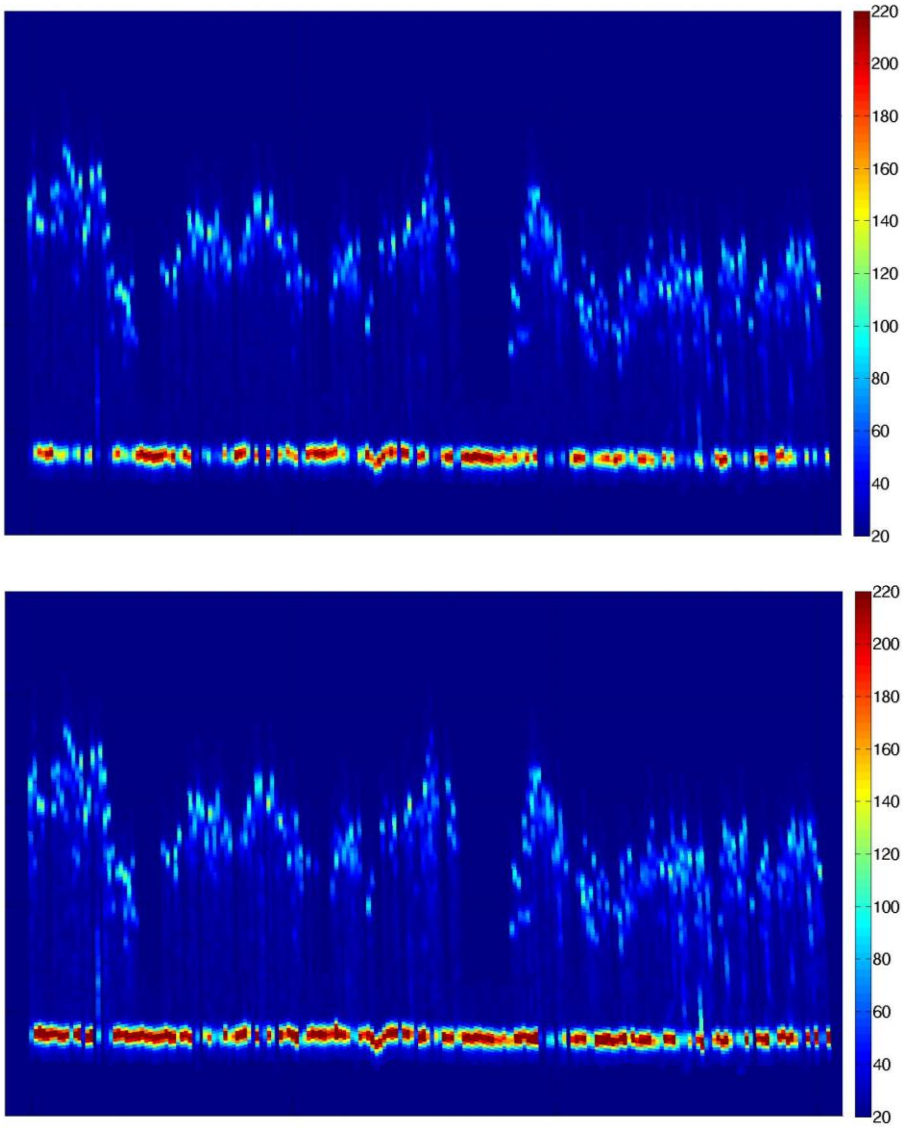

Figure 8: Vertical view of one scan line with color coded waveforms, top: raw data, bottom: corrected data

Figure 9 shows the comparison of raw data and corrected data for two single waveforms. For the majority of the pulses, the attenuation correction produces plausible results. However, there are some unexpected correction results, where the corrected amplitude of the ground reflection (Figure 9, right) becomes higher than the amplitude of the reference waveform (Figure 7), that also result from ground reflections. Assuming a homogeneous reflectance of the forest floor, the amplitudes of both ground reflections should actually be equal. This problem is obviously related to a violation of the assumption that all surfaces, which interact with the emitted laser pulse, have a similar reflectance (section 3.2.). Nevertheless, the attenuation correction can be applied on those waveforms because the ground reflection is mostly of subordinate interest.

Assessing the quality of the attenuation correction method, we have to take into consideration that the size of the correction factor significantly depends on the selection of the reference waveform. If the reference value B_{ref} is too low, the correction factor c_i becomes too large, and vice versa. We expect that the reference value is more likely too low, because in a typical forest the floor has a lower reflectance than leaves and branches. Another important factor is the reliability of the

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peak detection. The used algorithm provides a simple and fast detection of peaks but is not able to find entirely every one.

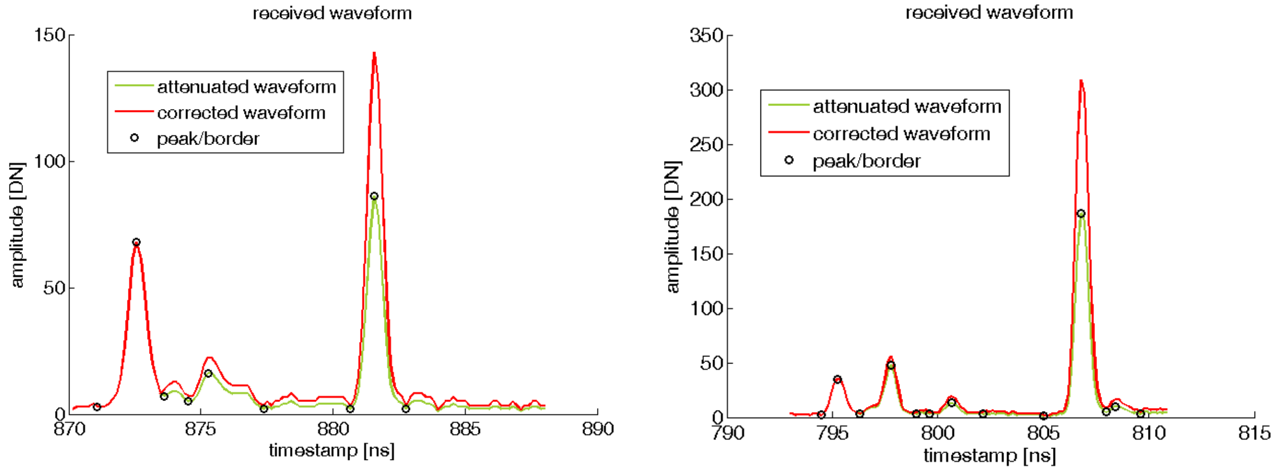

Figure 9: Comparison of good correction result, where the amplitude of the ground reflection is realistic compared to the reference waveform in Figure 7 (left) and poor correction result, where the amplitude of the ground reflection is much higher than the reference value (right)

5. Conclusion

In this study, we developed a discrete correction method to compensate the attenuation effects caused by reflections in higher regions of the canopy. Generating volumetric forest stand representations from corrected waveform data leads to a significant improvement of the radiometric quality of voxel data. Thus, the accuracy of forest parameters derived from the volumetric representation will improve, especially for application which extract information on the vertical structure of the lower canopy parts. Undoubtedly, the presented correction method is based on confinedly valid assumptions. Nevertheless, accepting those assumptions will usually be better than determining forest parameters from uncorrected data.

In current work, the discrete segment-based correction method will be extended to an integral method correcting the waveform at each recorded sample and avoiding the necessity of peak detection [23]. Further experimental investigations are needed to assess which correction approach conforms best to the physical reality. For this purpose, a recreated tree model of exactly known geometry will be scanned with a terrestrial full waveform laser scanner to evaluate the functionality of the correction methods. In addition, the selection of the reference value for attenuation correction needs further optimization.

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