ECHO DETECTION AND LOCALIZATION IN FULL-WAVEFORM AIRBORNE LASER SCANNER DATA USING THE AVERAGED SQUARE DIFFERENCE FUNCTION ESTIMATOR

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ABSTRACT

Full-waveform airborne laser scanners (ALS) transmit short laser pulses towards the Earth’s surface and record the complete backscattered echo. The backscattered echo from flat terrain is simply a replica of the original laser pulse, but over vegetated and built-up areas the backscattered echo is often rather complex. The waveform is commonly modelled as a superposition of a number of distinct echoes, which involves the detection and localization of these echoes and a non-linear optimization of the model. This paper discusses the averaged square difference function (ASDF) method for detecting and localizing echoes in full-waveform ALS data. The ASDF is analytically equivalent to the direct correlation method. The results of echo detection and range estimation by ASDF were compared empirically with those derived by classical pulse detection in combination with Gaussian Decomposition. Furthermore, the ASDF approach was also tested for its adequacy to suppress false echoes caused by the so-called ringing effect which may occur in ALS data in case of strong echoes. It is found that the results of the ASDF approach coincide to a high percentage with those of Gaussian Decomposition. Moreover, this approach suppresses the detection of false echoes due to the ringing effect.

1. INTRODUCTION

Airborne laser scanning (ALS) is an optical measurement technique for obtaining information about the Earth’s surface such as the topography of the land surface, the vegetation cover and the seafloor elevation in shallow waters. This technique is also often referred to as LIDAR, which stands for Light Detection And Ranging. Most ALS instruments use pulse lasers, i.e. they send out short laser pulses in the visible and/or infrared part of the electromagnetic spectrum and measure some properties of the backscattered light to find range and/or other information of a distant target. While many of the first ALS systems provided only range information, ALS systems that digitize and record the complete echo waveform are becoming increasingly available.

Bathymetric lidar instruments designed for measuring depth of relatively shallow, coastal waters were the first full-waveform systems. These sensors transmit pulses at green wavelengths that penetrate several meters into the water depending on water clarity and turbidity. According to Wozencraft and Millar (2005) the maximum detectable depth of the seafloor is about 60m. Scattering and spreading of the laser pulse at the air-water boundary, within the water column and the seafloor results in relatively complex echo waveforms (Tulldahl and Steinvall, 1999).
Therefore, as Guenther et al. (2000) point out, it has not been possible to calculate all depths with high accuracy and reliability in real time during data acquisition. Precise depths are determined via post-flight processing of stored waveforms. More recently, NASA developed a small footprint waveform-digitizing bathymetric lidar that is also capable of mapping topography and vegetation (Wright and Brock, 2002). Nayegandhi et al. (2006) demonstrate the capability of this sensor for depicting the vertical structure of vegetation canopies.

Also the echo waveform from vegetated areas is in general rather complex, in particular when the laser footprint is large (Sun and Ranson, 2000). Therefore also large-footprint airborne and spaceborne lidar systems designed for mapping of vegetation capture the complete echo waveform in order to allow the retrieval of geophysical parameters in post-processing. One of the airborne systems is the Laser Vegetation Imaging Sensor (LVIS) that transmits 10 ns long infrared pulses at repetition rates up to 500 Hz (Blair et al., 1999). Depending on flight altitude the footprint diameter is 1−80m. So far, no satellite lidar system designed for the primary purpose of global vegetation mapping is available. However, the Geoscience Laser Altimeter System (GLAS) on-board of the ICESat satellite has acquired waveform data not only over the ice sheets but also over land surfaces. This will allow testing the usefulness of large-footprint (66 m) satellite-based waveform measurements for characterizing forest structure and biomass (Harding and Carabajal, 2005).

For topographic mapping a small laser footprint and a high point density are required to collect a high number of geometrically well defined terrain echoes. Various filters that classify the echoes into terrain and off-terrain echoes based on purely geometric criteria can be used to reconstruct the terrain surface (Sithole and Vosselman, 2004; Kobler et al., 2007). Given that this approach has worked well for lidar systems with ranging capabilities only, the need for waveform digitizing lidar systems has not been evident for this application. Also, the benefit of waveform data for emerging ALS applications like 3D city modelling (Vosselman et al., 2005) and forest mapping (Hollaus et al., 2006) was not clear even though some early studies demonstrated the rich information content of small-footprint waveform data over land surfaces (Lin, 1997). Nevertheless, the first commercial waveform-digitizing laser scanner system started appearing in the market in 2004. 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:

- Jutzi and Stilla (2003) point out that recording the waveform is advantageous because algorithms can be adjusted to tasks, intermediate results are respected, and neighbourhood relations of pulses can be considered. For example, Wagner et al. (2004) show that depending on the observed target the range determined by different echo detection methods may differ by several decimetres for a laser footprint diameter of 1 m. Recording the waveform allows applying different detectors for different targets.
- over forested areas the number of detected echoes can be significantly higher for waveform recording ALS systems compared to first/last pulse systems (Persson et al., 2005; Reitberger et al., 2006).
- in addition to geometric information, waveform digitizing ALS systems also provide a number of physical observables such as the echo width, the echo amplitude and the backscatter cross section (Wagner et al., 2006). This opens the possibility to classify the echo point cloud based on geometric and physical properties.
- the echo from vegetation is in general broader than the echo from the ground surface (Persson et al., 2005). Doneus and Briese (2006) demonstrated that it is possible to improve the quality of terrain models by removing wide echoes before the filtering process.
the intensity of laser echoes, respectively the backscatter cross section, can be calibrated using portable brightness targets (Kaasalainen et al., 2005). This is important to enable the comparison of measurements taken by different sensors over different areas.

- in electrodynamics, scattering processes are described quantitatively by the cross section. The cross section is hence a fundamental quantity in radar and lidar remote sensing. Since it can be derived from calibrated waveform data, the gap between experimental results and electromagnetic theory could be bridged (Wagner et al., 2008).

The waveform recorded by small-footprint waveform-digitizing ALS systems is essentially the result of a convolution of the ALS system waveform and the cross section profile of the observed target (Wagner et al., 2006). Therefore, deconvolution methods such as the Wiener filter can be used for retrieving the surface response (Jutzi and Stilla, 2006). A more commonly used waveform processing method is to decompose the original waveform into a series of Gaussian pulses (Hofton et al., 2000). This method is referred to as Gaussian decomposition and is applicable when the ALS system waveform resembles a Gaussian pulse (Wagner et al., 2006). Chauve et al. (2007) extended the method to allow for pulse shapes more complex than the Gaussian model, such as the lognormal or the generalized Gaussian function.

The decomposition of the waveform typically consists of two main steps. In the first step the number of individual echoes is estimated, along with initial estimates of the echo parameters such as location, amplitude and width. Then non-linear optimization methods such as the Levenberg-Marquardt algorithm (Hofton et al., 2000; Wagner et al., 2006; Reitberger et al., 2006; Chauve et al., 2007) or the Expectation—Maximization algorithm (Persson et al., 2005) are applied to obtain final estimates of the echo parameters. As noted by Chauve et al. (2007) the optimization relies strongly in the initial parameter estimates. Initial estimates of the number and position of echoes can be obtained by classical pulse detection methods such as zero crossing or constant fraction (Wagner et al., 2004). Unfortunately, these methods are typically very susceptible to measurement noise.

The impact of noise may be reduced by using correlation techniques for pulse detection (Thiel et al., 2005). Therefore, we tested the Averaged Square Difference Function (ASDF) described in Section 2.1 for detecting echoes in waveforms recorded by the RIEGL full-waveform sensor LMS-Q560 (Wagner et al., 2006). The ASDF method is closely related to the Direct Correlation (DC) method, as discussed in Section 2.2. Because ASDF can use reference pulses of different shape, it can also be applied for non-Gaussian pulse forms. Therefore, it was also investigated whether ASDF might alleviate the problem of laser pulse “ringing”, which is an effect due to bandwidth limited receiver electronics that causes a smaller peak right after the main peak.

2. THEORY

2.1 Averaged Square Difference Function

The Averaged Square Difference Function (ASDF) is a time delay estimation technique based on the correlation of a reference signal \( x_1(t) \) and the measured signal \( x_2(t) \) (Jacovitti and Scarano, 1993). In our case, \( x_1(t) \) may be a copy of an emitted laser pulse and \( x_2(t) \) is the recorded echo waveform. Both \( x_1(t) \) and \( x_2(t) \) are equidistantly sampled time series with sampling interval \( T \). A suitable distance measure between \( x_1(t) \) and the shifted waveform \( x_2(t + \tau) \) is the response value \( R_{ASDF}(\tau) \) of their ASDF which is defined as follows (Jacovitti and Scarano, 1993):
where the time shift $\tau = -NT, (-N + 1)T, ..., NT$ is an integral multiple of $T$. Figure 1 shows a typical example of an ASDF appearing in full-waveform laser scanning.

![Figure 1: Two discrete time series $x_1(t)$ (copy of the system waveform) and $x_2(t)$ (backscattered waveform) and their ASDF.](image)

The goal is to detect and to localize precisely the echoes of the emitted laser pulse. As $R_{ASDF}(\tau)$ becomes minimal for $x_1 = x_2$ and $\tau = 0$, tentative echoes are located at positions $d$ (integer values) with

$$d = \arg\min_{\tau} (R_{ASDF}(\tau))$$

(2)

Since multiple echoes may appear, not only the global minimum of $R_{ASDF}(\tau)$, but also its local minima have to be taken into account. To retrieve initial estimates for those minima, several criteria for minima detection have been applied as follows:

- classical minima detection: $R_{ASDF}(d)$ has to be lower or equal than its “neighbours” $R_{ASDF}(d - T)$ and $R_{ASDF}(d + T)$
- 1st derivative $\frac{\partial R_{ASDF}}{\partial \tau}(\tau) := 1/2(R_{ASDF}(\tau + T) - R_{ASDF}(\tau - T))$:
  $$\left(\frac{\partial R_{ASDF}}{\partial \tau}(d - T) < 0 \quad \text{and} \quad \frac{\partial R_{ASDF}}{\partial \tau}(d + T) > 0\right)$$

The first derivatives of the neighbouring points are used to decrease the sensitivity of the algorithm to saw tooth distortions in the waveform. The above criteria were also applied to detect local maxima of $R_{ASDF}(\tau)$ using $-R_{ASDF}(\tau)$. To make the echo detection more robust, three additional criteria were used:

- To avoid the detection of noise peaks, the maximum of $x_2(t)$ has to be greater or equal than a certain threshold $x_{\min}$ which is empirically chosen.
To avoid the detection of subsequent minima in a minimal “plateau” of \( R_{\text{ASDF}}(\tau) \), there has to be a local maximum of \( R_{\text{ASDF}}(\tau) \) at a position \( d_3 \) between two subsequent local minima at positions \( d_1 \) and \( d_2 \), i.e. \( d_1 < d_3 < d_2 \).

Subtle local minima as shown in Figure 2 (min₁ and min₄) are suppressed by the following threshold criterion

\[
\max\{(R_{\text{max,}l} - R_{\text{ASDF}}(d)), (R_{\text{max,r}} - R_{\text{ASDF}}(d))\} \geq \Delta R \geq 0.3(R_{\text{MAX}} - R_{\text{MIN}})
\]

where \( R_{\text{max,}l} \) and \( R_{\text{max,r}} \) are the response values of the left and right neighbouring local maxima of \( R_{\text{ASDF}}(d) \), and \( R_{\text{MAX}} \) and \( R_{\text{MIN}} \) are the absolute maximum and minimum of \( R_{\text{ASDF}}(\tau) \), respectively. The threshold \( \Delta R \) was empirically selected.

After the echo detection, the echo positions were estimated with sub-sampling accuracy by using parabola fitting (Jacovitti and Scarano, 1993). Given a coarsely estimated echo at a position \( d \), its final position \( d_{\text{final}} \), i.e. the peak of the parabola is at

\[
d_{\text{final}} = - \frac{T}{2} \frac{R_{\text{ASDF}}(d + T) - R_{\text{ASDF}}(d - T)}{R_{\text{ASDF}}(d + T) - 2R_{\text{ASDF}}(d) + R_{\text{ASDF}}(d - T)} + d \quad (3)
\]

### 2.2 Relation with Direct Correlation

In this section, it is shown that ASDF is equivalent to the Direct Correlation (DC) method if normalized in the interval \([0, 1]\). \( (R_{\text{ASDF}}(\tau) \) has to be multiplied by \(-1\) prior to the normalization.)

The direct correlation function is defined as follows (Jacovitti and Scarano, 1993; Moon and Stirling, 2000):

\[
R_{\text{DC}}(\tau) = \frac{1}{N} \sum_{k=1}^{N} (x_1(kT)x_2(kT + \tau)) \quad (4)
\]

If Equation (1) is re-formulated as follows:

\[
R_{\text{ASDF}}(\tau) = \frac{1}{N} \sum_{k=1}^{N} (x_1(kT))^2 - 2 \frac{1}{N} \sum_{k=1}^{N} (x_1(kT)x_2(kT + \tau)) + \frac{1}{N} \sum_{k=1}^{N} (x_2(kT + \tau))^2
\]
this yields \((a \text{ and } b \text{ are constant for given } x_1(t) \text{ and } x_2(t))\)

\[
R_{ASDF}(\tau) = a + b - 2R_{DC}(\tau)
\]

As one can see that \(R_{ASDF}(\tau)\) and \(R_{DC}(\tau)\) have their extreme values at the same positions because they are linearly dependent. \(R_{ASDF}(\tau)\) becomes minimal if \(R_{DC}(\tau)\) becomes maximal and vice versa.

Without loss of generality, we can enlarge the domains of \(x_1(t)\) and \(x_2(t)\) by zero padding at the margins of the respective domain. If \(N\) or more zero values are added at each margin, the original domains do not overlap any more and therefore \(R_{DC}(\tau)\) becomes minimal for \(\tau \leq -NT\) and \(\tau \geq NT\). Since neither \(x_1(t)\) nor \(x_2(t)\) contain negative values when dealing with ALS waveforms, \(R_{DC} = 0\) for these \(\tau\); thus, \(R_{ASDF}(\tau)\) becomes maximal as stated above:

\[
\max\{R_{ASDF}(\tau)\} = a + b
\]

Now, we can normalize both \(R_{ASDF}(\tau)\) and \(R_{DC}(\tau)\) into the interval \([0, 1]\) by first changing the sign of \(R_{ASDF}(\tau)\), then subtracting the respective minimum of both functions and dividing by the new maximum:

\[
R_{ASDF,norm} = \frac{-R_{ASDF} - (a + b)}{-\min\{R_{ASDF}\} - (a + b)} = \frac{2R_{DC}}{(a + b) - \min\{R_{ASDF}\}}
\]

By performing the same substitution (5) in the denominator, one gets

\[
R_{ASDF,norm} = \frac{2R_{DC}}{(a + b) - (a + b) + 2\max\{R_{DC}\}} = \frac{2R_{DC}}{2\max\{R_{DC}\}} = R_{DC,norm}
\]

3. DATA SETS

Two data sets acquired using the RIEGL full-waveform digitizing sensor LMS-Q560 have been used within this study. The sensor is typically operated at flight altitudes between 300 and 1000 m. Given a laser beamwidth of 0.5 mrad, the laser footprint thus varies between about 15 and 50 cm. The width of the laser pulse at half maximum is 4 ns and the digitizing interval is 1 ns. The laser wavelength is 1.5 μm. For more technical details see Wagner et al. (2006) and http://www.riegl.com/.

3.1 Schönbrunn 2005

The first data set used in this study stems from a flight campaign over the Schönbrunn area in Vienna carried out in the year 2005. This campaign consisted of 14 flight strips (side overlap 60%) with an altitude of 500 m above ground and an average point density of 4 points per square metre within the strip. The data were acquired on April 5, 2005 before the greening-up of the vegetation. The two selected samples contain the waveforms of 10,000 consecutive laser pulses each and were taken from areas with rather dense vegetation to observe a high number of complex echoes (see Figure 3).
3.2 Leithagebirge 2007

The second data set was used to study the performance of the ASDF method for recognizing laser ringing effects. It stems from a flight campaign with the LMS-Q560 carried out over the Leithagebirge in Eastern Austria (terrain height 200-500m) in the year 2007 and showed a large number of artificial echoes due to the ringing effect. The whole measurement campaign consisted of more than 200 flight strips (side overlap 70%) with an average flying height of 750 m above sea level and an average point density of four points per square metre within the strip. We selected the longest flight strip (number 16) which was acquired on April 5, 2007. Figure 4 shows a visualization of the digital surface model (DSM) of the acquired flight strip which includes open land as well as urban areas and forests. The sub-region displayed in Figure 4 shows a football field surrounded by forests and some buildings.
4. METHOD

To evaluate the performance of the ASDF method the retrieved number of echoes and their position estimates were compared to the results of the Gaussian decomposition method as described in Wagner et al. (2006). The latter method derives its initial estimates by combining the maximum detection method (maximum detection considers those points whose values exceeds the respective values of its immediate neighbours) with zero crossing (sign change of first derivative). Then the Levenberg-Marquardt method is used to refine the initial estimates of location, amplitude and width of each echo. However, the number of echoes is not subject to the optimization step which means that any effects of an initially wrong guess can not be recovered. This highlights the importance of a correct detection of echoes prior to optimization in this decomposition approach.

The ASDF method was tested with two different reference pulses $x_1(t)$. In the first case, $x_1(t)$ was determined by averaging all copies of the transmitted laser pulses as recorded by LMS-Q560 during the respective overflights (Figure 5). In the second case an ideal Gaussian pulse was used as reference pulse $x_1(t)$. It was determined by fitting a Gaussian function to the observed system waveform of LMS-Q560 (Figure 5).

In the first step of the evaluation it was tested how many echoes are detected by the three methods described above. Then the range estimate of “identical” echoes was compared by calculating the difference of the echo position in the time domain. Echoes were taken as identical when their absolute difference in range was lower than the digitizing interval (1 ns). These tests were performed using the test data acquired over Schönbrunn in 2005 (Section 3.1).

![Figure 5: Mean reference pulse (blue solid line) and fitted Gaussian pulse (black dotted line).](image)

To evaluate the capability of ASDF to avoid false echo detection in case of laser ringing, the LMS-Q560 data set acquired over the Leithagebirge (Section 3.2) was analysed. The ringing effect is caused by the scanner’s internal signal processing chain from the photo diode via the amplifier chain to the input of the signal digitizer. Especially strong optical pulses yield non-linear saturation effects in the photo diode and the electronics. According to the signal compressing design of the amplifier chain, the ratio of the second local maximum to the main echo signal increases with increasing signal strength of the optical echo signal. This artefact often accompanies the recorded copy of the emitted laser pulse as well as the recorded echoes in case of high signal strength. The delay between the true and the “ringing” mode lies typically within the range from 10 to 14 ns (corresponding to 1.5 to 2.1 m). Figure 6 shows a typical example of a
waveform “suffering” from the ringing effect. This effect has not only been observed in case of LMS-Q560 but also for the TopEye Mark II full-waveform ALS sensor (Reitberger et al., 2006; Nordin, 2006).

Figure 6: Emitted laser pulse and echo waveform both “suffering” from the ringing effect

5. RESULTS

5.1 Number of Echoes

The results of the experiment concerning echo detection described above are summarized in Table 1. As can be seen, the reference pulse used for the ASDF method does not influence the number of echoes significantly. However, the number of echoes detected using maximum detection is some 5% higher than the number of echoes detected using the ASDF method. Furthermore, one can learn from Table 1 that maximum detection is much more likely to detect two echoes per pulse than the ASDF-based method. This might be an indication for the increased likelihood of the detection of false echoes due to the ringing effect.

Table 1: Number of echoes computed with maximum detection vs. ASDF-based echo detection. Top: Sample 1 (Strip 2), bottom: Sample 2 (Strip 5), each containing 10,000 laser pulses. This table refers to the Schönbrunn data set.

<table>
<thead>
<tr>
<th>Method</th>
<th># detected echoes</th>
<th>detected echoes per pulse (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>0</td>
</tr>
<tr>
<td>Maximum Detection</td>
<td>15,044</td>
<td>0.82</td>
</tr>
<tr>
<td>ASDF (Gaussian Pulse)</td>
<td>14,422</td>
<td>1.47</td>
</tr>
<tr>
<td>ASDF (Mean Reference Pulse)</td>
<td>14,566</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Detection</td>
<td>16,263</td>
<td>0.43</td>
</tr>
<tr>
<td>ASDF (Gaussian Pulse)</td>
<td>15,497</td>
<td>0.61</td>
</tr>
<tr>
<td>ASDF (Mean Reference Pulse)</td>
<td>15,653</td>
<td>0.61</td>
</tr>
</tbody>
</table>
5.2 Position of Echoes

Table 2 shows a summary of the results of our experiment concerning the comparison of range estimates. It can be seen that in more than 85% of all cases, the positions of the echoes detected with Maximum Detection (finally estimated with Gaussian Decomposition using the Levenberg-Marquardt algorithm) coincide with those detected with ASDF and estimated using parabola fitting. In case of a "match" the range estimates obtained with Gaussian Decomposition and ASDF can be regarded as equivalent: the absolute values of the medians of difference are well below 1/1000 of the sampling rate of 1 ns, while the standard deviations of the differences are lower than 0.15 ns. In metric dimensions, this corresponds to 2.25 cm in the direction of the laser beam which is a very low value in comparison to the ranges appearing in ALS. In analogy with the results shown in Section 5.1, the reference pulse had a negligible influence on the results.

Table 2: Comparison of echo estimation, referring to the Schönbrunn data samples.
Id. Echoes ... Percentage of identical echoes, med ...median of difference (in ns), $\sigma$ ... standard deviation of difference (in ns)

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian Decomposition / ASDF (Gauss.Pulse)</td>
<td>86.7% -0.0004 0.12</td>
<td>86.4% -0.0004 0.13</td>
</tr>
<tr>
<td>Gaussian Decomposition / ASDF (Mean Ref. Pulse)</td>
<td>86.9% 0.0002 0.12</td>
<td>86.8% -0.00007 0.13</td>
</tr>
<tr>
<td>ASDF (Mean Ref. Pulse) / ASDF (Gauss.Pulse)</td>
<td>98.7% -0.0008 0.05</td>
<td>98.7% -0.001 0.05</td>
</tr>
</tbody>
</table>

5.3 Ringing Effect

As stated above, the second experiment focused on how the use of ASDF/correlation-based techniques could suppress the detection of false last echoes due to the ringing effect. For this purpose, the range estimates for the last echoes derived by Gaussian Decomposition and ASDF were compared for the data of flight strip 16 in which 19.8% of all pulses were affected by this phenomenon (see Table 3).

In contrast to the Schönbrunn example, the recorded emitted laser pulse – rather than the idealized or averaged pulses used in the previous experiments – was taken as reference pulse, since the delay and the amplitude of the false ringing echoes may change slightly for each emitted pulse. For this experiment, last echoes within range 1.5–2.1 m to the penultimate echo and amplitude below 1/5 of that of the penultimate echo were regarded as false positives due to ringing (Reitberger et al., 2006). Table 3 shows the results of this range comparison.

Table 3: Histogram of a manually selected subset of echoes which were likely caused by “ringing” (top) and core figures of the Leithagebirge data set (bottom)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of laser pulses</td>
<td>12968847</td>
</tr>
<tr>
<td>Number of pulses “ringing”</td>
<td>2568231</td>
</tr>
<tr>
<td>Median difference in range (ASDF minus Gaussian Decomp.)</td>
<td>-1.865m</td>
</tr>
<tr>
<td>Standard deviation of the differences</td>
<td>0.840m</td>
</tr>
</tbody>
</table>
Table 3 shows that the majority of the differences has a value of approx. −1.9 m which corresponds to approx. −12.5 ns in the time domain, as was expected. Figure 7 shows a detail of the digital surface model of the football field displayed in Figure 4, middle. The left image was derived with the results of Gaussian decomposition. It is a typical example for how the ringing effect causes depression artefacts in the surface model. The right image shows the DSM of same area, now derived using the results of the ASDF method. It shows that in this area the use of the ASDF method for echo estimation successfully suppressed false echoes due to the ringing effect.

![Figure 7: DSMs of a part of the football field shown in Figure 4 (resolution: 0.5 m), derived by the last echoes. The green spots are typical depression artefacts caused by the ringing effect. Left: DSM derived using the results of Gaussian Decomposition; Right: DSM derived using the results of ASDF](image)

6. CONCLUSION

This study provided evidence that echo detection and pulse localization using the ASDF method is a promising approach. To a high percentage, the results of ASDF/correlation-based techniques coincide with those achieved using a Gaussian decomposition method which involves an initial parameter estimation and non-linear optimization step. Thus, using ASDF, it may not be necessary to determine the exact position of the echoes with non-linear fitting methods but the number and location of echoes could already be fixed after applying the ASDF method. This would speed up the processing of full-waveform ALS data which is important due to the high data volume acquired by this sensor type. Furthermore, it was shown that it is possible to suppress the detection of false echoes due to the ringing effect. Since this effect highly influences the detection and localization of the last echoes, its suppression is essential for ensuring a high quality of derived digital terrain models. Since the ASDF is not sensitive to the pulse shape, it is possible to use its results not only in combination with Gaussian decomposition, but also with more general approaches.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


