

HIGH-RESOLUTION WAVEFORM ACQUISITION AND ANALYSIS OF LASER PULSES

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KEY WORDS: Urban, Waveform, Analysis, Laser scanning, LIDAR, Measurement, Feature.

ABSTRACT:

In this paper we describe investigations for digital recording of received laser pulses and a detailed analysis of the pulse waveform. An experimental system was constructed using an airborne laser scanning system and a receiver unit with a high-resolution sampling rate, which is above the sampling rate of current commercial laser systems. Capturing the temporal waveform by simultaneous scanning of the scene delivers a data volume (space-time cube). Such a data cube of the received signals allows exploiting different features without selecting a special feature or a measuring technique in advance. For the main investigation a ground based sensor platform is used to measure the urban scene. Surface variations within the spatial beam width result in special waveforms. We explored the capabilities of analyzing the shape of the waveform for surface features in form of distance, roughness, and reflectance for each backscattered pulse. An iterative estimation algorithm (Gauss-Newton method) is proposed to get a parametric description of the original waveform by a Gaussian. Single responses and more than one response (multiple pulses) are investigated. Additionally, the data cube opens the possibility of considering neighborhood relations for space-time filtering or segmentation. Image slices extracted from the data cube were processed to estimate line segments for surface features. This has a significant advantage: the estimated lines are not based on single range points received from a pulse detector which delivers more or less accurate range values, but they are based directly on the intensity distribution of the backscattered signal. Since many values of the intensity distribution have contributed to each line segment, the accuracy of location can be much better than the pixel dimension of the image slice.

1. INTRODUCTION

The automatic generation of 3-d models for a description of man-made objects, like buildings, is of great interest in photogrammetric research. In photogrammetry a spatial surface is classically measured by triangulation of corresponding image points from two or more pictures of the surface. The points are manually chosen or automatically detected by analyzing image structures. Besides this indirect measurement using object characteristics, which depends on natural illumination, active laser scanner systems allow a direct and illumination-independent measurement of the range. Laser scanners capture the range of 3-d objects in a fast, contactless and accurate way. Overviews for laser scanning systems are given in (Huising & Pereira, 1998; Wehr & Lohr, 1999; Baltsavias, 1999).

Current pulsed laser scanner systems for topographic mapping are based on time-of-flight ranging techniques to determine the range of the illuminated object. The time-of-flight is measured by the elapsed time between the emitted and backscattered laser pulses. The signal analysis to determine the elapsed time typically operates with analogue threshold detection (e.g. peak detection, leading edge detection, constant fraction detection). Some systems capture multiple reflections, caused by objects which are smaller than the footprint located in different ranges. Such systems usually capture the first and the last backscattered laser pulse (Baltsavias, 1999). Currently first pulse as well as last pulse exploitation is used for different applications like urban planning or forestry surveying. While first pulse registration is the optimum choice to measure the outer envelope of partially penetrable objects (e.g. canopy of trees), last pulse registration should be chosen to measure non-penetrable surfaces (e.g. ground surface).

Beside the first or last pulse exploitation the complete waveform in between might be of interest, because it includes the backscattering characteristic of the illuminated field. Investigations on analyzing the waveform were done to explore the vegetation concerning the bio mass, foliage or density (e.g. trees, bushes, and ground). NASA has developed a prototype of a Laser Vegetation Imaging Sensor (LVIS) for recording the waveform to determine the vertical density profiles in forests (Blair et al., 1999). The spaceborne Geoscience Laser Altimeter System (GLAS) determines distance to the Earth's surface, and a profile of the vertical distribution of clouds and aerosols. In some applications (e.g. observation of climate changes), clouds are objects of interest. In others, clouds can be considered as obstacles that limit the visibility of the illuminated object. Recent developments of laser scanner systems led to systems that allow capturing the waveform with approximately 1GSample/s: RIEGL LMS-Q560, LITEMAPPER 5600, OPTECH ALTM 3100, TOPEYE II. This waveform sampling rate provides a range resolution of 0.15m. Our experimental system measures at a sampling rate of 20GSample/s (0.0075m) and resolves fine structures with high accuracy. For interpretation of this backscattered waveform a general understanding of the physical principles is necessary. The physical measurement process and the influence of the surface on the emitted waveform have been discussed in previous papers (e.g., Jutzi & Stilla, 2002; Wagner *et al.*, 2004).

In this paper we describe investigations for a detailed analysis of laser pulses. In Section 2 different techniques for measurement are discussed. The experimental system for a fast recording of signals is described in Section 3. The performed experiments are explained in Section 4 and the obtained measurements are depicted in Section 5 and 6. We finish with a discussion about the received surface features.

2. MEASUREMENT TECHNIQUES

2.1 Laser scanning systems

Depending on the application, laser scanning systems can be designed in different ways (Jelalian, 1992; Kamermann, 1993). They may differ in techniques concerning e.g. the modulation, detection, or measurement.

Concerning the modulation techniques laser systems can be split between continuous wave (cw) laser and pulsed laser. For applications in remote sensing the pulsed laser with the higher power density compared to cw laser is of advantage, because it allows operating at long ranges. In this work, we focus on pulsed laser systems.

Detection techniques can be split between coherent detection and direct detection. Coherent detection considers the wave front of the received signal compared to a reference signal emitted from a cw laser. In direct detection laser systems the received optical energy is focused onto a photosensitive element that generates a value that depends on the optical power.

Measurement techniques for range determination can be distinguished by the exploited signal properties like phase, amplitude, frequency, polarization, time, or a combination of them. We are interested in measuring and analyzing the received pulse form, i.e. the dependence of the intensity over time.

The classical measurement technique for direct detection operates with a photodiode. The photodiode generates an electrical signal (voltage or current) that is directly proportional to the optical power of the incident light (multi photon). For a detailed analysis of the waveform a digitizing receiver unit is essential. Analyzing the waveform of the emitted short duration laser pulse with only a few nanoseconds requires a receiver unit processing the data with a bandwidth of some GHz and an appropriate sampling rate. Increasing bandwidth results in decreasing sensitivity of the photodiode which can be compensated by increasing power of the emitting laser source.

3. EXPERIMENTAL SETUP

An experimental setup was built up for exploring the capabilities to recognize urban objects using a laser system. For the main investigations of the influence of different object properties on the waveform, a pulsed laser system with multi photon detection is used.

The measurements were carried out by an experimental setup consisting of a laser system and a captured scene with typical urban objects and materials.

3.1 Laser system

The laser system has three main components: an emitter unit, a receiver unit, and a motion control unit.

3.1.1 Emitter unit:

We use a short duration laser pulse system with a high repetition rate (42 kHz). The pulsed Erbium fiber laser operates at a wavelength of 1.55 μm . The average power of the laser is up to 10 kW and pulse duration is 5 ns (FWHM).

3.1.2 Receiver unit:

The receiver unit to capture the waveform base on an optical to electrical converter. This converter contain a InGaAs detector sensitive at the wavelength of 900-1700nm. We used a 250MHz receiver for measuring the backscattered waveform, and sampled the data with 20GSample/s.

3.1.3 Motion control unit:

For the 2-d scanning process a fiber array is used for azimuth scan (63 raster steps) and a moving mirror for elevation scan (320 raster steps). The field of view is ± 15 degrees for horizontal and vertical direction.

3.2 Targets

Depending on the application different properties of urban surfaces can be sensed by a laser system (Jutzi & Stilla, 2003b). According to the size of the focused surface geometry in relation to the beam (footprint d and wavelength λ) we divide surface structures into macro, meso, and micro structures (Figure 1).

3.2.1 Macro Structure:

We interpret macro structures as structures which are much more extended than the beam footprint d . Laser range measurements taken by a scan (which is for aerial survey typically spaced greater than the spatial beam width) allow a reconstruction of large object structures like different roof shapes (e.g. flat roof, gabled roof, hip roof, etc.).

3.2.2 Meso Structure:

We interpret meso structures as structures which are much less extended than the beam footprint d and much greater than the wavelength λ . Different elevated object surfaces within the beam corridor lead to a mixture of different range values. This may be caused by small elevated objects (e.g. a chimney), a slanted plane, large roughness (e.g. grass, small bushes), or vegetation (e.g. branches, leaves).

3.2.3 Micro Structure:

We interpret micro structures as structures which are less extended than the wavelength λ . Depending on the roughness the irradiance is more or less reflected. A single measurement of the backscattered beam intensity (amplitude) gives information about the roughness of the surface and the material. Small roughness results in specular reflectance and large roughness in diffuse reflectance.

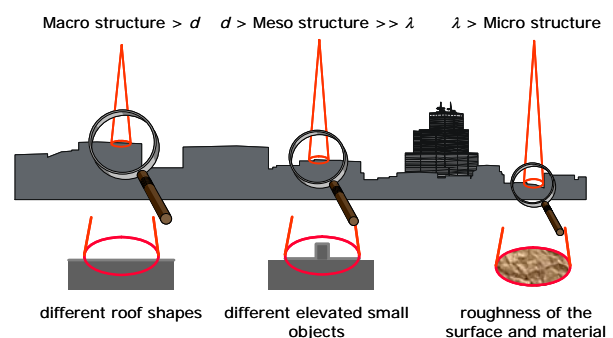


Figure 1. Different levels of details sensed by a laser system

4. EXPERIMENTS

4.1 Test scene

According to the focused scale of structure relevant waveform features has to be examined. A test scene was captured which consist of typical man-made and natural objects (Figure 2). The objects of interest for our experiments are, e.g. buildings, streets, cars, parking slots, trees and meadow. Most objects are partly occluded and the materials have different backscattering characteristics.

4.2 Scan

The test scene was illuminated by a pulsed laser with a wavelength of approx. $1.55 \mu\text{m}$ and a beam divergence of approx. 1 mrad. The complete waveform of the backscattered pulse was recorded with a range resolution of 8 mm per value. The scene was scanned by 320 elevation steps in y direction (± 15 degrees) and 63 azimuth steps in x direction (± 15 degrees). The laser system was positioned 15 m above the ground.

4.3 Data

A 3d data set was captured by scanning the test scene in x and y direction and the waveform over the time t . Interpreting each intensity value of a waveform as single distance values, then the measured pulses, which are included in the data set, can be seen as a spatial distribution. Assuming Cartesian coordinates the spatial distribution may be seen as a data cube filled up with intensity values for each (x, y, t) coordinate, where the intensity values depend on the backscattering characteristic of the illuminated surface. This data cube can be processed in different ways.



Figure 2. Test scene with different urban objects.

5. 1D ANALYSIS

For gaining surface characteristics each waveform of the cube is analyzed without neighborhood relations. To characterize the surface the pulses of the waveform have to be extracted. For pulse detection a noise dependent threshold is estimated to separate a single pulse from the background noise. Therefore the background noise is estimated, and if the intensity of the waveform is above $3\sigma_n$ of the noise standard deviation for the duration of at least 5 ns (FWHM of the pulse), then the waveform will be accepted for further processing.

Typical surface features which we wish to extract from a waveform are distance, roughness, and reflectance. The corresponding waveform features of this surface features are: time, width and amplitude. Because of the strong fluctuations of the waveform, extracting the relevant features of the waveform can be difficult. Therefore, the recorded waveform is approximated by a Gaussian to get a parametric description. To estimate the relevant waveform features of the structures the

Gauss-Newton method (Hartley & Zisserman, 2000) with iterative parameter estimation is used. The estimated parameters for waveform features are the averaged time value τ (macro structure), standard deviation σ (meso structure) and maximum amplitude a (micro structure):

$$w(t - \tau) = \frac{a}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(t - \tau)^2}{2\sigma^2}\right) \quad (1)$$

To start the iteration, we use the actual parameter values (time at pulse maximum, width of signal at half pulse height, and pulse maximum) of the original waveform. In Figure 3 an example for a typical measured waveform is shown by a solid line. The overlaid dotted line shows the waveform derived from these estimated parameters; we refer to this as the *estimated waveform*.

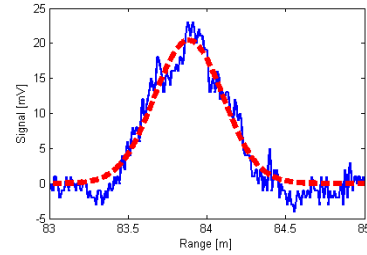


Figure 3. Pulse form representation: original waveform (solid line) overlaid by the estimated waveform (dotted line)

5.1 Pulse analysis for macro structures

For measuring macro structures with extended surfaces we process the data cube over the time t and assume that single pulses are received, i.e. we neglect the boundaries (discontinuities) within the footprint.

From the estimated waveform the averaged time value τ is used to exploit the temporal form of the received pulses for macro structures. The averaged range value r can then easily be determined with

$$r = \frac{\tau c}{2} \quad (2)$$

where c is the speed of light.

5.2 Pulse analysis for meso structures

Different elevated object surfaces within the beam corridor lead to a mixture of different range values. A plane which is slanted in relation to the viewing direction shows different range values within the footprint. This range interval which is given by the size of the footprint and the orientation of the plane leads to a temporal spread of the pulse (Figure 4b). A deformation of the pulse form can also be caused by perpendicularly oriented plane surfaces shifted by a small step in viewing direction (Figure 4c). A large step leads to two separate pulses (Figure 4d). Several surfaces with different range within the beam result in multiple pulses.

From the estimated waveform the standard deviation σ is used to exploit the temporal form of the received pulses for meso structures. The increased pulse width of meso structures indicates large roughness of vegetation or an uneven, slanted or small stepped surface.

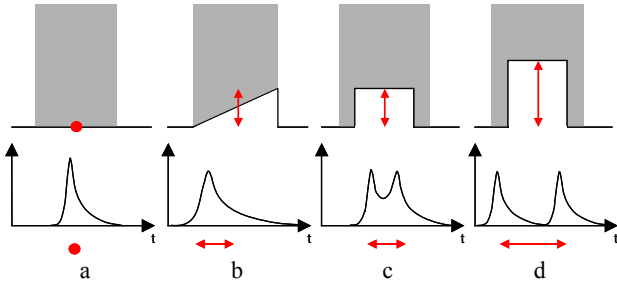


Figure 4. Surface and pulse waveform. a) flat surface, b) slanted surface, c) small step, d) large step

5.3 Pulse analysis for micro structures

Depending on the material and the surface roughness (micro structure) objects show different reflectance properties. The amount of backscattered photons varies with these properties.

From the estimated waveform the maximum amplitude a is used to exploit the temporal form of the received pulses for micro structures. The received maximal amplitude or pulse power can be used to discriminate different objects or materials.

5.4 Multiple pulses

Both first pulse and last pulse detection are used for photogrammetric applications which allow considering or neglecting the presence of vegetation. Generally, vegetation leads to a various number of pulse reflections depending on the density and structure. These various number of pulses (we call them *multiple pulses*) can be considered by analyzing the complete waveform. This might be of interest for discriminating different types of vegetation. Multiple reflections can also be observed for urban structures which are smaller than the footprint (e.g. power lines).

Let us investigate a single signal with multiple pulses. Therefore an example of a signal profile consisting of multiple pulses is selected from the measured data set and it is depicted in Figure 5a. The waveform parameters for each detected pulse of this signal profile are estimated and described in Table 1. In contrast to the original waveform the estimated waveform is shown in Figure 5b.

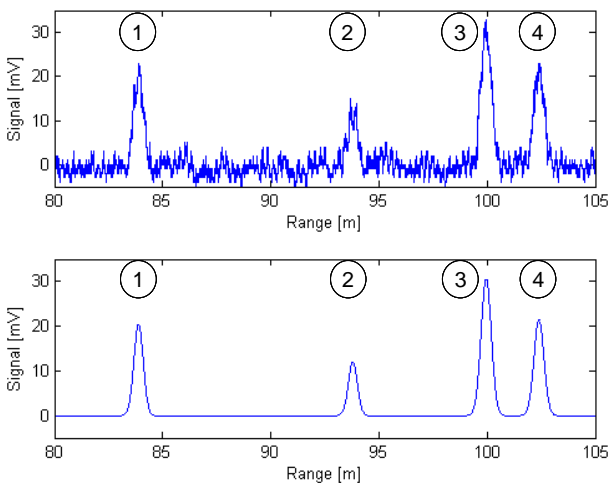


Figure 5. Waveform estimation. a) original waveform, b) estimated waveform

By comparing the averaged time values in Table 1, we can see, that the distance between the 1st and 2nd pulse is about 10 m and between the 3rd and 4th pulse about 2.5 m. The 3rd pulse shows the highest maximum amplitude and the standard deviation of the 1st and 2nd pulse is slightly lower than the 3rd and 4th pulse. The question arises: can this be helpful to classify the partly illuminated surfaces only by interpreting waveform features? It seems that the characteristics of the waveform features are not strong enough to accomplish this. Inside the beam corridor, several partly illuminated surfaces of various sizes and materials cause ambiguous waveform features. For interpreting each pulse of a signal profile which includes multiple pulses further information is needed. Only by considering neighborhood relations an interpretation might be possible.

Pulse	Object	Maximum amplitude a [mV]	Standard deviation σ [m]	Averaged time value r_m [m]
1 st	Vegetation	20.4	0.216	83.884
2 nd		12.0	0.207	93.792
3 rd	Building	30.6	0.236	99.956
4 th		21.4	0.232	102.396

Table 1. Estimated parameters of waveform features

To visualize the neighborhood relations, the measured data cube (x,y,t) was sliced vertically in $y-t$ planes. Figure 6 shows a set of image slices ($y-t$ planes). The 2nd slice from the left in Figure 6 shows vegetation in the center (near range) and building structures on the right side (far range). The grey values correspond to the intensity of the signal. The intensity values along the marked solid line are the intensity values of the waveform described in the paragraphs above.

By considering the neighborhood relations of the waveform the interpretation and classification of each single pulse is now possible. We can say that the crown diameter of the tree is at least the distance between the 1st and 2nd pulse (10 m). Furthermore we can say that the 3rd and 4th pulse result from a building edge. If the scene context (e.g. vegetation, buildings) is known, then an interpretation of the pulse features gets much easier. Beside the interpretation, the processing of multiple reflections caused by vegetation can be improved by readjustment and adaptation of the predetermined threshold to detect vegetation structures with low reflectance.

It has to be remarked that this kind of slice image in Figure 6 can not give a real side looking view. We still have to consider that the data cube includes 2.5d and not real 3d information. Depending on the area size in relation to the beam footprint it is possible, that the complete pulse intensity is backscattered from the first illuminated surface in propagation direction and the following surfaces give only poor or none reflections. For instance, a tree with dense foliage may return only a single reflection response per laser pulse illumination.

To give an example, the scene was scanned with 20160 scan points of which 9014 scan points include at least a single reflection response. The number of received reflections per scan point in percent with at least a single reflection response (Table 2) shows that 20% of multiple reflections are received. It was quite rare to receive 4 and more pulses (4%).

Number of reflections	1	2	3	4 and more
%	79.6	12.2	4.1	4.1

Table 2. Number of received reflection responses

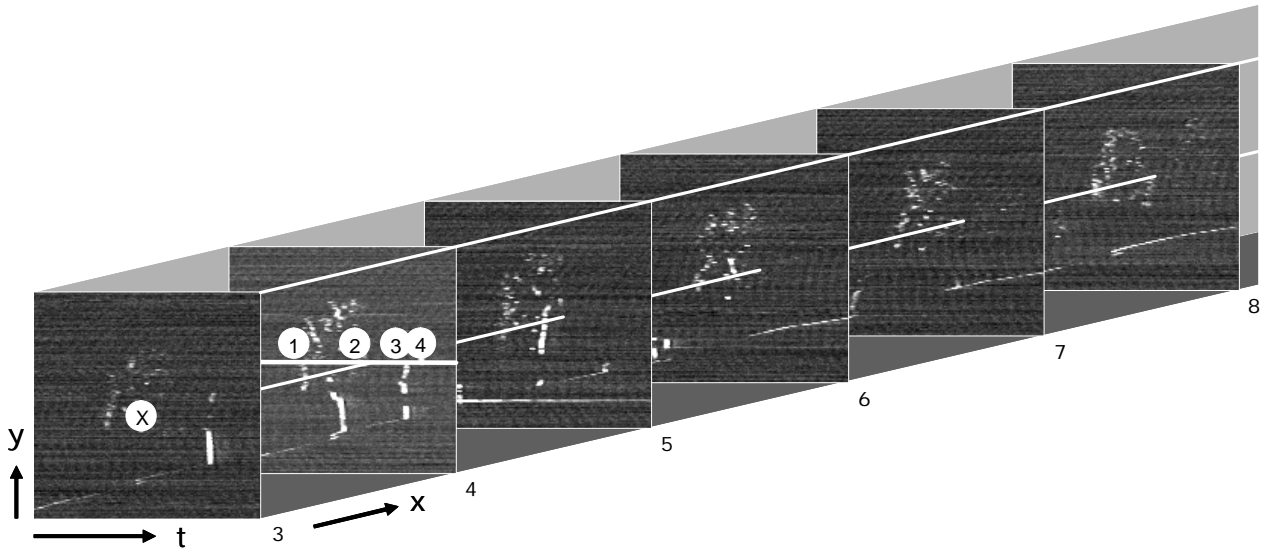


Figure 6. Vertical image slices with ground, vegetation and building structures

6. 2D ANALYSIS

In this section we will present a way to analyze the data cube for line segments. Until now processing laser scanner data in form of point clouds depends on the strength and weakness of the pulse detection algorithm. However the received range values of the algorithm in form of points have then been used to obtain line segments or planes. Instead of the traditional processing of laser scanner data in terms of point clouds, distributed intensity values are now directly considered. This method has the advantage of omitting the pulse detection algorithm by directly processing distributed intensity values of the data cube for higher level segments in form of lines or planes.

A simple way to analyze the data cube is to slice the complete

cube in x , y and t direction to obtain image slices from different points of view. These image slices can then be used for visualization as shown in Figure 6 or for processing, as will be shown in this section. The main goal of this processing here is not to increase the accuracy, but to obtain line segments which give a description of the surface on a higher level than point clouds.

But before we start to process the image slices we have to understand what we receive if we slice the data cube. Therefore we suppose a scene with a plane surface perpendicular to the direction of the beam propagation. This surface is scanned in one direction and the waveform of each scan point is recorded. For each recorded measurement we get a 1d distribution of intensity values with respect to time. By aligning neighboring (in y -direction) measurements side by side, we get a y - t plane of

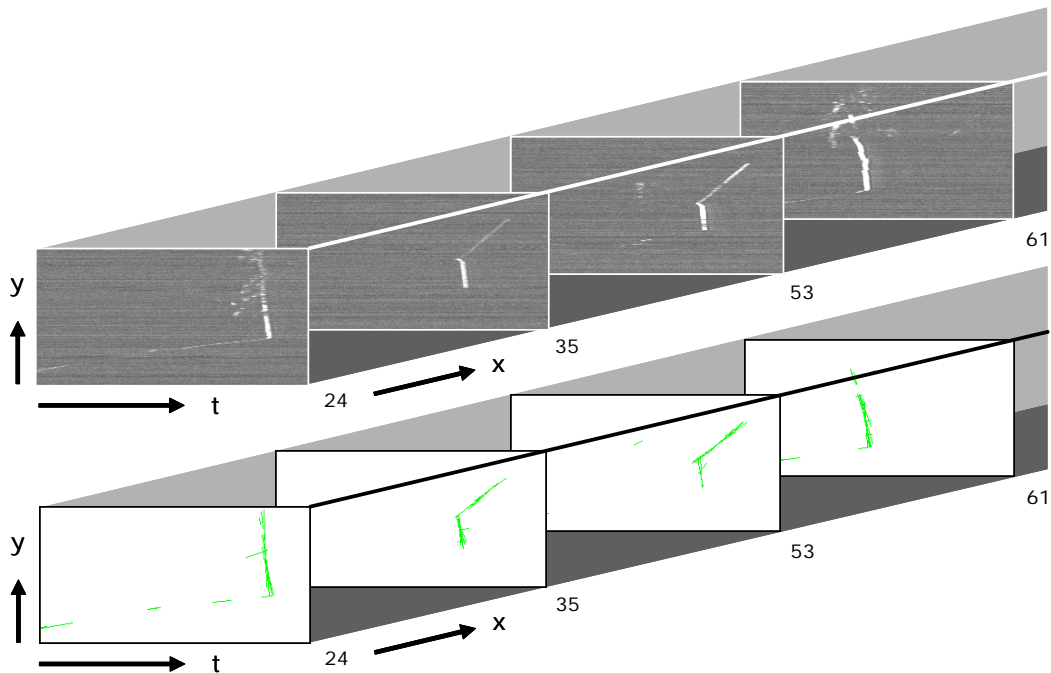


Figure 7. Analyzing the data cube a) vertical image slices, b) corresponding line segments

intensity distributions with a pronounced maximal line parallel to the y -axis. The time value of this line corresponds to the distance of the surface from the detector.

In our investigations, for example, we slice the data cube vertically in y direction and receive 63 image slices (y - t planes). Each single image consisting of intensity values induced by the scattering effects of the surface roughness can now be processed by a line detector to estimate plane object surfaces.

For straight line detection the Standard Hough Transform (SHT) (Ballard, 1981) can be used. To apply this algorithm, the region of interest (ROI), covering the areas where surfaces are expected, has to be extracted. This can be done by calculating the intensity distribution of all intensity values of an image slice and setting all intensity values below 2σ of the image standard deviation to zero. The remaining intensity values above zero (ROI) are further processed with the detector to get a line description of illuminated plane surfaces. To feed the accumulator space of the SHT each nonzero pixel is transferred and weighted with its intensity value. In Hough space we obtain superimposed sinusoids with local peaks. Peak values in this space represent potential lines in the image slice and have to be extracted and transformed back to the image space. The length of the straight line segment is determined by an overlap criterion of the line with the ROI (nonzero pixels). Line segments shorter than a specified value are discarded. Since many values of the intensity distribution have contributed to each straight line segment, the accuracy of location can be much better than the pixel dimension of the image slice.

An example of an image slice (Figure 7a) and the estimated straight lines (Figure 7b) are depicted. Parts of the ground and the main building's facade and roof, are estimated by lines.

Processing the measured data cube yields line descriptions for each slice (Figure 8). The ground (left side and foreground) and the main building (right side) are detected, but also some tree trunks. If the raw data cube is processed, then the detected line segments can easily be transformed from spherical into cartesian coordinates. Whether the inverse procedure of transforming the data cube first and performing the line detection in cartesian coordinates afterwards yields better results remains to be tested.

Furthermore it has to be considered that only if the illuminated surface is larger extended than the length of the intensity distribution or at least larger extended than the pulse width, then the extracted line segment can have the same orientation as the illuminated surface plane.

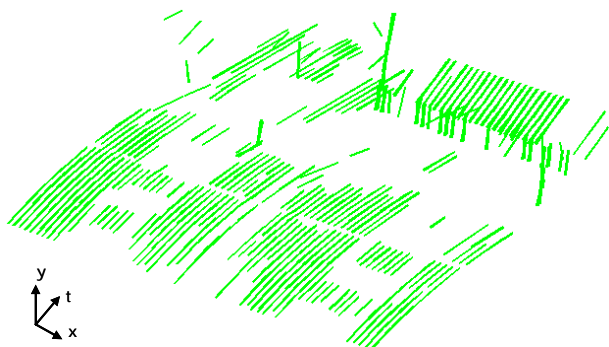


Figure 8. Estimated line segments of the investigated test scene

7. CONCLUSION

In this paper we explored the capabilities of analyzing the shape of the waveform for surface features in form of distance, roughness, and reflectance for each backscattered pulse. Because of the strong fluctuations of the waveform, an iterative estimation algorithm is proposed to get a parametric description of the original waveform by a Gaussian. Beside the investigations on single responses the extracted parameters of more than one response (multiple pulses) do not lead to significant surface features. Only by considering neighborhood relations (e.g. material characteristic) an interpretation becomes possible.

Space-time analysis was introduced to investigate the measured data volume (space-time cube). The image slices extracted from the data cube were processed to estimate line segments for surface features. This has a significant advantage: the estimated lines are not based on single range points received from a pulse detector which delivers more or less accurate range values, but they are based directly on the intensity distribution of the backscattered signal. Since many values of the intensity distribution have contributed to each line segment, the accuracy of location can be much better than the pixel dimension of the image slice. Further work will also deal with the segmentation of plane segments in the 3d data cube.

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