A new Algorithm for Processing Fullwave Laser Scanner Data

Karl-Heinz Thiel, Aloysius Wehr
Institute of Navigation, University Stuttgart, Breitscheidstr. 2, D-70174 Stuttgart, Germany

Christoph Hug
GeoLas Consulting, Sultenstr. 3, D-85586 Poing, Germany

Keywords: airborne laser scanning, pulsed ranging, cw-lasers, full-wave laser scanner, phase difference, correlation technique

ABSTRACT: Recently a new generation of airborne laser scanners appeared on the market performing fullwave ranging. Basically these laser scanners are pulse laser systems, however, they do not only detect first and last pulses or several pulses but digitize the total backscattered laser signal with a high sampling rate. These systems require new advanced processing algorithms. First the different major ranging measurement principles are explained. MATLAB simulations are carried out to analyze the performance of different measurement methods. The simulation results are used to select the optimum signal processing algorithm for fullwave systems with regard to accuracy and robustness. The promising algorithms based on correlation techniques are tested with fullwave data sets gathered during a helicopter survey.

1 INTRODUCTION

All laser scanners consist of the key items shown in figure 1. Their performances are determined by the ranging accuracy, the precision of the laser beam deflection mechanism - the opto-mechanical scanner - and the measurement rate. Also intensity images are becoming of greater interest. Laser scanners measure the 3D-coordinates by sampling synchronously the slant range and the instantaneous deflection angles of the scanning device. Regarding earth fixed laser scanners, the precision of the opto-mechanical scanner determines the position accuracy of the laser spots in the plane where as the slant range accuracy of the ranging unit determines accuracy of the depth coordinates. For airborne laser scanners the position accuracy of the laser spots in the plane are additionally dependent on the accuracy of the position and orientation system (POS) besides the scanner and the slant range accuracy. With regard to other remote sensing sensors (e.g. multi spectral scanners), it can be concluded that the depth measurement is the key parameter of laser scanners, which determines the main performance. Therefore, this paper deals only with the ranging performance of laser scanners as far as concerning the carried out simulations with MATLAB. This means, only the ranging unit is regarded. Covering longer distances or facing high range dynamics time of flight ranging principles are applied in commercial laser scanning systems. Here two main groups must be distinguished: pulse ranging and ranging by measuring the phase difference between the received and transmitted signal. Today only pulsed laser systems are applied for airborne laser scanning, where as for near range measurement tasks also continuous wave (cw) laser systems are used which carry out ranging by measuring the phase difference between the modulated transmitted and received signal. Cw-systems have the capability to carry out range measurements with accuracy better than one tenths of a mm whereas pulse laser systems cover greater distances but achieve only moderate accuracy down to centimeters. Recently a new generation of airborne laser scanners appeared on the market performing fullwave ranging. Basically these laser scanners functioning as pulse laser systems. However, they do not only detect first and last pulses or several pulses but digitize the total backscattered laser signal with a high sampling rate. This means for each transmitted laser pulse the transient of the received signal is stored which results in a vast amount of data. Here new sophisticated algorithms are required assuring an efficient, reliable and cost effected processing. These algorithms must not degrade the accuracy and the information of the raw signal.

To identify the potential of fullwave laser scanning, first the performance of pulse ranging and cw-ranging are studied and compared by simulations with Matlab. These simulations lead to an algorithm for fullwave ranging. This algorithm based on correlation techniques is first applied on computer generated data. Here it shows very promising results. In a second step the algorithm will be tested using real fullwave data.

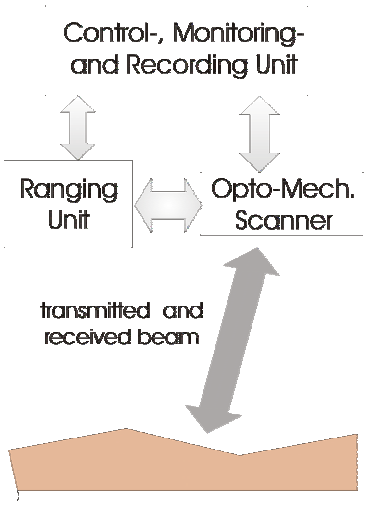

Figure 1: Key components of laser scanner

2 PULSE RANGING

Carrying out ranging by measuring the travelling time of a short laser pulse from the laser aperture to the target surface and back to the receiver (two way ranging) is the typical laser ranging method. It makes optimum use of the laser transmitter which has the capability to generate very short pulses with very high peak power levels with high repetition rates. The pulse length T_P determines the ranging resolution and the ranging accuracy (s. figure 2). For pulse ranging systems the range resolution tells how far apart two targets have to be, so that they can be resolved as two targets. The power loss of the received signal determines the maximum possible range. Figure 2 shows the ideal case. In reality several returns for one laser pulse are possible. Further more the backscattered laser signal is disturbed by noise and the amplitude is dependent on the object´s surface properties as e.g. reflectivity and topology. These effects are regarded by different sig-

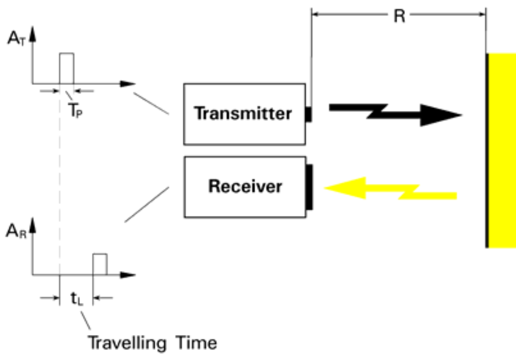

Figure 2: Pulse Ranging

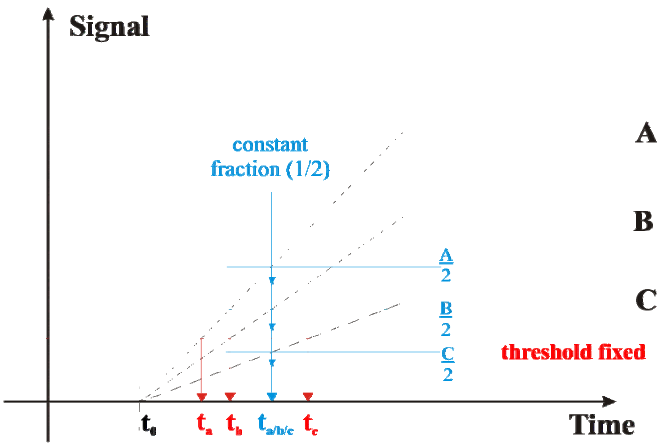

Figure 3: Detection of pulse return

nal processing procedures and sampling methods which will be discussed in the following chapters.

2.1 *Threshold Detection*

Figure 3 depicts the detection of a return laser pulse by thresholding. As soon as the received signal passes a certain threshold the time counter which was started by the transmit pulse is stopped. Thresholding is normally carried out at the rising slope, because the rising part of the laser pulse is more steep. Figure 3 shows that this detection process is very dependent on the reflectivity of the target. If the return signal becomes weaker (A→B→C) the threshold level will be passed later. This means, a too long traveling time of the laser signal is measured and by that a too great slant range is estimated. To compensate this intensity dependent effect, the power of the return signal must be determined and a computed correction is applied to the measuring result. The correction t_k is reducing the traveling time of the laser pulse to t_0, the theoretical arrival time of a rectangular pulse.

$$t_k = \frac{P_{thr} \cdot t_r}{P_{peak}} \qquad t_0 = t_x - t_k \qquad (1)$$

with P_{thr} the threshold level,
P_{peak} the peak level and
t_r the rise time.
t_x actual measurement time (eg. t_a, t_b …)

2.2 *Constant Fraction Discriminator*

To relax the dependency on the amplitude of the pulse return signal more advanced laser ranging systems use a constant fraction discriminator to trigger the stop signal. Here the pulse amplitude of the return signal is regarded and determines the instantaneous threshold. Figure 3 shows the effect on measurement accuracy, assuming almost linear situation. The time of arrival is now to a large extend independent of the reflectivity of the ground.

2.3 *Full Wave Detection*

Using pulsed laser scanners for airborne surveys soon revealed, that for each transmitted laser pulse several returns can be observed, e.g. from the tree branches and from ground. Therefore, today airborne laser scanners can discriminate between first and last return pulse. Either they take both or they have a mode switch where the user can select between first or last return. To improve the performance of laser scanners the next technical improvement is to detect and measure the travelling time of multiple returns. In this case it will be possible to resolve different elevation layers of e.g. vegetation, because especially in forest areas multiple returns can be expected. In pursuit of this idea the return signal is sampled along the reflected pulses. This means to sample the total backscattered laser signal (Blair, 1999) with high frequency. The comprehensive sampling of a return signal is known as full wave detection.

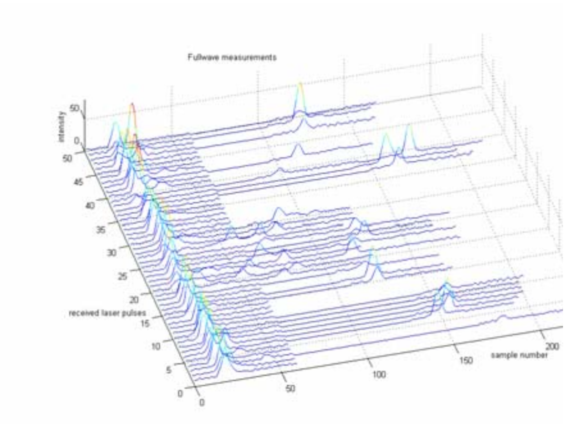

Figure 4: Data from fullwave measurement

The sampling rate is a measure for the possible height discrimination and the accuracy of the overall measurement. In figure 4 a sequence of 50 consecutive fullwave measurements is given. The fullwave measurement starts a selected number of samples before the first detectable signal return is acquired and stops m samples after the last signal pulse. If only one return pulse is detected, a number of 60 samples were taken in this case for one laser pulse. One fullwave measurement can be analyzed offline, allowing to process the acquired data conventionally or with correlation algorithms, trying to determine single slant ranges as first or last pulse or even multiple pulses for describing elevation layers.

3 PERFORMANCE COMPARISON

In this chapter the performance of the introduced ranging methods are going to be compared by simulations. A model laser ranging system for pulse and phase difference measurement was built up with MATLAB. This developed MATLAB tool can well be used to simulate different measurement scenarios by modifying various parameters, e.g. range, reflectivity, surface roughness and distribution of multi height levels within the measurement spot. Furthermore, the user can select between different measurement methods such as a pulse system with either fixed or variable threshold and correlation techniques, and a phase difference ranging system with direct phase difference measurement. Here we will mainly concentrate on pulse measurement with respect to fullwave operation.

3.1 *Simulation Overview*

In the simulation model the transmitted signal is traveling from the laser radar to the reflecting surface, which is subdivided into n small elements each of them with its own parameter set with regard to its radar cross section. In the receiving unit all these n backscattered signals are evaluated to form the received signal. In a first step a quasi analogue signal is modelled, where time of arrival and signal power is available for each of the n signal elements. In a second step this signal is transformed in a digital one. Sampling rate and word length (number of bits) can be changed to study the effect of these parameters. Another module provides different filters to simulate either band limiting systems or the noise reduction on the ranging signal if phase measurements are regarded. Figure 5 depicts a received digital laser pulse without and with noise and the result of an applied 1 GHz lowpass filter. The selected sampling rate is 10 GHz and the pulse length is 10 ns.

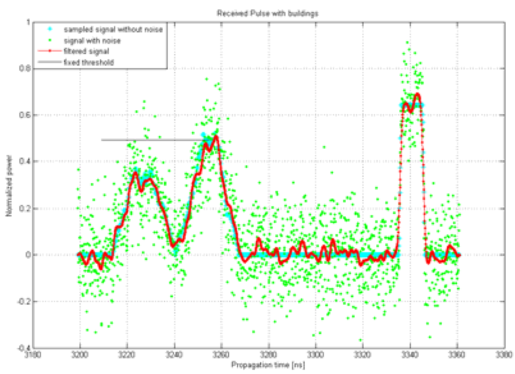

Figure 5. Received Laser Pulse from a Surface Showing three height levels

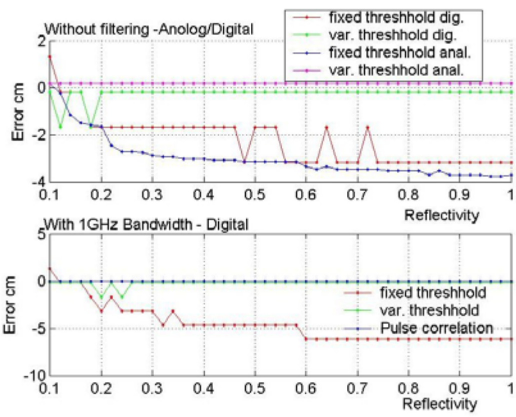

Figure 6: Effect of Ground Reflectivity on Range Measurement

3.2 *Simulation of Pulse Ranging*

In case of pulsed laser systems the ranging value is determined by threshold detection of either the analog or sampled received signal. If correlation techniques are applied the digital signal is used only. The signal to noise ratio (S/N), mainly defined by the surface reflectivity, induces only a higher standard deviation if the phase difference is measured, whereas a systematic offset appears for pulse measurements, if a fixed threshold is used (s. figure 3 and figure 6). Figure 6 gives the resulting errors for pulse ranging. In the upper diagram the threshold dependent offset can be calibrated. A result with calibration is displayed in the lower figure, where no offset remains for a variable threshold. Analog and digital solutions mainly differ with respect to the digital resolution, here 1.5 cm. By the simulation the main differences are identified between fixed and variable threshold. Fixed threshold discrimination produces S/N dependent constant errors, while a variable threshold using power measurement gives accurate ranging values. Also pulse correlation method shows almost no dependency on S/N.

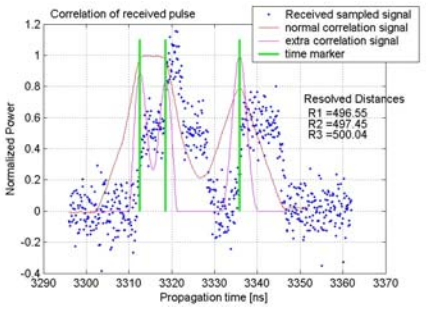

Figure 7: Full Wave Technique with Special Correlation Method

Pulse correlation shows the best results but demands for high sampling rates and sufficient computational power. One advantage can be seen in noise reduction, resulting from the length of the correlating reference signal. Another feature is the multi peak detection in combination with the estimation of the powers of the individual correlation peaks. This last feature allows for accurate power estimation of the received signal and the generation of intensity images. The multi peak discrimination, shown in figure 7, is a special correlation technique, which allows a height resolution below the pulse length, assuming flat subareas. In figure 7 three height levels are within the laser spot, ground with a distance of 500 m between ground and laser system, first height step with 2.5 m (497.5 m distance) and a second height step at 3.5 m (496.5 m distance). Both height levels steps occupy 31% of the spot. The maximum values of the extra correlation signal are marked with time markers and the resolved distances with respect to these time markers are given in the figure. Compared to the fixed threshold in figure 5, the improvement of correlation techniques can be seen clearly.

3.3 *Comparison of Measurement Methods*

In figure 8 a comparative simulation was carried out with respect to pulse ranging and measuring the phase difference using the same target topography. The offset between ground and roof is held constant at 6 m and the fraction between ground and roof in the backscattered signal varies from zero to 100 percent. The phase measurement shows a continuous range changing from ground to roof. However, the pulse system exhibits a more complex ranging behavior which can strongly influence the ranging result. For a constant threshold system the range measurement remains at ground level value up to a ratio of 30% roof and 70% ground. There is only a small increase in percentage when using a filter. A correlation detection using maximum correlation signal detection, which can be realized by full wave systems, jumps at 50% from ground range to roof range. Already from this simulation it can be concluded, that a full wave system with correlation technique and discrimination of multiple peaks is able to produce accurate ranging measurement for a ratio from 10% to 90%.

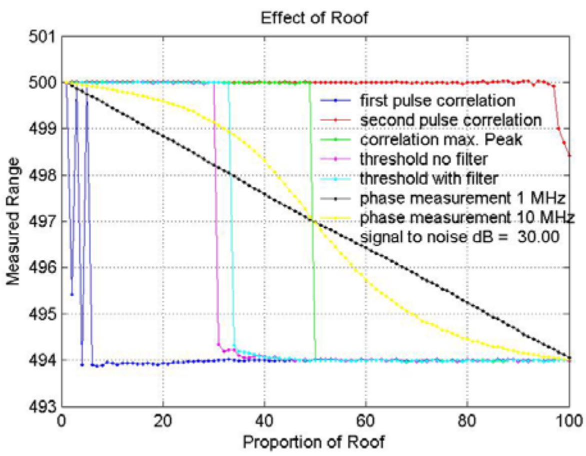

Figure 8: Effect of a Second Height Level within the Laser Spot on Ranging Performance

The carried out simulations give the impression that pulse and cw-systems achieve almost the same performance. However, looking at the achievable ranging accuracy σ_R which is

$$\sigma_{R\,pulse} = \frac{c}{4\pi} \cdot T_P \cdot \frac{1}{\sqrt{S/N}} \quad (2)$$

for pulse ranging systems and for cw-systems

$$\sigma_{R\,cw} = \frac{\lambda}{4\pi} \cdot \frac{1}{\sqrt{S/N}} \quad (4),$$

if c is the speed of light, T_P is the pulse width and λ the wavelength of the ranging signal (Bachman, 1979) and regarding that laser can produce very short pulses with high peak energy levels, pulse systems are preferable for longer ranges. Therefore commercially available airborne laser scanners apply pulse ranging by using lasers with high peak power levels to achieve ranging accuracies of better than 10 cm even over several thousand meters. Flying altitudes of more than 10 km are possible and state-of-the-art (Blair, 1999).

4 ANALYSIS OF REAL FULLWAVE-DATA

Two data sets with fullwave laser measurement were analyzed. The surveying was carried out by a helicopter using a commercial laser scanner system with integrated GPS/inertial navigation (LiteMapper 5600 with Digital Waveform Recording). Figure 4 demonstrates some sampled pulse returns. As already mentioned, the number of samples per pulse depends on the signal echo characteristic. If several returns are detected then the number of samples is increased to collect all height information for this single pulse. Further technical data is given in table 1.

Flight height	≈ 500 m (helicopter)
Air speeed	≈ 30 m/s
Scanning mechanism	rotating polygon mirror
Scanning rate	34 Hz
Sampling rate	1 GHz
Pulse repetition rate	50 kHz
Beam divergence	0.5 mrad
Pulse width	≈ 5 ns
Wavelength	near infrared

Table 1: Technical data of fullwave laser scanner

For the detection of an accurate traveling time it is necessary to know the passed time for the first sample of the pulse sequence with respect to the time where the pulse was transmitted (figure 9). With an accurate sampling frequency now each sample can be provided with time stamps, relative to the start pulse. In an offline analysis thresholding and correlation methods can be applied to extract all reflecting levels on ground and to determine the signal delay for all different peaks and the received power for the complete return. The nearly Gaussian shape of the pulses demands

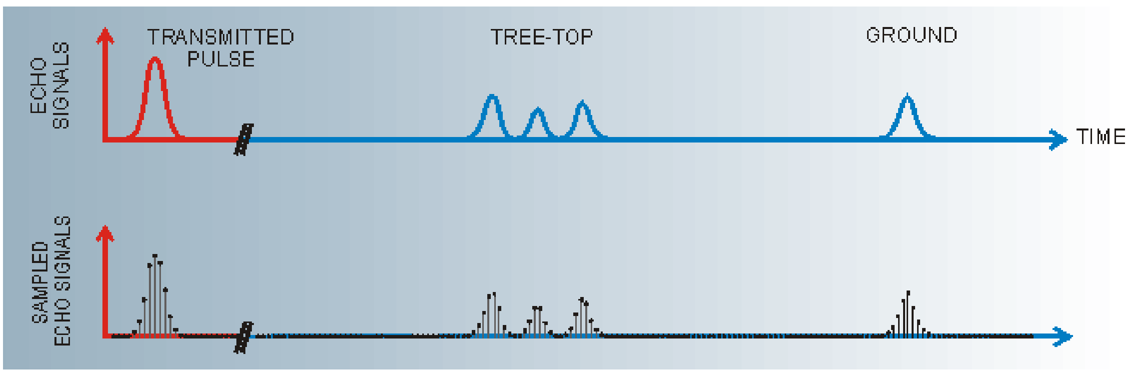

Figure 9: Fullwave measurement with multi reflections (Source: http://www.riegl.com)

for the estimation of the centroid for each pulse to provide an accurate estimate of the delay time. This has also to be done for the transmitted pulse, which gives the starting time of the delay measurement. Applying the centroid method or a correlation technique allows to resolve the delay not only in sampling time increments but with an accuracy, depending on the signal to noise ratio of the received signal.

Figure 10: Aerial view of the scanned region

In figure 10 the aerial view of the scanned area does not cover the complete swath (small portions are missing on both sides), but presents a good overview of the surface cover. The red lines are marking scans within the swath, where the detected height values are given in figures 11 and 12. The multi echo evaluation for each sample is demonstrated by different colored points. Up to six echoes can be detected in the sampled data for one return pulse. Although we have leafy trees at this time, a sufficient number of ground returns can be found. The reason can be seen in the small laser beam divergence, resulting in a spot diameter of about 30 cm on ground. This is likewise for a cornfield in figure 12, where one may well distinguish between ground and vegetation. In figure 11 the height of the trees is clearly mapped. The younger and closer canopy in the middle of the scan compared to the older tree population provides an idea of the capability of fullwave data. Ground points and reflections within the treetop give a wide field of specific investigations with respect to forest management. On the right side of the scan the roofs of the buildings show up quite accurate and even the fodder silo can be distinguished against the surroundings.

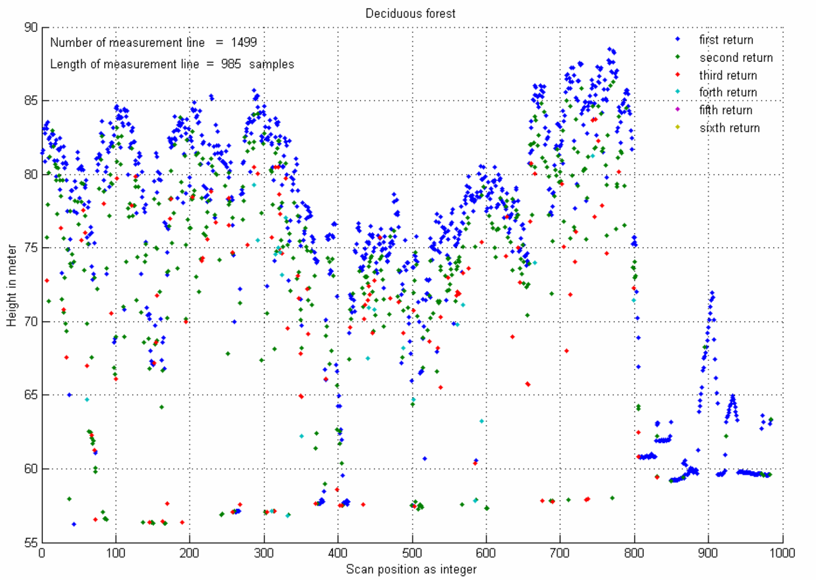

Figure 11: Complete scan line with multiple returns in a deciduous forest

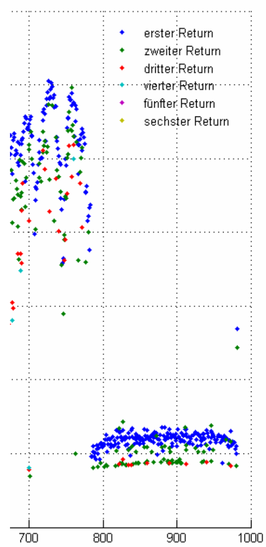

Figure 12: Measurements in a cornfield

We were not in position to analyze the ranging accuracy of the used system, because there were no reference data available. But during our investigation we got an impression that the system provides a high measurement quality. Flat areas reproduce very good, as can be seen with the roofs in figure 11. Even the slopes of the roofs were measured correctly.

5 CONCLUSIONS

The simulations indicate that for flat surfaces pulse systems with variable threshold or correlation techniques produce the same accuracy as phase measurement systems with comparable system parameters. Only systems with fixed thresholds generate systematic offsets with decreasing reflectivity. Multiple height levels within the laser spot can be resolved best by special correlation method, where height levels below the pulse width can be detected. However, this demands fullwave systems with very high sampling rates.

Before the fullwave data of the helicopter survey could be processed and analyzed, they were first visualized by MATLAB. Then areas featuring typical surface properties were cut out of the data sets and the MATLAB routines which were used to evaluate the performance of the different processing algorithms were adapted to the application to real fullwave data. Applying correlation techniques as pointed out in chapter 3.3 multiple returns in dense forests could be resolved. Typically three to four returns were detected. Even in areas with dense vegetation the earth surface was surveyed properly so that a precise digital elevation model could be derived. Comparable results were obtained by computing the centriod of each return. This is due to the fact, that only signals with a high signal-to-noise ratio were processed and the sampling frequency was 1 GHz. This means, the transmit laser pulse which is only 5 ns wide is described only by five samples. The simulations were carried out with a sampling rate of 10 GHz assuming a pulse width of 10 ns.

It can be concluded that correlation techniques are powerful processing tools for fullwavc laser scanner data. However, a more detailed analysis concerning the functional relation ship between sampling rate and sensitivity of detecting return pulses is appropriate.

6 REFERENCES

Bachman, Chr. G., 1979. Laser Radar Systems and Techniques, Artech House Massachusetts USA, p. 95.

Blair, J.B., Rabine, D.L., Hofton, M.A., 1999. The Laser Vegetation Imaging Sensor: a medium-altitude digitisation-only, airborne laser altimeter for mapping vegetation and topography, ISPRS Journal of Photogrammetry & Remote Sensing Vol. 54 NOS 2-3, ISSN 0924-2716, Elsevier Amsterdam, pp. 115-122.

Hug, Chr., Wehr, A., 1997. Detecting and Identifying Topographic Objects in Imaging Laser Altimeter Data, IAPRS, Vol. 32, Part3-4W2, 3D Reconstruction and Modelling of Topographic Objects, Stuttgart, pp. 19-26.

Wehr, A., 1994. Auslegungskriterien für ein abbildendes CW-Laserentfernungsmeßsystem und seine Realisierung (Teil 1 und Teil 2), Frequenz, 48, 2-4 and 5-6, pp. 79-83 and pp. 123-127.