LITEMAPPER-5600 –
A WAVEFORM-DIGITIZING LIDAR TERRAIN AND VEGETATION MAPPING SYSTEM

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ABSTRACT:

LiteMapper-5600 is a new high-accuracy airborne LIDAR system for corridor and wide-area mapping of terrain and vegetation with a unique feature: it digitizes the echo waveform of each measurement. This paper outlines the system and its components, presents first samples of data that were collected recently with a prototype in flight tests, and analyzes system performance. It highlights applications that take advantage of the waveform registration capabilities of LiteMapper-5600 with a special emphasis on forestry applications.
Being based on the new *RIEGL* LMS-Q560 laser scanner the LiteMapper-5600 system is one of the first commercial airborne LIDAR terrain mapping systems to use waveform digitization, thereby providing access to the full surface information content available from LIDAR measurements. Return waveforms can give detailled insights into the vertical structure of surface objects, surface slope, roughness, and reflectivity. By enabling the user to determine the target detection characteristics in post-processing, a more robust and accurate ground detection for example in areas with low vegetation becomes possible. For forestry applications, the vertical structure of the canopy and understory is revealed, facilitating the determination of species, vegetation health, as well as forest structure and biomass more accurately.

1. INTRODUCTION

During the last decade, airborne LIDAR mapping has gained general acceptance as an accurate and rapid method for three-dimensional surveying of the Earth's surface. Conventional systems output the three-dimensional coordinates of the surface locations hit by the laser pulse ("discrete ranges"). Most systems are able to distinguish two returns from multiple targets touched by a single laser pulse, some systems provide up to four returns.

For many applications, this has been deemed the suitable form of output. However, the user has no way of knowing how the electronics of his LIDAR system actually determine the location of the returns they report, nor of any distortions of the pulse shape that receiver electronics or surface structures may have imposed upon the pulse echo. LIDAR system manufacturers are tight-lipped about the pulse detection methods their systems employ. However, as Wagner et al. (2004) point out the choice of pulse detection methods has significant impact on accuracy, and in practice causes a number of effects that reduce the quality of the measurements, like amplitude dependant range walk, slope dependency of range, signal ringing causing outlier measurements below the terrain level, etc. In addition, with mere range output much of the informational content about structured surfaces is lost.

The solution is to digitally sample and store the entire echo waveform of reflected laser pulses. While waveform registration in topographic LIDAR systems is no new approach and early experimental setups date back to the 1970s (Marmon et al., 1978), only advances in digital electronics and harddisk size and performance have made it feasible in recent years to construct LIDAR systems that are self-contained and rugged enough for operational use (Blair et al, 1999). Data storage capacities and processing speeds available today make it possible to introduce this technology also into commercial systems. The advent of commercial waveform-digitizing LIDAR mapping systems like the LiteMapper-5600 finally gives the user the possibility to himself define the way "range" is calculated in post-processing – potentially making the ranging process more robust and improving accuracy. However, it also provides the opportunity for much more detailled analyses of distributed vertical surfaces for example in forest and vegetation areas. Instead of singular return locations generated by conventional LIDAR systems, a digitized echo waveform of the LiteMapper-5600 reveals all the information the laser pulse collected during its trip to the surface, like the detailled distribution of targets in the beam path, their reflectance (or relative surface area), and their vertical extent.

In forestry and agricultural applications this information is valuable for deriving several vegetation parameters: not only is tree/vegetation height available, but also vertical canopy expanse and density, height of second, third, and lower levels of vegetation, and the height and density of ground vegetation. Calculation of timber volume, biomass and other important vegetation descriptors is thus facillitated and made more precise.

The first part of this paper introduces the LiteMapper-5600 system and its components. In the second part examples and results of the first test flight are presented and discussed, highlighting the features of waveform data registration and the advantages and possibilities of this technology in agricultural and forestry applications.

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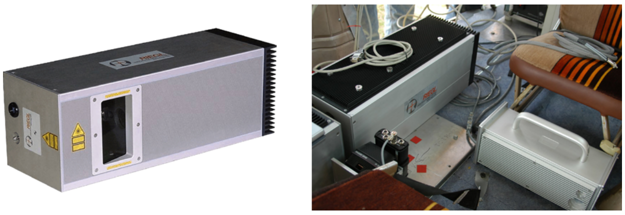
2. SYSTEM OVERVIEW

2.1 Components

The LiteMapper-5600 system basically consists of the components “laser scanner”, “direct georeferencing system”, and “digital camera”. For each of these components, units representing the cutting edge of technology were chosen to build a system meeting highest requirements to reliability and accuracy.

2.2 Laser Scanner

The laser scanner used in the LiteMapper-5600 LIDAR system is the *RIEGL* LMS-Q560. The use of this instrument gives access to detailed target parameters by digitizing the waveform of the echo signal of each laser measurement and storing these waveforms on a data recorder unit during data acquisition, and by analysing these digitized waveforms subsequently off-line. This approach proves especially valuable when dealing with challenging tasks, such as canopy height investigation or highly reliable automated target classification. Figure 1 shows the laser scanner head (1a) and the instrument integrated into a flight system for verification tests (1b).



(a) (b)

Figure 1. *RIEGL* LMS-Q560 Laser Scanner

The instrument makes use of the time-of-flight distance measurement principle with nanosecond infrared pulses, and fast opto-mechanical beam scanning providing absolutely linear, unidirectional and parallel scan lines. As the instrument digitizes the waveform of the transmitted laser pulse for every laser measurement, the laser pulse waveform can be extracted with high resolution and precision and can be used subsequently for in-depth waveform analysis in post processing.

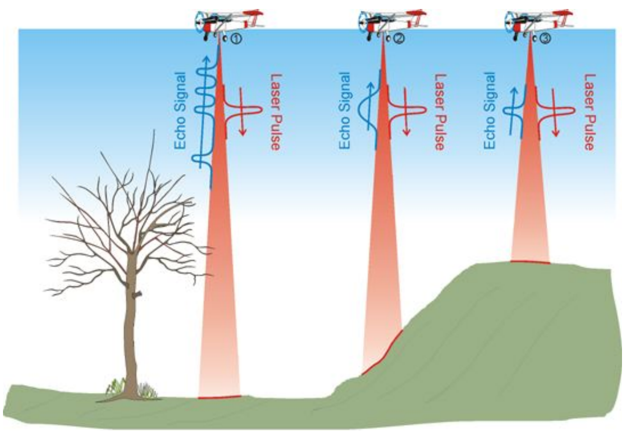


Figure 2. Data acquisition and post processing

Figure 2 illustrates the measurement principle on different types of targets. The red pulses symbolize the outgoing laser signals travelling towards the target with the speed of light. When the signal interacts with the diffusely reflecting target surface, a fraction of the transmitted signal is reflected back towards the laser instrument, indicated by the blue signals.

In situation 1, the laser pulse hits the canopy first and creates three distinct echo pulses. A fraction of the laser pulse also hits the ground giving rise to another echo pulse. In situation 2, the laser beam is reflected from a flat surface at a small angle of incidence yielding an extended echo pulse width. In situation 3, the pulse is simply reflected by a flat surface at normal incidence resulting in a single echo pulse with a similar shape as of the outgoing laser pulse.

The operational parameters of the *RIEGL* LMS-Q560 can be configured to cover a wide field of applications. The instrument is extremely rugged, therefore ideally suited for the installation on aircraft. Also, it is compact and lightweight enough to be installed in small single-engine planes, helicopters or ultra-light planes. The instrument provides online monitoring range and angle data while logging the precisely time-stamped and digitized echo signal data to the rugged *RIEGL* Data Recorder DR560. Table 1 summarizes the key features of the *RIEGL* LMS-Q560.

Measurement range[1]	≥ 850 m @ ρ = 0.2, ≥ 1500 m @ ρ = 0.8
Measurement accuracy [2]	± 20 mm
Waveform sampling interval	1 ns
Dynamic range of waveform capture	16 bit
Multi-target resolution	better 0.6 m
Laser pulse repetition rate (PRR) [3]	up to 100 000 Hz
Laser beam divergence	0.5 mrad
Eye safety class	Class 1
Scan angle range [4]	±22.5 deg
Scan speed	5 – 160 line scans per seconds
Scan angle accuracy	0.0025 deg

[1] target size in excess of laser foot print, normal incidence, visibility ≥10 km, PRR <40kHz, ρ gives reflectivity of diffusely reflecting target [2] standard deviation, plus distance depending error ≤20 ppm, [3] User selectable, average measurement rate ≤ 66 kHz @ ±30 deg scan angle, [4] up to ±30 deg with 90% of maximum measurement range.

Table 1. Key specifications of the *RIEGL* LMS-Q560.

Figure 3 illustrates the process of echo signal digitization. The top most line depicts the analog signals: the first (red) pulse relates to a fraction of the laser transmitter pulse, and the next 3 (blue) pulses correspond to the reflections by the branches of the tree; the last pulse corresponds to the ground reflection. This analog echo signal is sampled at constant time intervals (middle line) and subsequently AD converted, resulting in a digital data stream (bottom line of the acquisition section). After pre-processing the data stream for data reduction it is stored in the *RIEGL* Data Recorder DR560 and is thus available for off-line post processing, as indicated in the post-processing section of the diagram. The instrument is recording the full waveform information of the echo signal over a wide dynamic range. Thus, in post-processing the signal can be perfectly reconstructed and analyzed in detail yielding target distance, target type, and other additional parameters.

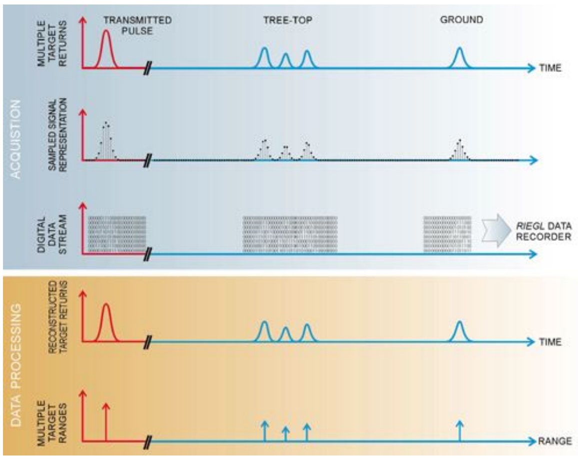


Figure 3. Data acquisition and post processing

1.3 Direct Georeferencing System

In the LiteMapper-5600 system, in-flight sensor position and attitude are provided by the integrated *IGI* AEROcontrol-IId direct georeferencing system. The inertial measurement unit (IMU) is rigidly mounted to the laser scanner to provide highly accurate positioning and attitude information. Table 2 lists the specifications of the *IGI* AEROcontrol IId system:

GPS	integrated 12-channel L1/L2 receiver
GPS sampling rate	up to 2 Hz
IMU	fiber-optic gyro
IMU angular accuracy (roll / pitch / yaw)	≤ 0.005° / ≤ 0.005° / ≤ 0.01°
IMU sampling rate	128 Hz, optional 256 Hz

Table 2. Specifications of the integrated *IGI* AEROcontrol-IId direct georeferencing system

With the AEROcontrol IId and the LMS-Q560 being some of the most accurate components on the market the LiteMapper-5600 system achieves a relative accuracy of surface measurements of better than 0.2 m horizontally and 0.05 m vertically (flat surface). Regarding absolute accuracies, the dGPS system is, of course, the limiting factor.

1.4 Digital Camera

To complement the LIDAR data the *IGI* DigiCAM digital camera is integral component of the LiteMapper-5600 systems. It is available in three configurations of 14 MPixels RGB, 22 MPixels RGB, and 22 MPixels CIR.

Figure 4. DigiCAM 14K sensor

The camera covers the same swath the LIDAR system sees providing high-resolution imagery of the surface in true-color or color infrared to aid surface classification and to provide extra planimetric resolution – traditionally the weak side of LIDAR. Figure 4 shows the DigiCAM 14K sensor head. Table 3 lists the key specifications of the IGI DigiCAMs.

Version	DigiCAM 14K	DigiCAM 22R/RI
Pixels	4.500 x 3.000	5.400 x 4.100
Sensor	CMOS	CCD
Spectral channels / radiometric resolution	R-G-B, 12 bit	R-G-B, 16 bit or IR-R-G, (CIR) 16 bit
Frame rate	0.6 s – 4 s	
GSD @ 500 m AGL	0.14 x 0.14 m^2	

Table 3. Specifications of the *IGI* DigiCAM digital camera

The DigiCAM is provided with calibrated lenses, and is tightly integrated with the LiteMapper-5600 and the *IGI* CCNS-4 flight management systems to provide reliable and easy operation. It is mounted together and boresighted with the laser scanner and the IMU to enable direct georeferencing of its images and automated orthoimage generation using the DSM output of the LIDAR system.

3. RESULTS

At the writing of this paper the first test flight with a prototype system has just been completed. In this section we therefore present and discuss some measurement results of a short segment of this flight. As the flight operator did not provided any trajectory information a linear flight movement at constant altitude and attitude was assumed. An analysis of the absolute accuracy was therefore not performed at this stage. Digital camera data was also not available from this flight.

The flight was performed at the end of August 2004. Data was recorded from an altitude of approx. 340 m above ground at about 65 m/s (234 km/h) in one overflight. The swath is about 300 m wide. The laser scanner was operated with a PRF of 50 kHz. Therefore the median point density is 1.35 measurements/m^2 corresponding to an average point spacing of 0.86 m. The laser beam footprint diameter was 0.17 m.

3.1 Sample Area

Figure 5 gives an overview of the data sample. It covers an area of approx. 658 m x 314 m. The image shows a shaded-relief view of the digital surface model (DSM, highest points), generated to cell size of 1 x 1 m^2.

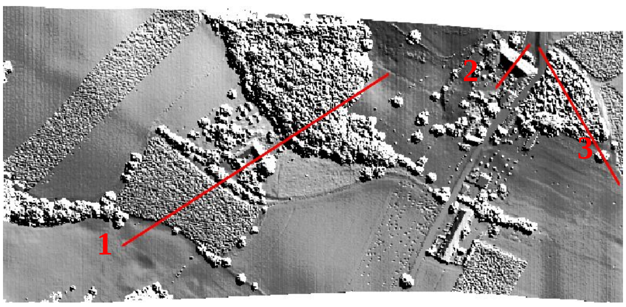


Figure 5. Test site

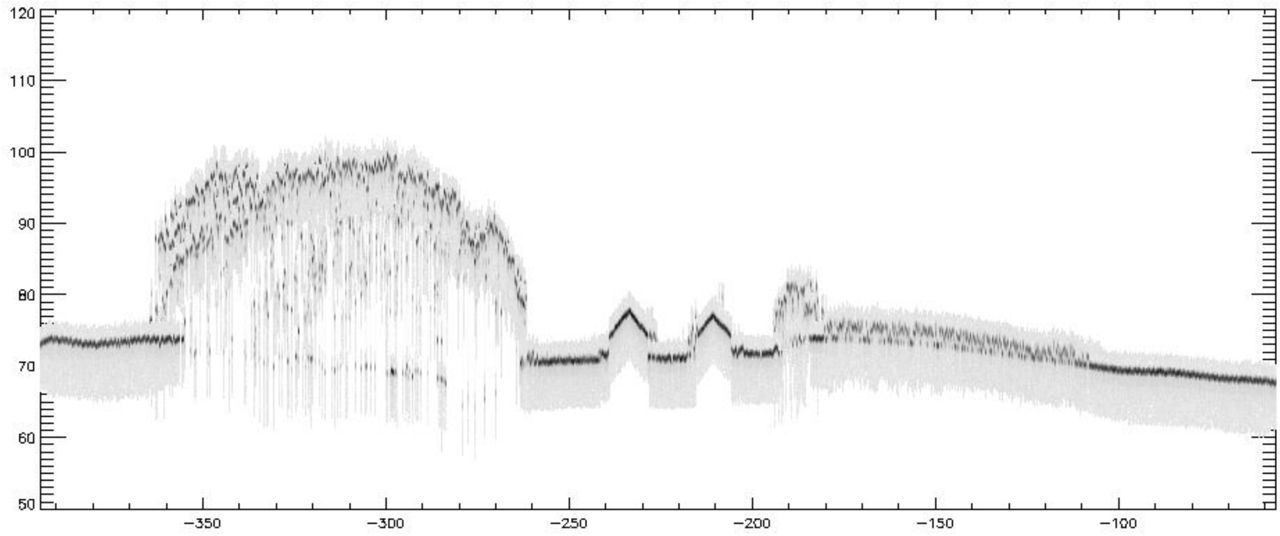


Figure 6. Profile 1 through forest, buildings, and corn field

3.2 Profiles and Waveforms

The scene in figure 5 shows a rural setting with some corn fields (intersected by line 1), individual trees and mainly deciduous forest, as well as some buildings (lines 1 and 3).

The red lines in figure 5 indicate the position of the profiles that are presented below. In the following discussion of the results we will use individual waveforms along these profiles to highlight the possibilities arising out of the availability of waveform information and to illustrate system performance.

Figure 6 shows the profile along line 1. The amplitudes of the waveforms are represented by the gray level, darker color representing a higher amplitude. Minimum amplitude values are shown in light gray to indicate where waveform data was registered. The x-axis indicates meters along the profile, the y-axis shows relative height in meters. On the left a dense deciduous forest area is shown. In the center two gable-roofed buildings can be recognized, followed by a row of trees and a corn field on the right.

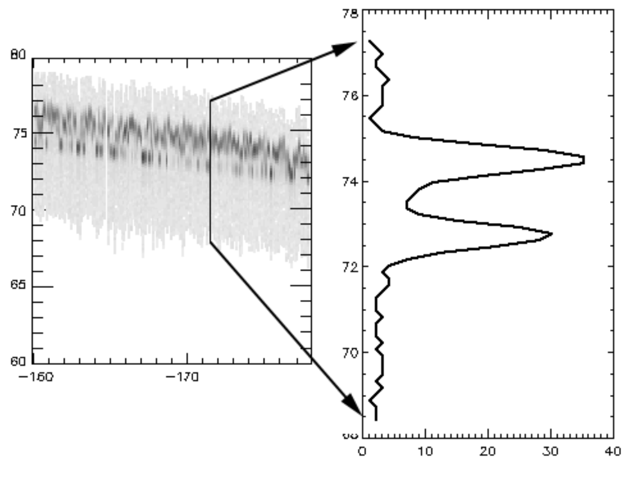


Figure 7. Detail of profile 1: Corn field

Figure 7 shows an enlarged detail of profile 2, a section through the corn field. Both in the height profile on the left and on the waveform plot on the right the separate returns from ground (at about 72.7 m) and the top of vegetation (about 74.5 m) can be distinguished well. General crop height is around 2 m.

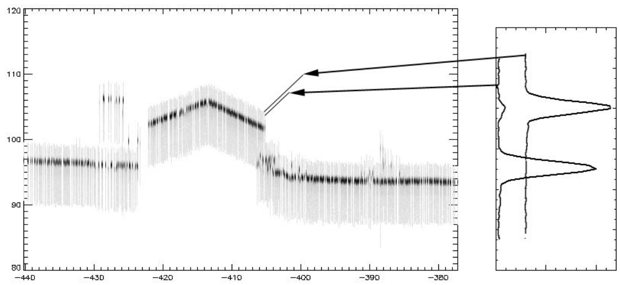


Figure 8. Profile 2: Building

In figure 8 we show how waveform registration can improve on the inability of LIDAR measurements to pinpoint breaklines. In this case point spacing was approximately 0.9 m in both directions while the diameter of the laser beam on the ground was only about 0.17 m. Therefore, in general a break line (like the edge of a roof) will not be detectable directly in LIDAR data. Some measurements will hit the roof, and some will hit the ground. However, the chance of a measurement partially hitting both roof edge and ground are relatively small. In figure 8 the first waveform actually shows both roof and ground returns while the second waveform only shows roof. Depending on the reflectances of roof and ground, waveform data can be used to calculate how much of the beam was reflected off the roof and how much off the ground, so the lateral position of a break line can be determined to sub-beam-diameter accuracy in individual waveform measurements.

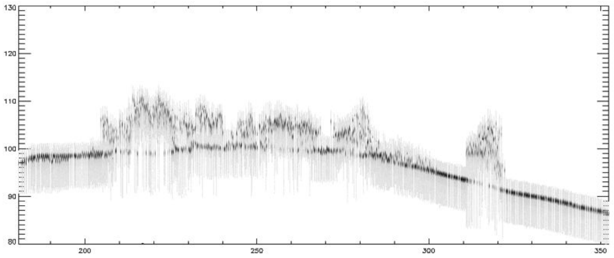


Figure 9. Profile 3: Trees and vegetation of different sizes

Figure 9 shows a profile through trees and vegetation of varying height and density. In the left part of the profile two large trees can be discerned due to the relatively high measurement density possible with the LMS-Q560 laser scanner even from fixed-wing aircraft.

Figure 10 gives a number of sample waveforms from forest areas. In each diagram the amplitude of the return is plotted on the x-axis while the height is displayed on the y-axis.

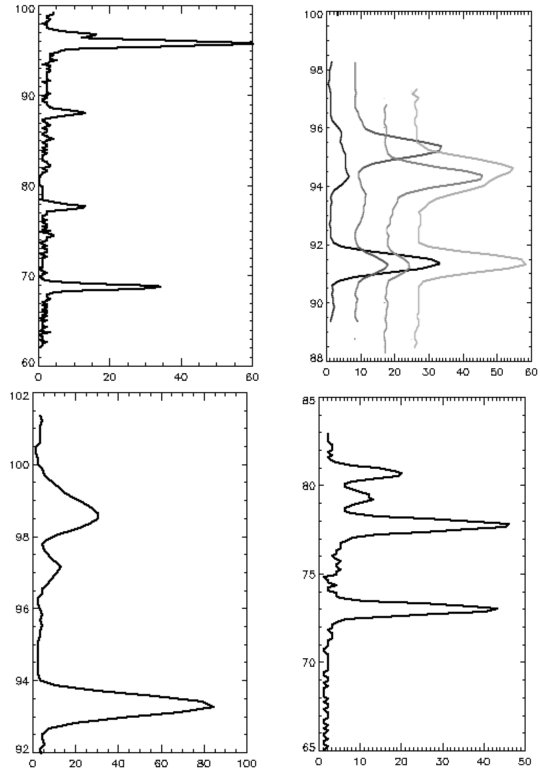


Figure 10. Examples of forest waveforms: multiple levels of vegetation (top left), multiple adjacent waveforms (top right), complex canopies – the lowest pulse represents ground (bottom).

The first waveform shows multiple levels of vegetation within the forest by distinct peaks on four different levels. The lowest peak represents ground. The top peak has a small sub-peak on its leading edge indicating some structures (branches?) at the canopy top. This example makes it quite obvious that the height of the vegetation can be determined more accurately from waveform data than with discrete range data. In this case the user has the freedom to decide if the branches define the canopy top or if the canopy starts at the first major peak.

The second diagram displays an aggregation of four subsequent waveforms. While the ground return is common on all shots, the canopy returns illustrate different effects very well: the left-most canopy return is a low-amplitude but wide curve indicating overall canopy thickness; the second waveform clearly shows a single return from the canopy top and a much weaker return from second-level vegetation; the third waveform shows a strong return from a lower canopy top merged with a weak response from second-level vegetation at the trailing edge; finally the fourth waveform shows a response from the two top-level canopies where both pulses are overlaid.
The bottom diagrams show examples of complex canopies – the top pulses are widened, and overlays of multiple returns can be observed there which may have been caused by branches or second-level vegetation.

Figure 11 illustrates how waveforms can help to detect low ground vegetation. The diagram shows a flat-ground waveform (black) and a waveform from ground and low vegetation (gray). Quite clearly the low vegetation causes the return pulse to widen. The high fidelity of the waveform detection and digitization within the *RIEGL* LMS-Q560 laser scanner also allows an accurate determination of the peaks of overlaid pulses down to a target separations of only about 0.5 m. In this case pulse peaks are only about 0.5 m apart – a separation impossible to detect with a conventional LIDAR system. Furthermore, even if the leading edge of the ground return pulse is distorted by low vegetation, the user can still use the trailing edge to determine ground height accurately.

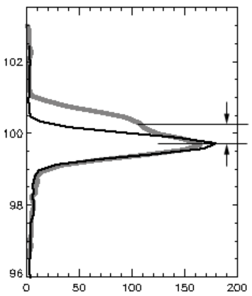


Figure 11. Low vegetation and the limits of multi-target resolution

Figure 12 shows pulse widenings. The gray waveform is about 15 cm wider than the black waveform. The reason for the pulse widening in this case is probably due to a rough surface like a ploughed field.

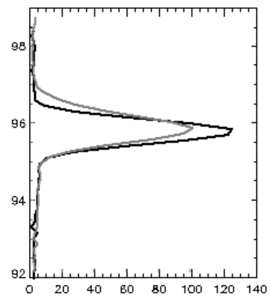


Figure 12. Pulse widening

While in theory also surface slope (angle of incidence) leads to a widening of a return pulse it is unlikely that it can be observed reliably with the currently implemented system parameters. The outgoing pulse width is about 4 ns or 0.6 m FWHM. The beam diameter is only 0.17 m. So even an angle of incidence of 45° would only stretch the return pulse by 7 cm, half of a sampling interval.

A larger beam divergence of more than 1 mrad and a shorter pulse width of perhaps 2 ns could, however, improve the sensitivity sufficiently to allow slope detection to some extent. With the flexible design of the *RIEGL* LMS-Q560 these parameters can be made available for special applications.

4. CONCLUSIONS

This paper introduced the LiteMapper-5600 system as one of the first commercially available airborne LIDAR terrain mapping systems featuring waveform digitization. It showed that this system is able to produce at least as accurate measurements as conventional LIDAR systems while adding significant capabilities for increased accuracy, advanced surface analysis, and in-depth information gathering for numerous applications.

Several examples were shown to illustrate the possibilities for detailled analysis of vegetation structures. Especially forestry and agriculture applications can benefit from the additional information available through waveform registration.

The advantages of using LiteMapper-5600 waveform data can be summarized as:

- potential for more reliable and accurate measurements compared to discrete range systems,
- ability to locate surface discontinuities with an accuracy of less than the laser footprint diameter,
- ability to distinguish an “unlimited” number of targets in each measurement,
- detection of canopy height, shape, density, vertical extent,
- detection of multiple lower vegetation levels.
- target separation as low as 0.5 m possible,
- distinction of ground and ground vegetation,
- detection of macroscopic surface roughness.

On the other hand, waveform registration increases data volume by a factor of 50 – 200. While the capacity of modern hard disks is sufficient for capturing LIDAR waveforms also during flights of several hours, download and post-processing of these data volumes requires more time than for conventional systems.

While the hardware prototype used for generating the samples presented was already able to impress as a highly reliable, stabile, and accurate measurement system, further optimization of operational parameters like pulse width and beam divergence will be necessary to exploit the potential of this technology to its fullest. Also, developments are ongoing to improve and accelerate the handling of the huge data volumes generated by the waveform registration process, and to provide efficient means of extracting the wealth of information available in these data sets automatically (Hug, 2004).

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