PERFORMANCE CAPABILITIES OF LASER SCANNERS
- AN OVERVIEW AND MEASUREMENT PRINCIPLE ANALYSIS -

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ABSTRACT:

Today for airborne laser scanning only pulsed laser systems are applied. Where as for near range measurement tasks cw-laser systems are used which carry out ranging by measuring the phase difference between the transmitted and received signal. First the different major ranging measurement principles are explained. MATLAB simulations are carried out to analyse the performance of different measurement methods. The simulation results can be used to select the optimum system in dependence of the application and to optimise the signal processing algorithm with regard to accuracy and robustness. Reasons, why pulsed laser systems are the first choice for airborne applications, are given by accuracy formulas derived from link budget equations. The advantages of full-wave laser scanner are discussed and recent developments are presented.

1. INTRODUCTION

With the advent of semiconductor lasers very robust and small in size laser scanner systems can be built. The state of the art systems are therefore very mobile and can be used for diverse applications e.g. airborne topographic mapping, surveying of buildings and plants, model generation for animation purposes. Potential users are facing the problem to select the system which is optimal for the desired measurement and surveying tasks respectively. The objective of this paper is to support the user with parameters and decision criteria in selecting the optimum laser scanner.

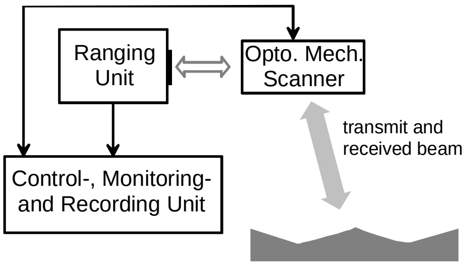

Figure 1. Principle Laser Scanner Set-Up

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 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 overall performance. Therefore, this paper deals only with the ranging performance of laser scanners. 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. The following simulations were carried out with MATLAB for both principles to identify advantages and disadvantages and to work out the optimum application field.

2. RANGING PRINCIPLES

Before simulation results are presented the different ranging principles will be explained.

2.1 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

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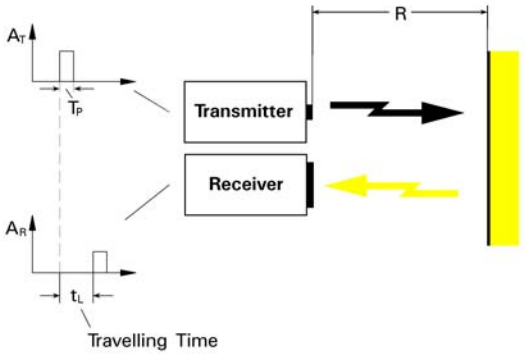

Figure 2. Pulse Ranging

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

2.1.1 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 the threshold level will be passed later (s. Figure 3). This means, a too long travelling time of the laser signal is measured and by that a too long slant range. To compensate this intensity dependent effect, the level of the return signal must be determined and a correction is applied to the measuring result. A possible one correction t_k is

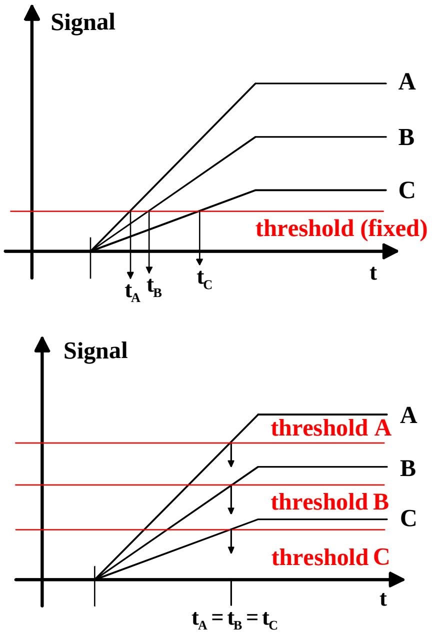

Figure 3. Detection of a Return Pulse

$$t_k = \frac{P_{thr} \cdot t_r}{P_{peak}} \tag{1}$$

if P_{thr} is the threshold level, P_{peak} the peak level and t_r the rise time.

2.1.2 Constant Fraction Discriminator: To relax the dependency on the level of the pulse return signal more advanced laser ranging systems use a constant fraction discriminator to trigger the stop signal. Here the level of the return signal is regarded and determines the instantaneous threshold.

2.1.3 Full Wave Detection: Applying pulsed laser scanners for airborne surveys soon it became clear, that for each transmitted laser pulse several returns can be observed, e.g. from the tree tops and from ground. Therefore, today airborne laser scanners can discriminate between first and last return pulse. Either they sample both or they have a mode switch where the user can select the mode. To improve the performance of laser scanners the next logical step 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 observed. Therefore, the idea was to sample the total backscattered laser signal (Blair, 1999). This allows, to process the acquired data conventionally or with correlation algorithms and to determine single slant ranges or even elevation layers. The comprehensive sampling of a return signal is known as full wave detection.

2.2 CW-Ranging by Measuring the Phase Difference

In continuous wave (cw) laser ranging the laser intensity is modulated with a well defined function, e.g. a sinusoidal or a square wave signal. The modulation signal has a time period T_P. The laser emits light continuously with moderate average power levels and therefore is called cw-laser. The time of flight of the signal T_L is determined by measuring the phase difference between the transmitted and received signal. The period time T_P or its equivalents the frequency f or wavelength λ defines the maximum unambiguous range R_{un}, which is $\lambda/2$ for two-way ranging, and the range resolution ΔR. For a given phase resolution $\Delta\theta$, the range resolution ΔR is calculated by

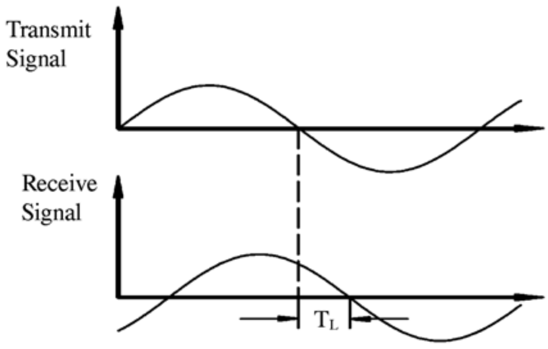

Figure 4. Phase Difference

$$\Delta R = \frac{\lambda}{2} \cdot \Delta\theta \tag{2}$$

Formula 2 shows, that the range resolution can be easily improved by using signals with shorter wavelengths if the phase resolution is kept constant. However, shorter wavelengths mean reduced maximum unambiguous ranges. Therefore, satisfying ranging capabilities with high range resolution are only possible

if several modulation signals with different frequencies are applied. Such method is also known as multi-tone-ranging or multi-frequency-ranging. Here the highest frequency determines the resolution and the lowest frequency the unambiguous range.
This method can be easily realised with semiconductor laser diodes, because here the intensity of the light can be directly modulated by the drive current. Due to the high electrical bandwidth of the laser diodes high frequencies up to more than 10 GHz are possible. However, the available cw-power is very limited. Therefore, the ranging method of measuring the phase difference is primarily applied in near range scanning systems.
Multiple target returns cannot be directly distinguished, because the receiver detects only the resultant phase of all returns. Therefore, the range resolution ΔR is not a measure for resolving two targets. As the modulation signals are recovered by synchronous demodulation techniques, the intensity of the backscattered laser light can be detected without disturbing background radiation. This means that these systems are very robust against high background radiation, e.g. sun light and external illumination sources.

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.

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 constructed, 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.

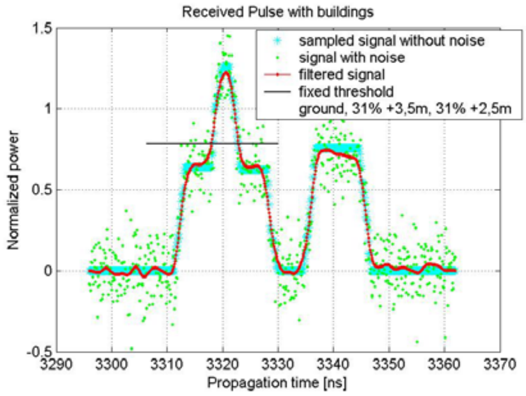

Figure 5. Received Laser Pulse from a Surface Showing Three Height Levels

3.2 Simulation of Phase Difference Measurements

For simulating the phase difference measurement typical parameters of ScaLARS are used which are described by (Hug, 1997). This semiconductor laser system works with two modulation frequencies at 1 MHz and 10 MHz and carries out direct phase measurements. The accuracy for different S/N ratios was calculated by (Wehr, 1994 and 1998). In Figure 6 the effect of different heights within the laser spot are shown. Here the signal cannot be plotted over propagation time, as the integral signal is evaluated. This is the main difference to pulse systems, because the received signal is a sine-signal which phase comprises the integral of all phases originating from the n delayed signal components.
Figure 6 shows the results of phase measurements at 504 m above ground, where the signal is partly reflected from ground and roof. The height offset between ground and roof varies from 0 m to 10 m. The results for both frequencies are quite different. While the received power for the 1 MHz signal remains almost constant, the 10 MHz signal comes down to 10%, in the extreme case a complete canceling may occur. The range measurement is a superimposition of the two height components ground and roof in the received signal. With respect to the different wavelengths the range for 1 MHz is almost linear to the ratio ground to roof, while for the 10 MHz signal the error shows a nonlinear behavior, especially for height offsets at quarter wavelength. The ambiguity resolution for the complete system is also more complex, resulting in positive and negative errors. With respect to the different errors for 1 and 10 MHz it is possible to analyze the measurement situation and to discriminate between measurement on flat surface and backscattering from forest or urban areas. First trials to resolve for the ground signal are quite promising and we hope to improve these results with the help of a third modulation frequency.

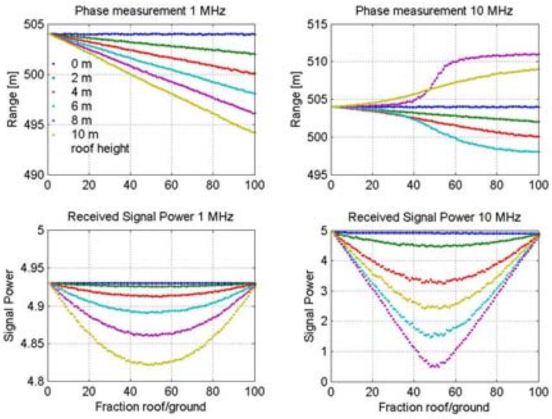

Figure 6: Phase Measurement for 1 MHz and 10 MHz with Two Height Levels within the Laser Spot

3.3 Simulation of Pulse Ranging

In case of pulsed laser systems the ranging value is determined by threshold detection of either the analog or digital 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 7). Figure 7 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 shows almost no dependency on S/N.

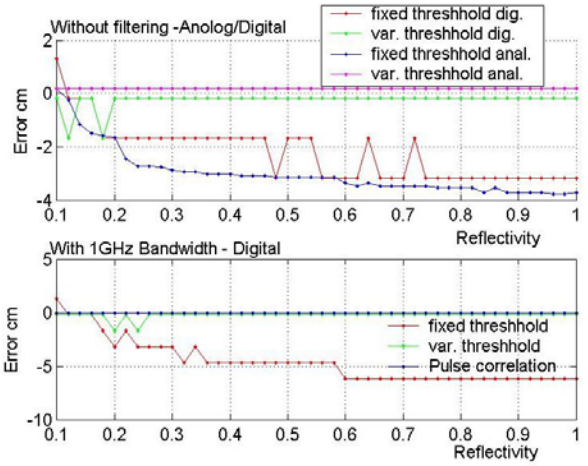

Figure 7: Effect of Ground Reflectivity on Range Measurement

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 8, is a special correlation technique, which allows a height resolution below the pulse length. In Figure 8 the same received pulse is used as in Figure 5. 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.

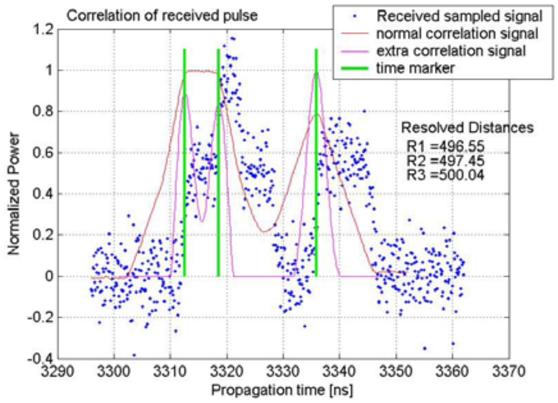

Figure 8: Full Wave Technique with Special Correlation Method

3.4 Comparison of Measurement Methods

In Figure 9 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, comparable to Figure 6. 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%.

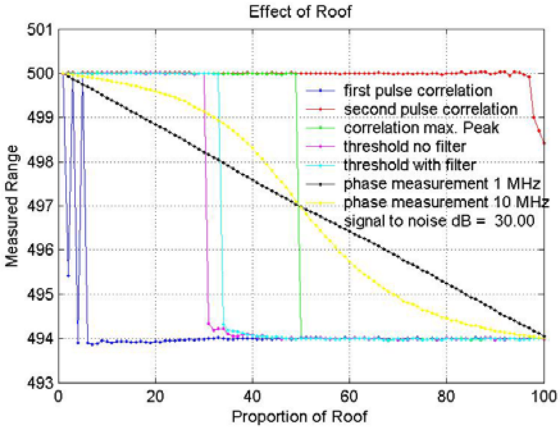

Figure 9: Effect of a Second Height Level within the Laser Spot on Ranging Performance

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

$$\sigma_{R\,\mathrm{pulse}} = \frac{c}{4\pi} \cdot T_P \cdot \frac{1}{\sqrt{S/N}} \tag{3}$$

for pulse ranging systems and for cw-systems

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

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. If very high accuracies e.g. better than millimeter or even submillimeter in near range are required, cw-systems using the phase difference measurement principle are favourably.

Ranging signals with GHz modulation frequencies are possible. But cw semiconductor laser which can be directly modulated through the drive current are limited in the transmitted optical power. Therefore, cw laser systems are mainly applied for terrestrial surveying tasks. For airborne applications centimetre accuracies are adequate and therefore pulse systems are commonly used, because the commercially available pulse lasers offer the required peak power to achieve the necessary S/N despite the long range. Flying altitudes of more than 10 km are possible and state-of-the-art.

4. CONCLUSIONS

On flat surfaces pulse systems with variable threshold or correlation techniques show the same accuracy as phase measurement systems with comparable system parameters. Only systems with fixed threshold produce systematic offset 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. Another big advantage can be seen in the feature of power estimation of the received signal.

For the phase measurement a multi frequency system offers some possibilities to extract ground levels and to provide good power measurements. With respect to our simulation results a pulse system is preferable for laser ranging from aircraft in forested and urban areas. This statement is underlined by the fact that all commercial airborne laser scanners work with pulse lasers. In addition, the simulations clarify that the signal evaluation with correlation techniques offers optimum results. This processing technique requires full wave sampling. First laser scanners with full wave detection are going to come into the market, e.g. the Digitizing Airborne Laser Scanner LMS-Q560 of the company Riegl and the ALTM 3100 from Optech. New processing algorithms must be developed to make full use of those advanced laser sensors.

For near ranging applications the accuracy of phase measurement can easily be improved by using higher modulation frequencies. Also the effect of backlight can be eliminated by using narrow band pass filters, which extract only the modulation signal. Therefore, the power of the received laser signal is measured only and noise is suppressed. These systems offer extreme high measurement rates of e.g. more than 600 k pixel/sec. Due to the limited available laser power, they are used for high definition terrestrial surveys as e.g. survey of historic buildings, industrial plant surveys and data generation for virtual reality applications. Simulations show that cw-laser systems may face ranging problems if elevation differences of a quarter wavelength of the ranging signal are within the instantaneous laser spot. These simulations were verified with the 3D laser scanner of the Institute of Navigation. Supported by the simulations and the experiments advanced algorithms will be developed and possible hardware modifications concerning this fact will be carried out.

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