

# Suitability of a laser rangefinder to characterize winter wheat

Detlef Ehlert · Michael Heisig · Rolf Adamek

Published online: 17 September 2010  
© Springer Science+Business Media, LLC 2010

**Abstract** In recent years, laser rangefinder sensors have been introduced to the practice and research of agricultural engineering. In research, laser rangefinders have been investigated in horticulture and agriculture. For vehicle-based determination of crop biomass, commercially available laser rangefinders have been analysed and tested to measure aboveground biomass in oilseed rape, winter rye, winter wheat, oats and grassland. Resulting from limited measuring range and fixed beam types, the laser rangefinder models that were investigated only partially met the specific demands for agricultural field and crop conditions. Therefore, a new laser rangefinder scanner (ibeo-ALASCA XT) was chosen. This sensor was specifically developed for driver assistance and autonomous guiding of road vehicles. The scanner was tested in 2008 focusing on the measurement of crop stand parameters in winter wheat under field conditions. The sensor achieved good results with reproducible measurements. Measuring from a stationary vehicle, the standard deviation for the measurements of crop height to characterise the crop stand was less than 3 mm in low, medium, and high biomass areas. The ground speed of the vehicle, ranging from 6 to 24 km h<sup>-1</sup>, did not significantly influence the readings. For measurements in front of tractors and self-propelled machines (field sprayers, combines and forage harvesters), the sensor has to scan the crop stands at different inclination angles. It was shown that the inclination angle of the laser beam, which varied from 10° to 80°, significantly influenced the readings. Higher inclination angles resulted in apparent increased heights of the crop stand. For the functional relationship between reflection height levels (95th, 75th, 50th and 25th percentiles, and mean values) and crop biomass density, the coefficient of determination ( $R^2$ ) was greater than 0.9.

**Keywords** Crop production · Winter wheat · Laser rangefinder · Crop height · Crop biomass

---

D. Ehlert (✉) · M. Heisig · R. Adamek  
Leibniz-Institute for Agricultural Engineering Potsdam-Bornim (ATB), Potsdam, Germany  
e-mail: dehlert@atb-potsdam.de

## Introduction

In precision agriculture, crop height, leaf cover and biomass are important parameters for the assessment of crop stands. Based on these parameters, expected crop yields can be estimated, and the amount of fertilisers and pesticides for site-specific crop management may be optimised. The first approaches to optimize site-specific crop management have been reported in the literature (e.g. Heege et al. 2004; Ehlert and Dammer 2006). Moreover, during harvesting, combine parameters, such as ground speed or rotation speed of functional units (rasp-bar cylinder and cutter head), can be adapted to crop conditions. Furthermore, autonomous guidance of agricultural machinery along tramlines and crop edges are of great interest to increase machinery performance and to reduce the workload for the driver. To gather these parameters, sturdy and low-cost suitable sensors are needed.

Commercially available laser rangefinder sensors use one of the following measuring principles: light time-of-flight, phase modulation, interferometry and triangulation. In many cases, the first three principles are summarised as time-of-flight measurement. Triangulation sensors measure short ranges (maximum of several meters) with high accuracy while time-of-flight sensors are more suitable for long ranges.

Laser rangefinders are already used on combine harvesters. The company Claas offers the “Laserpilot” from the Lexion series to detect the edge of crop stands for autonomous guidance, which results in optimal cutting width and threshing performance. A similar solution called the “SmartSteer” can be found on CX combine harvesters from Case-New Holland. However, these laser rangefinder sensors are not able to detect specific crop stand parameters, such as crop height, leaf cover and biomass.

Commercially available low cost laser rangefinders have been investigated in both horticultural and agricultural research. In horticulture, Tumbo et al. (2002) measured the canopy volume and structure in citrus. Different spray volume deposition models using light detection and ranging (LIDAR) measurements of apple orchards have been compared (Walklate et al. 2002), and the advances in the measurement of structural characteristics of plants (peach trees) with a LIDAR scanner have also been reported (Sanz et al. 2004). Furthermore, a ground LIDAR scanner has been used to measure vineyard leaf area and canopy structure variability of grapevines (Arno et al. 2009).

In agriculture, Ehsani and Lang (2002) used a laser scanner to estimate the volume of geometric objects with defined shapes (cylinders) and soybean plants under laboratory conditions. The aim was to develop a method for measuring plant volume or biomass to monitor plant growth rate in the field at early growth stages. Quantitative relationships between laser scanner readings and crop biomass were not presented. Thösink et al. (2004) made a first approach to measure the height of oat plants with a fixed beam laser. They calculated the crop height, and the level of the soil surface was discriminated from the distribution of height classes. Crop plant density in small grains has been predicted using LIDAR sensors (Saeyns et al. 2009). Furthermore, crop biomass density was measured by laser triangulation and time-of-flight principles in oilseed rape, winter rye, winter wheat and grassland (Ehlert et al. 2007). The authors assessed low-cost laser rangefinders for vehicle-based crop biomass estimation. High functional correlations were found between mean reflection height, which was calculated from measured reflection range and sensor height, and fresh crop biomass from measuring ranges up to 2.5 m. The coefficient of determination for linear regression was more than 0.90 ( $R^2 > 0.9$ ) for oilseed rape, winter rye and winter wheat. However, the accuracy was lower in grassland (pasture).

Each model of laser rangefinder has instrument specific technical parameters, such as wavelength, beam dimensions, divergence, minimum and maximum measuring range,

signal sensitivity, measuring frequency and angle resolution, which result in individual measuring properties. Therefore, focused scientific investigations are necessary for the comprehensive assessment of the potential for laser based crop sensors.

The distances between the sensor and the crop or soil have been reported to be less than 3.5 m resulting in small strips being scanned. Agricultural spreaders and sprayers have working widths up to 36 m. To ensure a representative measurement, the scanned strip should be adequately related to the working width. The same problem exists for scanning the area in front of harvesters because the crop biomass, crop stand edges and obstacles must be detected from large distances to cope with the speed aboveground, navigate the harvester or stop the machine in time before contacting obstacles. To meet these demands, laser rangefinder sensors should be able to measure up to 20 m with high reliability.

Because vehicle based laser rangefinder measurements in crop stands for large distances have not been investigated until now, the objectives of this paper include the following:

- To analyse commercially available laser rangefinders and to select the most promising one.
- To investigate the reproducibility of crop measurements.
- To compare the readings of the chosen laser scanner for four layers implemented.
- To assess the influence of vehicle ground speed on the crop height.
- To assess the influence of the inclination angle of the sensor on measured crop height.
- To estimate the functional relation between measured height and crop biomass density in winter wheat.

## Materials and methods

### Choice of a laser rangefinder

The laser rangefinder sensors used in previous investigations were assessed for measuring crop stand parameters for short ranges that were less than 2.5 m. The authors suggested that these sensors did not fully meet the demands required to work on vehicles in field conditions (Ehlert et al. 2009). Therefore, a prerequisite for testing the potential of laser rangefinders in crop production was to find a suitable sensor model. Based on previous experience and analysis of commercially available laser rangefinders, a laser scanner that was developed for automobile driver assistance (Ibeo ALASCA XT, Automobile Sensor GmbH, Hamburg, Germany) was chosen (Fig. 1, Table 1).

The laser scanner is based on LIDAR technology measuring the pulses of time-of-flight. The built-in laser generates short rapid-fire pulses, which are transmitted by a tilted rotating mirror. The intensity of the reflected laser pulse is recorded by a photo diode inside the scanner. If the intensity is below the threshold, the measured value is discarded. The laser scanner transmits and analyses up to four echo pulses of different target distances over a period of one measurement pulse, which indicates that from a single pulse up to four individual echoes are recorded. Furthermore, the sensor measures in four layers that have an angle of divergence of  $0.8^\circ$  with respect to each other. A single beam has a vertical divergence of  $0.8^\circ$  and horizontal divergence of  $0.08^\circ$  according to the user's manual. The beam has a cross sectional area of 140 mm (height)  $\times$  14 mm (width) at a range of 10 m. The layers are arranged on top of each other. From the four layers (1–4) and four echoes (A–D), a  $4 \times 4$  matrix resulted and is shown in Table 2. With this structure, the four layers together scan a band of 0.56 m in height at a range of 10 m.

**Fig. 1** Laser scanner Ibeo ALASCA XT**Table 1** Technical data of laser scanner Ibeo-ALASCA XT (time-of-flight principle)

Measuring range	0.3–200 m
Wave length	905 nm
Scan frequency	12.5 Hz
Angle resolution	0.125/0.25/0.5°
Voltage	12–15 V DC
Power requirement	20 W
Safety class	1
Length/height/width	204/215/377 mm
Mass	ca. 3.0 kg
Price (2009)	12,500 €

**Table 2** Layer/echo matrix of the laser scanner

Layer	Echo pulse			
	A	B	C	D
4 (top)	4A	4B	4C	4D
3	3A	3B	3C	3D
2	2A	2B	2C	2D
1 (bottom)	1A	1B	1C	1D

In the investigations, the sensor worked with a rotation frequency of 12.5 Hz. The specific hardware construction of the scanner resulted in the following scan angular ( $\gamma$ ) resolutions according to the user's manual:  $0.125^\circ$  for  $\gamma < \pm 16^\circ$ ,  $0.25^\circ$  for  $\gamma = \pm 16^\circ$  to  $\pm 60^\circ$ , and  $0.5^\circ$  for  $\gamma = \pm 60^\circ$  to  $\pm 90^\circ$ . During scanning, the laser beam rotates in a plane. The sensor does not deliver the measured range and corresponding scanning angle  $\gamma$  (polar co-ordinates). However, it delivers the x and y Cartesian co-ordinates. The x co-ordinate is the co-ordinate of reflection point related to the sensor axis (scanning angle  $\gamma = 0^\circ$ ), and the y co-ordinate is the lateral distance of the reflection point to the x-axis. The potential scanning width is determined by the sensor hardware, inclination angle ( $\varphi$ ) and sensor height ( $h_s$ ). Furthermore, the scanning width can be adapted according to the measurement task by the user software.

The measuring principle is demonstrated in Fig. 2. The measured range ( $l_R$ ) of the scanner depends on the height of the laser scanner ( $h_S$ ) above the ground and inclination angle ( $\varphi$ ) of the sensor. The height for a single plant can be exactly measured by a ruler or by a laser, but the crop height of a crop stand is difficult to define. In an area of 1 ha, there are approximately 4–7 million single haulms at different heights, which makes it difficult to define the height of a crop stand. The measured range is an inverse proportional to crop stand parameters (height, density and crop biomass), which does not reflect the crop stand in a plausible manner. Therefore, the parameter mean reflection height ( $h_R$ ) was introduced to characterise a crop stand. As shown in Fig. 2, the reflection height of the laser spot ( $h_R$ ) was not only from the highest plant components but also from the lower plant components and the ground. In a rough approximation, it can be expected that the upper values of reflection height represent the crop stand height.

In this investigation, the readings of all four layers and echoes were recorded. The statistical programmes used were Microsoft® Office Excel® 2007 and SAS OnlineDoc® 9.1.3 2004 (SAS Institute Inc., Cary, NC, USA). The description of growth stages of the crop was based on the BBCH scale (Meyer 1977).

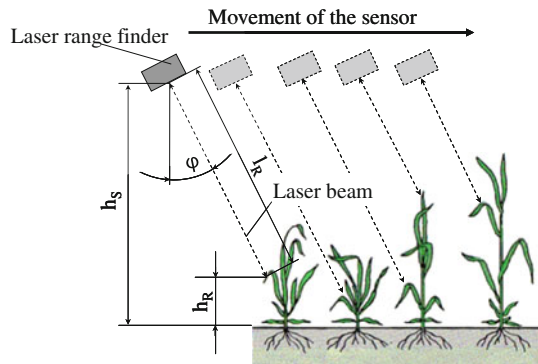
### Reproducibility

In a test series (May 28–29, 2008), the reproducibility of readings in winter wheat (BBCH 55–58) were checked. For this purpose, a tool carrier was statically positioned at places with different crop biomasses (low, medium and high) along a tramline. The laser scanner was oriented sideways on the tool carrier ( $h_S = 2.96$  m,  $\varphi = 45^\circ$  and scanning width  $y = \pm 3$  m). Under these conditions, it was guaranteed that the laser beam always scanned the same crop population. All individual readings were recorded. For each scan, the mean value was calculated. Furthermore, the standard deviation and coefficient of variation for mean values of single scans were calculated.

### Comparison of the layers

In a test series, the differences of the readings given from the four layers along a transect (tramline) with an approximate length of 700 m in a winter wheat field (May 30, 2008; BBCH 55–58) were investigated. For this purpose, the laser scanner was mounted in the driving direction on a tractor with the following parameters: inclination angle ( $\varphi$ ) at  $60^\circ$ , sensor height ( $h_S$ ) at 2.74 m, scanning width ( $y$ ) from 0 m to 1 m, and an approximate ground speed of  $1.7 \text{ ms}^{-1}$ . A DGPS system was used for positioning. For the analysis, the

**Fig. 2** Measuring principle and parameters for calculation of reflection height ( $h_R$ )



transect was divided into segments of 10 m in length for a more detailed analysis of measuring differences from the single layers.

#### Influence of vehicle ground speed

In a test series (June 26, 2008), the influence of ground speed on the readings was investigated. For this purpose, the laser scanner was mounted with an inclination angle ( $\varphi$ ) of  $45^\circ$  and sensor height ( $h_s$ ) of 2.74 m on a tractor. It was adjusted to the direction of tractor movement. A transect (tramline) of approximately 700 m in a winter wheat field (BBCH 75) was scanned with different ground speeds (6, 12, 18, and  $24 \text{ km h}^{-1}$ ). The ground speed was adjusted by using the tractor tachometer. To assess the influence of ground speed, the sensor readings and DGPS position along the transect were recorded for later analyses.

#### Influence of the inclination angle

In a test series (May 30, 2008), the influence of the inclination angle on the mean reflection height was investigated. For this purpose, the laser scanner was mounted in the driving direction on a tractor. A transect (tramline) with an approximate length of 700 m in a winter wheat field (BBCH 55–58) was sensed at different inclination angles ( $10, 20, 30, 40, 50, 60, 70$  and  $80^\circ$ ) with a sensor height ( $h_s$ ) of 2.74 m, scanning width ( $y$ ) from 0 to 1 m and an approximate ground speed of  $1.7 \text{ m s}^{-1}$ . A DGPS system was used for positioning. For the analysis, the transect was divided into segments of 10 m in length for a more detailed analysis of the influence of inclination angle on mean reflection height. The lag of the scanned area in relation to the tool carrier resulting from different inclination angles was compensated by a specific transformation program for co-ordinates.

#### Relation between reflection height and crop biomass

In a test series (May 28–29, 2008), the functional relation between reflection height and crop biomass density in winter wheat (BBCH 55–58) was investigated. For this purpose, a tool carrier was statically positioned at eleven places with different crop biomass densities (low to high) along a tramline (Fig. 3). The laser scanner was oriented sideways on the tool carrier with a scanning width ( $y$ ) of  $\pm 3$  m, scanning height ( $h_s$ ) of 2.96 m and an inclination angle ( $\varphi$ ) of  $45^\circ$ . While measuring, the tool carrier was not moved. To obtain reference values for biomass, the above-ground crop was cut at a minimal height (very short stubble) and weighed by an electronic scale. From the fresh weight and size of the harvested area (6 m length  $\times$  1 m width), fresh matter density FMD ( $\text{kg m}^{-2}$ ) was estimated. For calculation of the reflection height, the ground level must be known. Therefore, in a second sensing run, the harvested strip without (harvested) biomass was scanned for ground reference (Fig. 3).

## Results

### Reproducibility

The reproducibility of the measurements is presented in Table 3. The standard deviation for the measurements from the stationary vehicle in the winter wheat was less than 3 mm for plots with low, medium and high biomass. These low values are reflected in the



**Fig. 3** Estimation of crop biomass on crop plots

**Table 3** Standard deviations and coefficients of variation for measurements under the same conditions ( $h_s = 2.77$  m,  $\varphi = 45^\circ$  and  $y = \pm 3$  m)

Crop biomass (FM) ( $\text{kg m}^{-2}$ )	Mean of reflection height (m)	No. of measurements	Standard deviation (m)	Coefficient of variation (%)
0.80 (low)	0.21	57	0.0023	1.07
2.37 (medium)	0.42	54	0.0027	0.63
4.08 (high)	0.62	52	0.0019	0.31

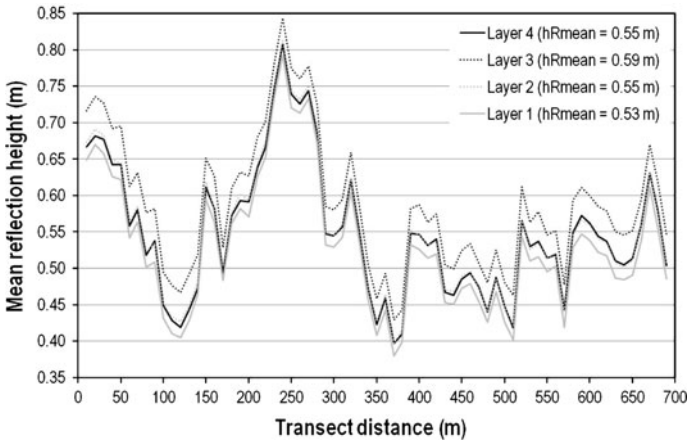
corresponding low coefficients of variation in the range of 1%. A clear dependency of standard deviation on crop biomass was not observed.

#### Comparison of layers

The mean reflection heights of 69 sub-transects are shown in Fig. 4. In all four curves calculated, a maximal mean reflection height was approximately at a distance of 250 m and minimal mean reflection heights were at a distance of 120, 370, 510 and 570 m. The curves should be congruent as is, but certain differences between sub-transects exist. Mean values along the entire transect were calculated and are as follows: layer 1, 0.53 m; layer 2, 0.55 m; layer 3, 0.59 m; and layer 4, 0.55 m. To check if these differences were statistically significant, a Wilcoxon rank-sum test was performed. *P*-values (probability of a larger statistic under the null hypothesis) less than 0.05 were considered statistically significant. No significant differences were found between layers 1 and 2 (*p*-value 0.168), layers 1 and 4 (*p*-value 0.190), and layers 2 and 4 (*p*-value 0.905). However, significant differences were found between layers 1 and 3 (*p*-value 0.000), layers 2 and 3 (*p*-value 0.011), and layers 3 and 4 (*p*-value 0.07). Because the crop strip with 69 sub-transects was identical for all layers, it is concluded from the differences that there was a systematic instrument error.

#### Influence of vehicle ground speed

A 1-m wide strip was used for analysing the influence of vehicle speed on the mean reflection height. The entire transect was divided into sub-transects with a length of 10 m



**Fig. 4** Readings for mean reflection height along the transect for the four layers

**Table 4** Parameters of regression lines for the relation between mean reflection height and ground speed of the vehicle ( $h_s = 2.74$  m,  $\varphi = 45^\circ$  and  $y = 0-1$  m)

y	x	6 km h <sup>-1</sup> (1st run)	12 km h <sup>-1</sup>	18 km h <sup>-1</sup>	24 km h <sup>-1</sup>	6 km h <sup>-1</sup> (2nd run)
6 km h <sup>-1</sup> (1st run)	a <sub>1</sub> (-)	-	0.99	0.96	1.04	1.04
	a <sub>0</sub> (m)	-	-0.01	0.01	-0.04	-0.05
	R <sup>2</sup> (-)	-	0.99	0.88	0.86	0.99
12 km h <sup>-1</sup>	a <sub>1</sub> (-)	1.00	-	0.96	1.05	1.05
	a <sub>0</sub> (m)	0.01	-	0.02	-0.04	-0.04
	R <sup>2</sup> (-)	0.99	-	0.87	0.87	0.98
18 km h <sup>-1</sup>	a <sub>1</sub> (-)	0.92	0.91	-	1.03	0.96
	a <sub>0</sub> (m)	0.07	0.06	-	-0.01	0.02
	R <sup>2</sup> (-)	0.88	0.87	-	0.87	0.87
24 km h <sup>-1</sup>	a <sub>1</sub> (-)	0.82	0.82	0.85	-	0.87
	a <sub>0</sub> (m)	0.12	0.11	0.09	-	0.07
	R <sup>2</sup> (-)	0.86	0.87	0.87	-	0.88
6 km h <sup>-1</sup> (2nd run)	a <sub>1</sub> (-)	0.95	0.94	0.91	1.00	-
	a <sub>0</sub> (m)	0.05	0.05	0.06	0.00	-
	R <sup>2</sup> (-)	0.99	0.98	0.87	0.88	-

each. Based on regression calculations ( $y = a_1x + a_0$ ) for each of the resulting 68 sub-transects, the correlation of mean reflection height was compared for all 10 combinations of vehicle ground speed (Table 4). The slope of linear function ( $a_1$ ) will equal one with an intercept ( $a_0$ ) of zero if there is no influence of vehicle speed on mean reflection height. The matrix in Table 4 shows that there were differences compared to the ideal conformity. To check if these differences were statistically significant, a Wilcoxon rank-sum test was performed (Table 5). The test results confirm that there were no significant differences between the runs with different ground speeds.



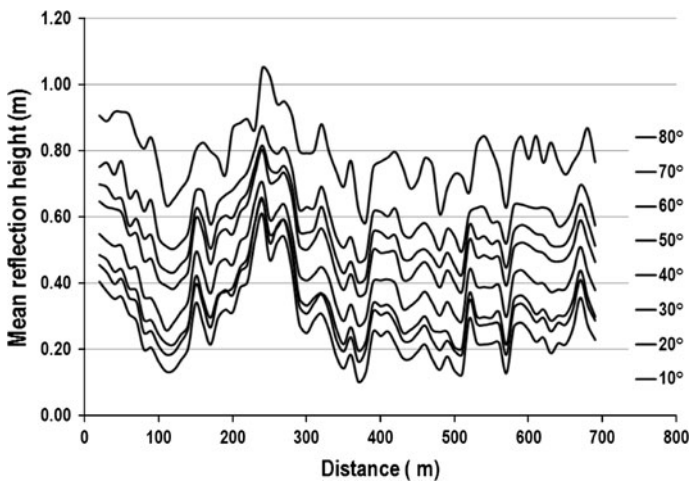
**Table 5** Differences of mean reflection height and *p* values (in brackets) for different ground speeds (68 sub-transects) according to the Wilcoxon rank–sum test

Speed	6 (km h <sup>-1</sup> ) (1st run)	(12 km h <sup>-1</sup> )	(18 km h <sup>-1</sup> )	(24 km h <sup>-1</sup> ) (2nd run)
6 km h <sup>-1</sup> (1st run)	–	–	–	–
12 km h <sup>-1</sup>	–0.013 (0.439)	–	–	–
18 km h <sup>-1</sup>	–0.019 (0.278)	–0.006 (0.654)	–	–
24 km h <sup>-1</sup>	–0.015 (0.221)	–0.002 (0.617)	0.004 (0.931)	–
6 km h <sup>-1</sup> (2nd run)	–0.023 (0.173)	–0.009 (0.449)	–0.003 (0.787)	–0.007 (0.875)

$Pr>|Z| = p\text{-value}$

**Influence of the inclination angle**

To investigate the influence of inclination angle ( $\varphi$ ) on the mean reflection height ( $h_R$ ), the mean values of reflection height ( $h_{R\text{mean}}$ ) for the 10 m sub-transects within a width of 1 m along the entire transect are plotted in Fig. 5. This figure demonstrates that increased inclination angles result in higher readings of mean reflection height. This measurement behaviour is demonstrated by a trend line calculation (Fig. 6). From the trend calculation, it is concluded that the mean reflection height increases approximately three-fold from 10 to 80°. For a more detailed analysis of this phenomenon, all readings of the runs along the transect were compared. Regression calculations ( $y = a_1x + a_0$ ) were performed for all 28 combinations of each inclination angle from 10 to 80°. The slope of linear function ( $a_1$ ) will equal one with an intercept ( $a_0$ , dotted line) of zero if there is no influence of inclination angle on the mean reflection height. Significant differences were observed when the results were compared to the ideal conformity. In general, these results indicated that increased inclination angles ( $\varphi$ ) caused significantly increased reflection heights ( $h_R$ ) (Fig. 7). The diagram shows that the relationship of the mean reflection height for inclination angles of 10 and 20°, which was expressed as a  $R^2 = 0.99$ , low  $a_0 = 0.061$  m and slope  $a_1 = 0.979$ , was similar to the ideal line ( $y = x$ ; dotted line). In the case of different inclination angles of 10 and 80°, which was expressed by low  $R^2 = 0.69$ , high



**Fig. 5** Mean reflection heights for inclination angles from 10 to 80° along transect

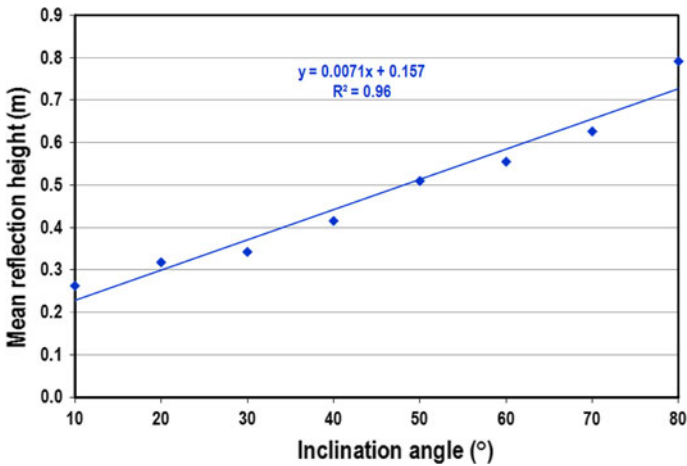


Fig. 6 Relation between mean reflection height and inclination angle

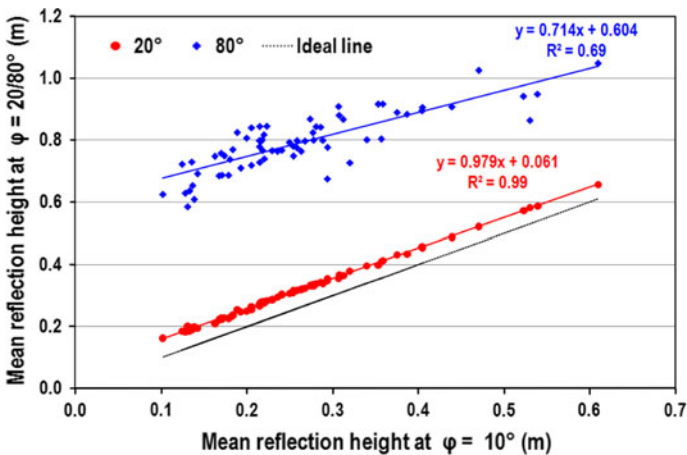


Fig. 7 Examples of correlations of mean reflection height for different inclination angles

$a_0 = 0.604$  m and slope  $a_1 = 0.714$ , the difference was substantial when compared to the ideal line.

Because the laser scanner generates up to four echoes for each measuring pulse, the absolute and relative number of readings registered for each echo were analysed (Table 6). The most dominant readings were generated from echo pulse A (first echo) with a decreasing trend to echo pulse D (fourth echo). For low inclination angles ( $10^\circ < \varphi < 30^\circ$ ), few echo pulses (B, C and D) were registered, but more echoes (B, C and D) were recorded with increasing inclination angles. This trend may be explained by the measurement properties of the sensor. The resolution of the echo pulses depends on the pulse time of the laser beam where a shorter pulse has a higher resolution. In specific tests with defined conditions, a 2 m depth resolution for the sensor was measured. This indicates that secondary targets with a distance less than 2 m cannot be discriminated. The cross sectional

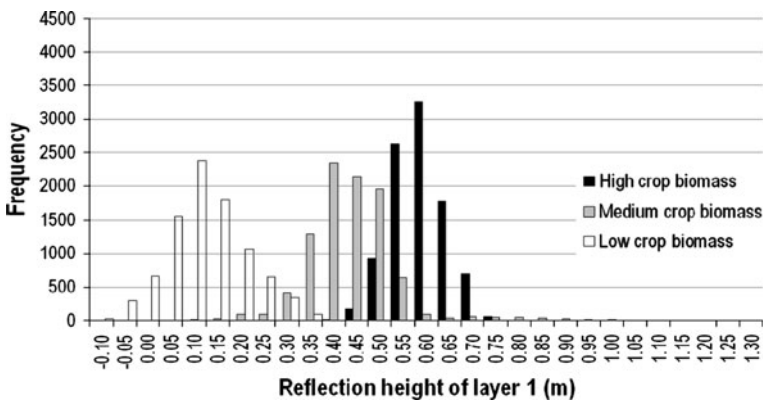
**Table 6** Number of absolute and relative readings registered for each echo pulse for the transect

Inclination angle $\varphi$ (°)	Echo pulse A		Echo pulse B		Echo pulse C		Echo pulse D	
	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
10	1779666	100.00	8	0.00	4	0.00	2	0.00
20	1698925	100.00	35	0.00	13	0.00	9	0.00
30	1616891	100.00	38	0.00	17	0.00	6	0.00
40	1558391	99.98	189	0.01	64	0.00	19	0.00
50	1440855	99.91	909	0.06	336	0.02	96	0.01
60	1154983	99.83	1365	0.12	454	0.04	123	0.01
70	895601	99.47	3471	0.39	1028	0.11	303	0.03
80	448441	96.67	12204	2.63	2491	0.54	751	0.16
Total	10593753	99.77	18219	0.17	4407	0.04	1309	0.01

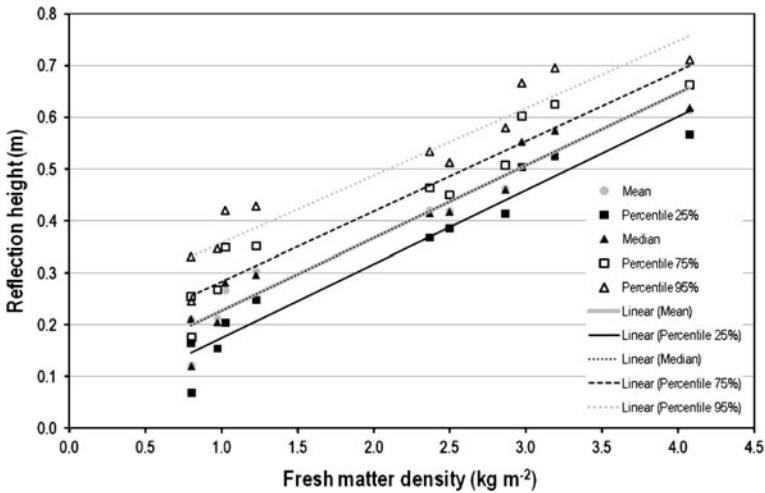
area spot striking the crop stand increases with higher inclination angles resulting in increased sensing depth and additional multiple echoes.

Relation between reflection height and crop biomass

A correlation between reflection height and crop biomass is crucial for the potential assessment of laser scanners in crop production. As shown in the previous section, the share of echoes (B, C and D) is low. Therefore, the dataset from the first echo (A) for regression calculations was used. Figure 8 demonstrates the frequency distributions of the reflection height for the three scanned plots in winter wheat (each 6 m long) for low, medium, and high crop biomass. As explained in the material and methods section (Fig. 2), the reflection height of the laser spot was not only from the highest plant components but also from lower components and the ground. Because of this, the representative value for crop stand height was expected to be to the extreme right of the frequency distributions. The height of a crop stand is not a clearly defined value. However, it is a question of definition. Based on this, the authors assumed that the 95th percentile represents the approximate crop stand height. To investigate which height level of reflection points has



**Fig. 8** Example of frequency distribution in different plots of winter wheat



**Fig. 9** Correlations of mean value and percentiles [95th, 75th, 50th (median) and 25th] of reflection height with crop biomass

**Table 7** Results for regression calculations with the 95th, 75th, 50th and 25th percentiles and mean value of reflection height related to crop biomass

Parameter	Unit	Percentile 95%	Percentile 75%	Percentile 50%	Percentile 25%	Mean value
Slope $a_1$	$m^3 \text{ kg}^{-1}$	0.130	0.136	0.140	0.143	0.140
Intercept $a_0$	m	0.228	0.147	0.087	0.032	0.088
Coeff. of determ. $R^2$	–	0.91	0.92	0.94	0.95	0.94
RMSE	m	0.050	0.047	0.044	0.042	0.043
Standard error	%	10.01	11.06	11.72	12.73	11.28

the best correlation to crop biomass (fresh matter density), regressions were calculated with the mean value of reflection height and the following percentiles: 95th (crop stand height), 75th, 50th (median) and 25th. For each of the 11 plots, readings of 40 scans were used. The calculations resulted in a linear relationship for all height levels of reflection points (Fig. 9). All slopes had comparable values, but the intercept varied.

Expressed by the coefficient of determination and RMSE (root mean squared error), the 25th percentile, 50th percentile and mean value achieved the best correlation whereas the 95th percentile had the lowest correlation to crop biomass (Table 7). However, it should be noted that these statistical parameters for the regression functions differed very little.

### Discussion

Under constant measurement conditions (constant inclination angle and identical crop stand), the laser scanner achieved a high level of reproducibility for mean values of single scans in a range of millimetres for standard deviation and approximately 1% for coefficient of variation. For a low level of reproducibility, the laser rangefinder measurements of crop

parameters would have to be negatively assessed (exclusion criterion). On the other hand, high reproducibility alone does not guarantee the sensor suitability in crop production.

The readings that were independent from the vehicle ground speed were a positive result. It can be explained with the high ratio of light speed (about  $300\,000\text{ km s}^{-1}$ ) to ground speed of the vehicle in the range of several  $\text{m s}^{-1}$ .

The dependency of readings on inclination angle of the laser beam is a problem that needs to be solved in future. The regression calculations demonstrated that the 25th percentile, 50th percentile and mean value of reflection height had a slightly better correlation to crop biomass than higher percentiles. This can be explained by the increased influence of gaps (sparse or no vegetation) in the calculation of low percentiles. Because the calculation of the percentiles is expensive, the mean value is preferred for crop biomass estimation. High values for coefficient of determination  $R^2 = 0.94$ , low values of  $\text{RMSE} = 0.043\text{ m}$  and standard errors of 11.28% confirm the potential of laser range-finders for measuring representative crop biomass in winter wheat and other cereals under field conditions.

## Conclusions

Range measurements by a laser scanner can be performed with agricultural machinery with high efficiency.

Based on calculations for the reflection height of the laser beam point, crop stand parameters, such as crop height and crop biomass, can be estimated.

Laser range measurements are reproducible for identical crop conditions, and they are independent from the ground speed of vehicles.

The inclination angle of the laser beam influences the measurements of crop height and biomass. Therefore, further research is necessary to determine compensation algorithms for avoiding the overestimation of crop height in the outer sections of sensed crop strips.

**Acknowledgment** The authors would like to thank Antje Giebel for her support in data analysis.

## References

- Arno, J., Valles, J. M., Escola, A., Sanz, R., Palacin, R., & Rosell, J. R. (2009). Use of a ground-based LIDAR scanner to measure leaf area and canopy structure variability of grapevines. In E. J. van Henten, D. Goense, & C. Lokhorst (Eds.), *Precision agriculture '09: Proceedings of the 7th European conference on precision agriculture* (pp. 177–184). Wageningen, NL: Wageningen Academic Publishers.
- Ehlert, D., & Dammer, K. H. (2006). Wide-scale testing of the Crop-Meter for site-specific farming. *Precision Agriculture*, 7, 101–115.
- Ehlert, D., Adamek, R., & Horn, H. J. (2007). Assessment of laser rangefinder principles for measuring crop biomass. In J. V. Stafford (Ed.), *Precision agriculture '07: Proceedings of the 6th European conference on precision agriculture* (pp. 317–324). Wageningen, NL: Wageningen Academic Publishers.
- Ehlert, D., Adamek, R., & Horn, H.J. (2009). Vehicle Based Laser Range Finding in Crops. *Sensors*, 9, 3679–3694; doi:10.3390/s90503679;http://www.mdpi.com/journal/sensors.
- Ehsani, R., & Lang, L. (2002). A sensor for rapid estimation of plant biomass. In P. C. Robert (Ed.), *Proceedings of the 6th International conference on precision agriculture* (pp. 950–957). Madison, WI, USA: ASA/CSSA/SSSA.
- Heege, H. J., Reusch, S., & Thiessen, E. (2004). Systems for site specific on the go control of nitrogen top dressing during spreading. In D. J. Mulla (Ed.). *Proceedings of the 7th international conference on precision agriculture*. Minneapolis, USA: Regents University of Minnesota. CDROM.

- Meyer, U. (1977). Growth stages of mono and dicotyledonous plants. Berlin: Blackwell Wissenschafts-Verlag, Wien ISBN 3-8263-3152-4.
- Saeyns, W., Lenaerts, B., Craessaerts, G., & De Baerdemaeker, J. (2009). Estimation of the crop density of small grains using LiDAR sensors. *Biosystems Engineering*, 102, 22–30.
- Sanz, R., Palacín, J., Sisó, J. M., Ribes-Dasi, M., Masip, J., Arnó, J., Liorens, J., Vallés, J.M., & Rossell, J. R. (2004). Advances in the measurement of structural characteristics of plants with a LIDAR scanner. In: *Proceedings of EurAgEng conference*, Leuven, Belgium, CDROM: Paper 277.
- Thösink, G., Preckwinkel, J., Linz, A., Ruckelshausen, A., & Marquering, J. (2004). Optoelektronisches Sensorsystem zur Messung der Pflanzenbestandesdichte. [Optoelectronic sensor system for crop density measurement]. *Landtechnik*, 59(2), 78–79.
- Tumbo, S. D., Salyani, M., Whitney, J. D., Wheaton, T. A., & Miller, W. M. (2002). Investigation of laser and ultrasonic ranging sensors for measurements of citrus canopy volume. *Applied Engineering in Agriculture*, 18, 367–372.
- Walklate, P., Cross, J., Richardson, G., Murray, R., & Baker, D. (2002). Comparison of different spray volume deposition models using Lidar measurements of apple orchards. *Biosystems Engineering*, 82, 253–267.