Laser profilometer testing by laboratory measurements

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Abstract: Measuring soil surface profile has many purposes in the field of agriculture and landscape management. For example, it concerns quantitative evaluation of work quality of soil cultivation implements, and related assessment of soil surface status prior sowing. For this purpose, a prototype of laser profilometer was produced whose key parts are a laser sensor Banner LT3 fixed together with a control section, a converter etc. on a carriage that travels propelled by an electromotor along an aluminum girder. In 20 mm intervals determined by an optical sensor, the laser sensor measures a distance to a soil surface. The aim of the work is to verify some laser sensor properties such as a linearity of measurement, sensitivity to surface color, and furthermore to establish appropriate window limits of laser sensor measurement.

Keywords: soil surface; profile; roughness; laser sensor; profilometer

Quantitative descriptions of surface roughness are important in evaluating tillage and in simulating erosion processes. Particles involved in soil erosion processes i.e. raindrops and soil particles, all have characteristic dimensions on a millimeter scale (Huang *et al.* 1988), thus soil surface data at millimeter scales are needed to study erosion processes. Tillage evaluation does not require generally such a detailed information.

The major concern for describing a rough surface is constructing an adequate model to characterize the apparent random nature of surface roughness and then finding an adequate means of measuring model parameters (Oelze *et al.* 2003). Different devices have been developed to generate soil surface elevation models. Such elevation models in digital format (digital elevation models – DEM) are widely used to determine soil surface water storage capacity, soil surface roughness, rill formation, and other significant processes.

Kuipers (1957) first introduced parameters that have been used in the past to describe surface roughness. Kuipers defined a roughness index that was based on the standard deviation of the elevations readings of the surface. A major critique with using the roughness index was that this roughness parameter did not describe the spatial dependence of the roughness elements. The roughness index characterized the variation of heights, or vertical roughness, but did not describe the spatial distribution of roughness on the surface. For example, two surfaces may have the same roughness index but one surface may have the roughness on average spaced farther apart on the surface. A more complete characterization would describe not only vertical scales of roughness but also the horizontal scales.

The spatial distribution and the spatial dependence of the roughness were evaluated by the autocorrelation function of the roughness parameter of successive transects. The correlation length for spatial independence was determined where the correlation function dropped to 0.2 of its initial value. A smaller spatial independence was found for surfaces that had been chiseled repeatedly as opposed to surface with little tillage (Römkens & Wang 1987). The more a surface is chiseled the smaller the clod sizes. Smaller scaled roughness should tend to become uncorrelated at shorter lengths than larger scaled roughness.

Several instruments have been used in the past to obtain the surface roughness statistical characterizations. Contact type microreliefmeters have been used to measure surface roughness, e.g. paint and paper profiling technique, chain method, and pin

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reliefmeter. Contact methods tend to be time-consuming, cumbersome, and have the great disadvantage of disturbing or damaging the soil surface. On the other hand, photogrammetry has been used to obtain elevation measurements from soil surfaces remotely. The photogrammetric method needed costly equipment for measurements and data processing and interpretation of the photogrammetric data is complicated. Another equipment for measuring elevation data of rough soil surfaces without disturbing the soil surface is the laser microreliefmeter. However, the equipment is expensive, somewhat bulky and scan times can take several hours for a plot of 0.6 by 0.6 m. FLANAGAN *et al.* (1995) developed an automated laser scanner that kept an equivalent elevation resolution as the laser microreliefmeter but decreased the scan time. An alternate noncontact method was proposed by OELZE *et al.* (2003) using acoustic backscatter techniques to measure surface roughness statistics. The goal was to find a quick, mobile, and inexpensive means to evaluate surface roughness statistics.

This work concerns a simplified laser profilometer scanning just in one dimension. In order to reduce scanning time, data are retrieved each 20 mm only. Accuracy of the equipment depends on a laser sensor used, on measured distance, color of surface and other factors. RAPER *et al.* (2002) estimated vertical accuracy of their portable tillage laser profiler within 2.3 mm for different soil color surfaces, and within 4.2 mm for objects painted black and white. BERTUZZI and CAUSSIGNAC (1988) achieved standard deviation less than 2 mm in their tests as well.

MATERIAL AND METHODOLOGY

The laser profilometer scheme and connection diagram are shown in Figure 1 and 2. The key element is the laser sensor LT3 manufactured by Banner Engineering Corp. It moves along a one-axe aluminum girder, which is 1.64 m long, and each 20 mm measures a distance to surface (i.e. 83 samples). The girder is mounted on adjustable shanks that allow to position it 0.3 to 0.7 m above the surface.

The laser sensor was programmed for negative analog output slope and response speed was set to slow (see Figure 3). The range of the laser sensor stretches from 0.3 to 3 m for grey surface, or to 5 m for white surface. Other characteristics are shown in Figure 3.

Within the carried out laboratory measurements, two window limits were tested (i.e. 1.3–0.3 m and 0.8–0.3 m). The window limits were taught using white color surface. With at least five repetitions, straight bars of three different colors in three different positions were measured. Output data were recalculated according to set window limits into the unit of length and analyzed.

Two parameters were evaluated. One of them was standard deviation of surface height (i.e. RMS – Root Mean Square – height) σ. For a one-dimensional surface profile, σ is computed by digitizing the profile into discrete values, $y_i(x_i)$, at an appropriate horizontal spacing, Δx. If the height variation, Δy, corresponding to a Δx is much smaller than the wavelength, λ, of the incident wave, the variation will have no effect on the reflection from the surface

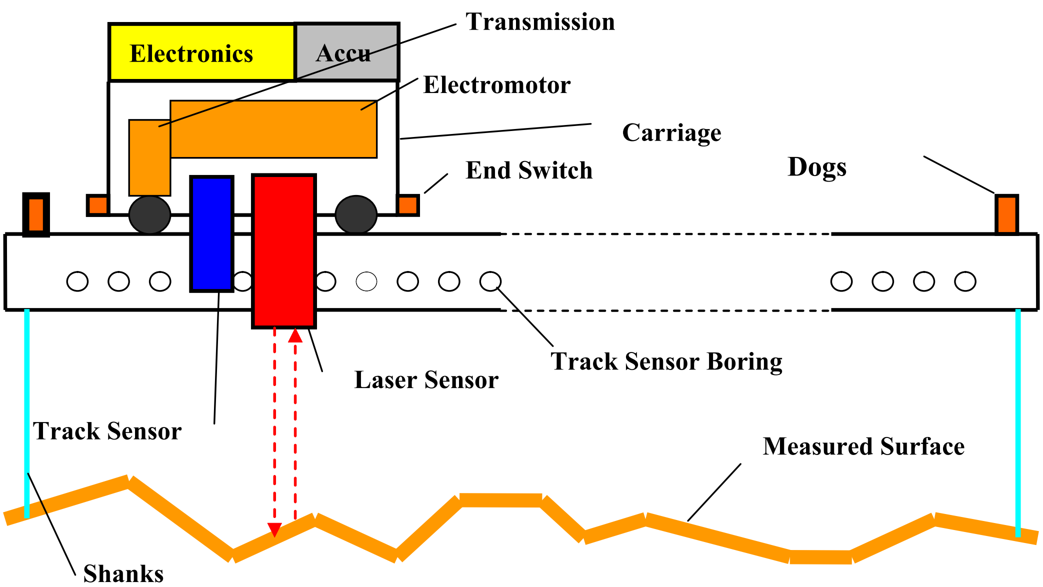

Figure 1. Scheme of laser profilometer construction

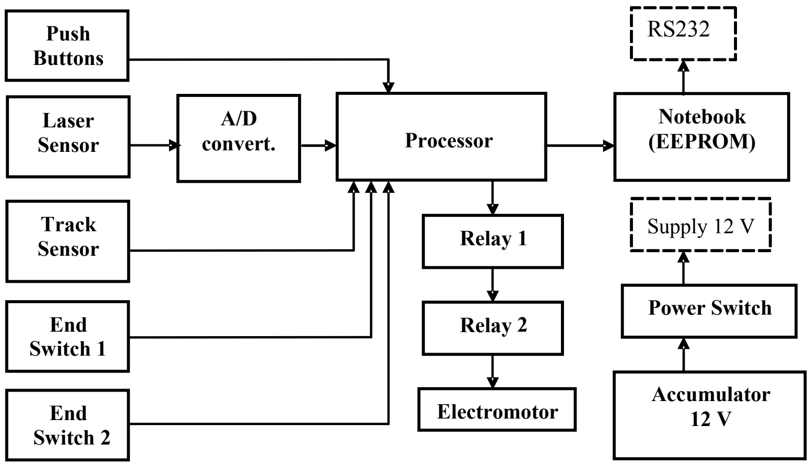

Figure 2. Connection diagram of laser profilometer

of Δx. Typically, $\Delta x \leq 0.1\ \lambda$. The standard deviation σ for the discrete one-dimensional case is given by

$$\sigma = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N}(y_i)^2 - N(\bar{y})^2\right)} \quad (1)$$

where:

N – number of samples and

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \quad (2)$$

The other parameter was the surface roughness originally used within the chain method. This method consists in measuring the horizontal distance between the tops of a roller chain laid out on a soil surface following the irregularities of the soil. The roughness is calculated as

$$C_r = \left(1 - \frac{L1}{L2}\right) \times 100 \quad (3)$$

where:

$L1$ – horizontal distance

$L2$ – actual length of the chain

This method was adapted so that $L1$ constituted the length of linear regression line and $L2$ the sum of distances between adjoining measured points.

The trend of a linear regression line affects both above mentioned parameters, e.g. RMS height value of a plain surface parallel to the profilometer girder is negligible in comparison to one at an angle. The girder should be positioned parallel to the surface. In order to achieve this, least squares linear regression was used to remove trend from samples. For the purpose of automated data processing, a macro calculating all the above mentioned was written within Visual Basic for MS Excel.

RESULTS AND DISCUSSION

Laboratory experiments (see Figure 4) were carried out that consisted of scanning a straight surface of three different colors, i.e. white, brown, and medium grey, positioned at various angles. Two laser sensor window limits were tested that were calibrated using white color surface.

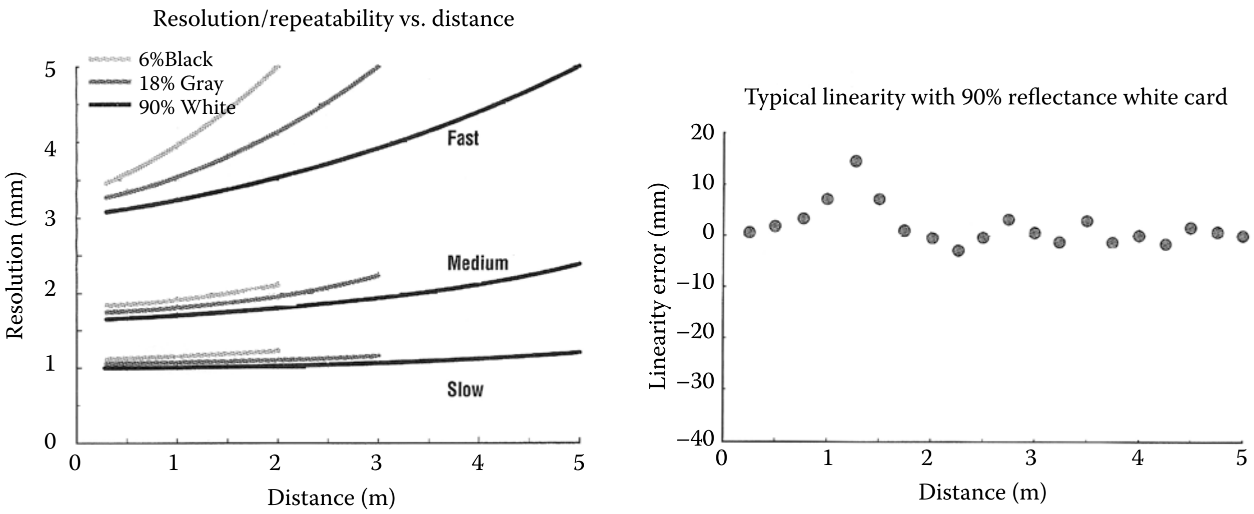

Figure 3. LT3 resolution (left) and LT3 linearity (right)

Figure 4. Photography of the laser profilometer laboratory experiment

The far limit of the first window was set to 1.3 m, the near one to 0.3 m. Measured elevation profiles are shown in Figure 5. The real value curves were acquired by fitting through calibration points. The white surface profiles lie nearest to the real value curve while the grey ones demonstrate the greatest divergence. The greatest gaps between sample points and the real value curves are situated from 0.45 m to 0.65 m of distance (y).

Precisely the same relationships can be seen in Figure 6 where the far and near window limits of the laser sensor were set to 0.8 m, respectively to 0.3 m.

Figure 7 compares elevation profiles at a given angle scanned with the two different window limits. White and grey surface profiles do not differ much within the different window limits. While the brown surface profile of the window limits 0.8–0.3 m seems to merge with the white ones, the brown one of the window limits 1.3–0.3 m resides aside.

The differences between real and measured values can be seen in more detail in Figure 8. For the brown surface with the window limits 0.8–0.3 m, and for all the white surfaces measured, the differences do not exceed 20 mm. But even this value is rather high, and occurs in the distance range (y) of 0.45 to 0.65 m where experimental measurements are expected to occur.

Table 1 shows the surface roughness parameters. RMS height (σ) has small validity, if the trend is not removed from the samples. The surface roughness (C_r) of samples with and without the trend is comparable. The roughness parameters of white and brown surfaces attain similar values. Concerning the distance range, the higher it is, the higher values of roughness parameters are generally reached.

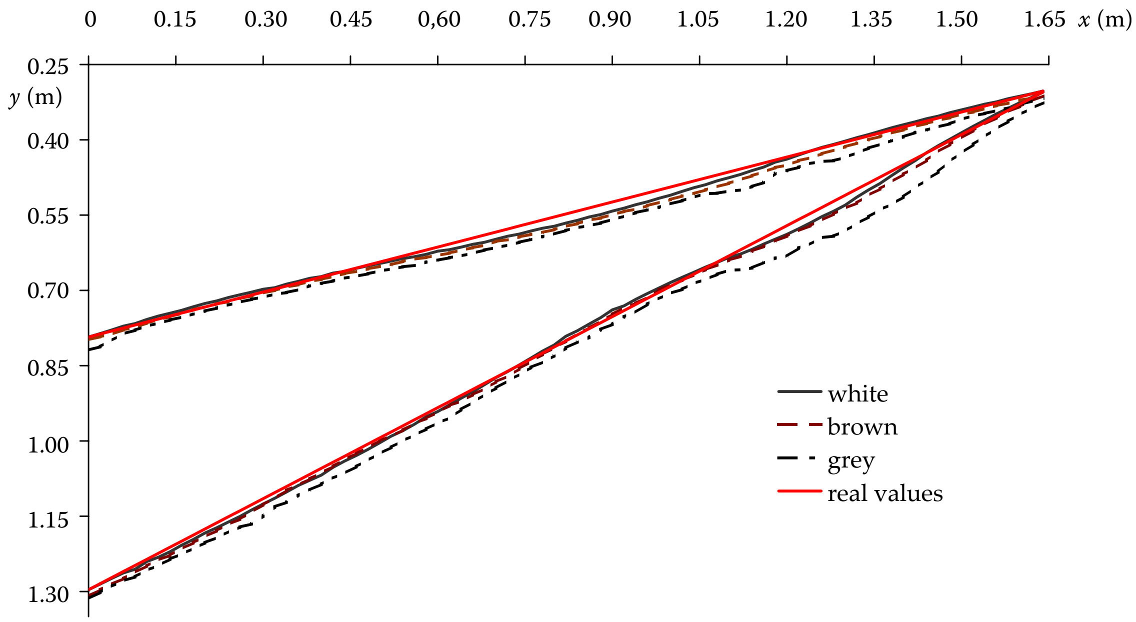

Figure 5. Graph of elevation profiles of a straight bar of three different colors positioned at two different angles (the laser sensor window limits are 1.3–0.3 m)

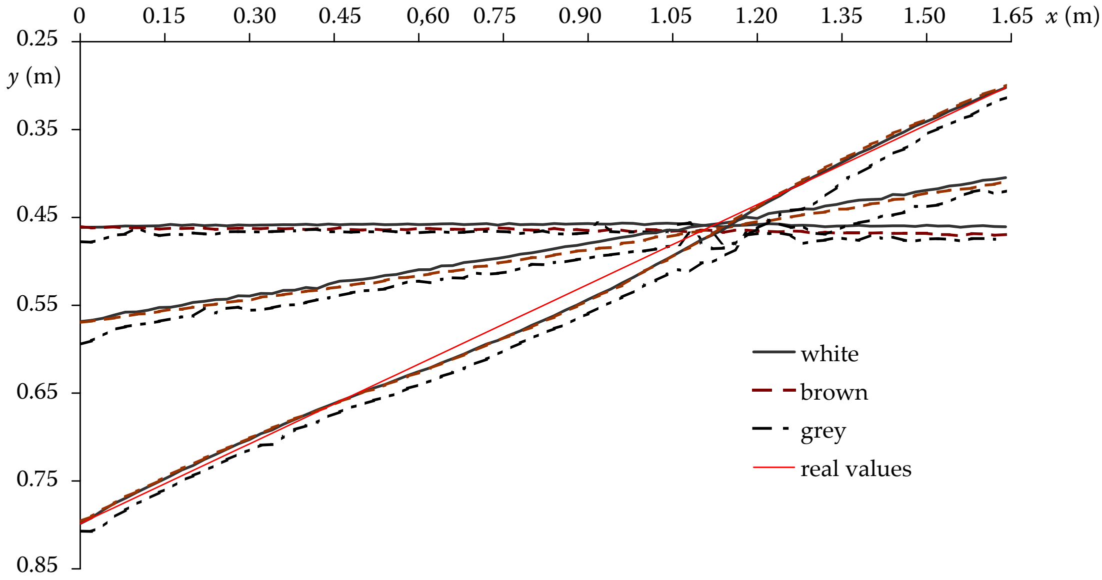

Figure 6. Graph of elevation profiles of a straight bar of three different colors positioned at three different angles (the laser sensor window limits are 0.8–0.3 m)

CONCLUSIONS

– The measurement linearity of the laser profilometer demonstrated sensitivity to the laser sensor window limits as well as to the measured surface color. Narrower window proved more accurate. The differences in measurements between brown and white colors were minor when compared to the differences between the both above mentioned colors and the grey one.

– In order to increase accuracy of measurements, output data of the laser sensor should be recalculated into the unit of length using calibration points located within the expected practical range of measurement, i.e. between 0.45 to up to 0.60 m of distance.

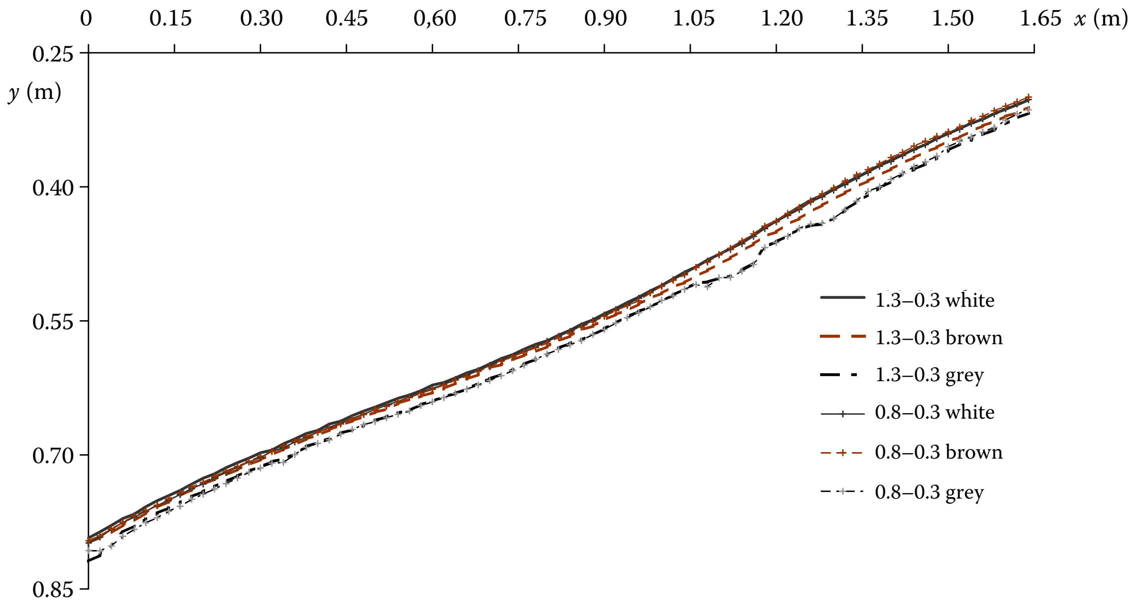

Figure 7. Graph of elevation profiles of a straight bar of three different colors with the laser sensor window limits set on 1.3–0.3 m and on 0.8–0.3 m

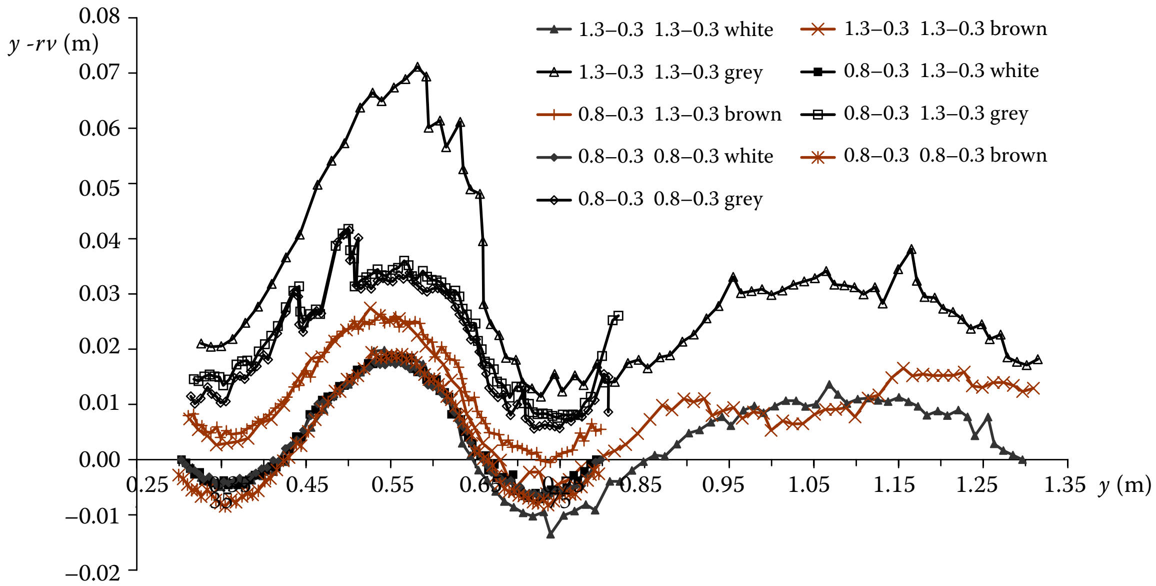

Figure 8. Graph of differences between measured points (*y*) and real point positions (*rv*) in dependence on measured distance (*y*) (in the legend from left: distance range/window limits/color)

Table 1. Parameters of elevation profiles of straight surface measured by the laser profilometer

Laser window limits[1] (m)	Surface		Elevation with trend		Least square linear regression ($y = a \times x + b$)			Trend removed	
	distance[2] (m)	color	σ[3] (mm)	C_r[4]	a	b (mm)	R^2	σ[3] (mm)	C_r[4]
1.3–0.3	1.30–0.30	white	291.39	0.116	−0.608	1303.45	0.999	8.09	0.493
		brown	289.78	0.390	−0.605	1306.36	0.999	7.88	0.454
		grey	283.38	1.401	−0.591	1316.97	0.997	14.62	1.505
	0.80–0.30	white	142.53	0.217	−0.297	795.12	0.996	8.61	0.193
		brown	141.18	0.267	−0.294	800.82	0.996	8.41	0.213
		grey	140.05	0.918	−0.292	809.69	0.996	9.22	0.670
0.8–0.3	0.45–0.45	white	1.22	0.088	0.000	458.46	0.010	1.21	0.088
		brown	2.45	0.187	0.005	460.91	0.816	1.05	0.186
		grey	4.98	1.910	0.004	465.86	0.159	4.57	1.913
	0.55–0.41	white	47.77	0.239	−0.100	568.95	0.999	1.23	0.242
		brown	47.09	0.137	−0.098	573.14	0.999	1.81	0.143
		grey	46.70	1.815	−0.097	583.81	0.989	4.88	1.748
	0.80–0.30	white	143.98	0.176	−0.300	799.90	0.997	8.22	0.127
		brown	144.80	0.172	−0.302	800.34	0.996	9.59	0.168
		grey	141.40	0.877	−0.294	812.26	0.995	9.72	0.845

[1]approximate values of the far and near laser window limits; [2]approximate values of the laser-to-bar distance range; [3]RMS height; [4]surface roughness; R^2 = coefficient of determination.

– Calculated roughness parameters, RMS height in particular, are sensitive to any linear trend contained in the elevation profile, i.e. sensitive to the measured surface and the laser profilometer girder not being parallel. It is appropriate therefore to remove the trend from measured data.

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Abstrakt

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Měření profilu povrchu půdy má v oblasti zemědělství a ochrany krajiny mnohostranné využití. Jde například o kvantitativní posouzení kvality práce strojů pro zpracování půdy a posouzení stavu povrchu půdy před setím. Proto jsme vyrobili prototyp laserového profiloměru, jehož hlavními částmi je laserový senzor Banner LT3 umístěný spolu s řídící jednotkou, převodníkem a dalšími částmi na vozíku pohybujícím se pomocí elektromotoru po hliníkové dráze. Tento laserový senzor v 20mm intervalech určovaných optickým snímačem měří vzdálenost k povrchu půdy. Cílem práce bylo ověřit některé vlastnosti laserového senzoru, jakými jsou linearita měření a citlivost na barevnost povrchu, a dále určit vhodné nastavení velikosti hranic měření laseru.

Klíčová slova: povrch půdy; profil; drsnost; laserový senzor; profiloměr

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