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Validation of automated measurements of soil tillage variables with laser and ultrasound sensors[1]

Validação das medições automatizadas das variáveis de mobilização do solo com sensores laser e ultrassom

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HIGHLIGHTS:

Ultrasound underestimates the variables modified roughness, elevated area, mobilized area, blistering, and thickness.
Readings of cut-out and mobilized profiles by ultrasound were divergent.
Readings of natural profile by both sensors was similar to that obtained with the conventional profilometer.

ABSTRACT: The quality of soil tillage can be measured with a specific device called profilometer, which provides information on roughness, mobilized area, blistering, and thickness in disturbed soils. However, it is an outdated device, requiring many hours of field and office work. Thus, the objective of the present work was to develop an electronic profilometer using laser triangulation and ultrasound sensors for measurement of digitally mobilized soil profile. The results obtained were compared to those acquired with a conventional sliding bar profilometer to evaluate the accuracy and efficiency of the sensors. The experiment was conducted in a completely randomized design under a controlled environment. The variables were measured seven times using the three profilometers (laser, ultrasound, and conventional) in the original, elevated, and mobilized soil profiles. The electronic profilometer with ultrasound differed in all the measurements when compared to the conventional profilometer, which differed from the laser sensor only in modified roughness.

Key words: conventional tillage, air and water infiltration, soil compaction

RESUMO: A qualidade desta operação de preparo do solo pode ser mensurada por equipamentos denominados perfilômetros, fornecendo informações quanto a rugosidade, área mobilizada, empolamento e espessura do solo trabalhada. Porém, trata-se de equipamento antiquado, com elevadas horas de trabalho no campo e escritório. Assim, o objetivo do trabalho foi construir um perfilômetro eletrônico utilizando triangulação a laser e sensores de ultrassom para medição de perfis de solo mobilizados digitalmente. Em seguida, os resultados obtidos foram comparados com os obtidos com um perfilômetro de barra deslizante tradicional para avaliar a precisão e eficiência dos sensores. Para o experimento conduzido em ambiente controlado, adotou-se o delineamento inteiramente casualizado. As variáveis foram mensuradas, sete vezes, através dos três perfilômetros (eletrônico a laser, eletrônico a ultrassom e o tradicional) nos perfis original, elevado e mobilizado do solo. Verificou-se que o perfilômetro eletrônico com ultrassom diferiu na totalidade das mensurações em relação ao perfilômetro convencional, com o sensor a laser apenas na rugosidade modificada.

Palavras-chave: preparo convencional do solo, infiltração de ar-água, compactação do solo

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Introduction

The consolidation of no-tillage in Brazil decreased the use of conventional tillage, which has been used mainly for soil decompaction. Conventional tillage usually includes subsoiling to promote root development and improve the capacity of roots to explore deeper soil layers (Ghosh & Daigh, 2020).

Soil tillage regulates and maintains the physical, chemical, and biological balances of soil properties, changing the soil environment and consequently affecting the root growth and distribution and crop yield (Noor et al., 2020).

The profilometry technique evaluates soil tillage quality (Bögel et al., 2016), determining the soil roughness, blistering, roughness modification index, mobilized cross-sectional area, and average layer thickness (Grundy et al., 2020).

These variables are evaluated using conventional devices, such as rod or sliding bar rod profilometers (Borges et al., 2019), and non-contact devices, such as drone imaging (Fanigliulo et al., 2020) and infrared (Mohammadi et al., 2022). Sampling automation of processes using open access platforms is increasingly used in agriculture (Tian et al., 2020), presenting homogeneous performance and operational viability for evaluating soil profilometry.

Thus, the objective of the present study was to build an electronic profilometer using laser triangulation and ultrasound sensors for measurement of digitally mobilized soil profile. Afterward, the obtained results were compared to those acquired with a conventional sliding bar profilometer to evaluate the accuracy and efficiency of the sensors.

Material and Methods

The conventional and electronic profilometers were developed and built at the Laboratory of Adaptation of Agricultural Tractors of the Federal University of Parana, Curitiba, PR, Brazil (25° 24' 45" S, 49° 14' 56" W, and altitude of 935 m).

The experiment was conducted from September to December 2021, from the construction of the profilometers to the completion of the evaluations. During the tests, the environment temperatures were monitored by a digital thermometer system, ranging from 16 to 21 °C.

A completely randomized experimental design was used to evaluate the conventional (bar) and electronic (laser and ultrasound) profilometers. Seven replications were carried out for each profilometer, which was leveled and installed transversely to the pot with soil. Five soil profilometry variables were measured: modified roughness, elevated area, mobilized area, blistering, and thickness, according to the methodology of Carvalho Filho et al. (2007). The readings were taken in the same month in which the construction of the profilometers was completed.

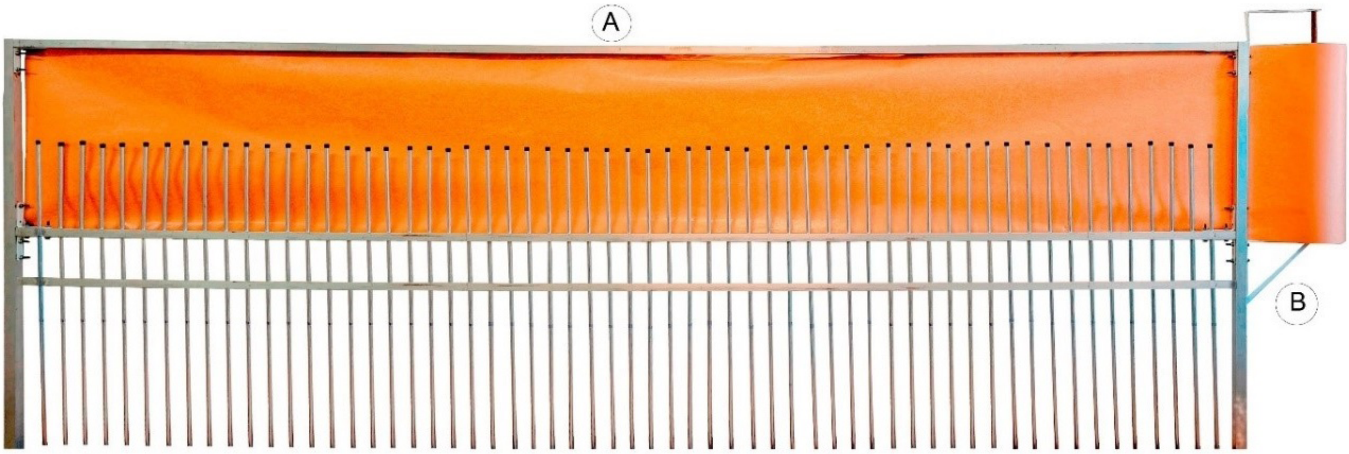
The conventional profilometer (Figure 1) consisted of a rectangular structure of 3.00 × 1.50 m (A), made with square pipe aluminum profiles (0.025 × 0.025 m) with weight of 0.387 kg m^{-1} each (Manufactured by Forseti™). Rails were positioned at the vertical ends of the bar to move the reading paper stored in a reel on the upper right side of the structure.

The reading system (B) was made of aluminum rods (0.0953 m diameter × 0.001 m thickness × 1.00 m length), density of 2700 kg m^{-3}, with plastic plugs placed at their ends to reduce unfavorable effects of deepening into the soil. The rods were spaced 0.05 m apart and distributed in a support line that allowed the acquisition of profile heights. A kraft paper coil (0.60 × 140.00 m) was placed on the mobile axis of the device, sliding the paper for manual marking to record the heights in each replication. After markings and profile surveys, the data obtained were entered into an electronic spreadsheet.

The electronic profilometer (Figure 2) consisted of a rectangular structure (3.00 × 1.00 m) made with anodized aluminum profiles (BOSH model) (A), electric drive (B), reading sensor (C), and data acquisition system (D).

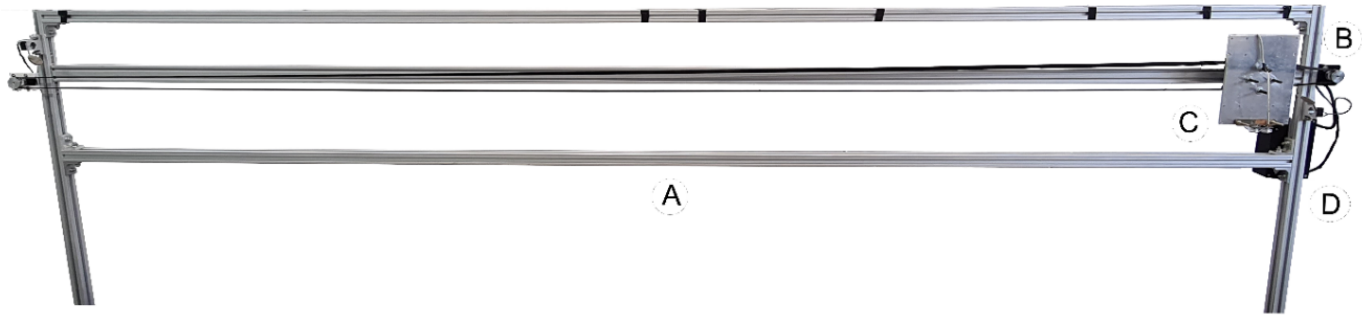
The profiles were also used as chassis, connecting by corner and makerlink L 90 connectors, T (M6) screws, and their auxiliary components. The ends received support for pulley transmission and a stepper motor, with a transverse linear displacement system, using an adjustable guide with pulleys coupled to a V-slot profile (0.02 x 0.04 m). A tool holder plate (0.15 × 0.20 m) was fixed on it to support the reading sensor.

The electric drive system was performed by a high-performance driver (NEO-DM322E; Leadshine™) with eight micro-step resolutions, reaching 12,800 pulses per revolution, operating at peak currents between 0.3 and 2.2 A and at 12



Structure (A) and reading system (B)

Figure 1. Conventional profilometer



Structure (A), electric drive (B), reading sensor (C), and data acquisition system (D)

Figure 2. Electronic profilometer

V voltage. The driver allows the adjustment of the current to the stepper motor, which drives the symmetric transmission shaft of the toothed belt and pulley, causing traction of the tool holder plate and the pulley guide assembly.

The linear drive system for carrying the reading sensor on the scan line was composed of a hybrid type stepper motor (NEMA 17; Leadshine™), which has bipolar and unipolar modes and torque of 0.785 Nm. It has an accuracy of 0.09° and 1.5 A, with 4.5 V in each phase, rotation angle of 1.8°, and 200 steps per revolution.

The toothed belt used to transfer the tensile force for displacement of the reading set (GT2; SLA™) was 6.00 m long, 0.002 m pitch, and 0.01 m wide. The pulley used (GT2; Inbearing™) had 0.028 m external diameter, 40 internal teeth, and 0.01 m of cradle width, and was connected to the motor shaft.

The laser optical reading sensor used (ODS 96M/V - 5010 - 600 - 421; Leuze Electronic Germany™) can measure the soil profile perpendicularly to the ground surface. The sensor had a reading range from 0.10 to 0.60 m, supply voltage from 18 to 30 V, resolution of 0.0005 m, repeatability ± 0.5%, and accuracy of ± 2.0%, with a response time of 0.05 seconds. During the readings, it captures, through an internal camera, the location of the light beam emitted on a surface; it is a three-dimensional laser triangulation scanner.

The ultrasonic sensor (HC - SR04; TZT™) had a reading range of 0.02 to 0.80 m (error margin ± 0.03 m), resolution of 0.03 m, and detection range of 15º, with current and nominal operating voltages of 0.015 A and 5 V. It allows the ultrasonic module to emit up to eight 40,000 Hz signals under situations where the trigger sends a 10 μs wide pulse to the signal pin. The sensor consisted of an ultrasonic emitter and receiver, in which the emitter sends signals that ricochet on the obstacle and return to the receiver, creating a time difference in the communication, resulting in the measurement of the distance.

Ten distance data were obtained by the sensors, in addition to displacements measured with a precision measuring tape. These data were needed to calibrate the sensor, resulting in a correlation between the distance and the input voltage in the data acquisition system calculated through a calibration equation. The obtained data pairs (V × m) were analyzed through linear regression to create the equation that generates the multiplier factor in the programming.

The profilometer's data acquisition system (DAS) was connected to a microcomputer (AT mega 328; Atmel™) that has a 10-bit analog to digital converter, eight analog inputs, Clock speed of 1.6107 Hz, supply voltage of 5 V, 14 software-programmed digital inputs and outputs, and a USB communication and power port. The acquisition frequency of 1 Hz, measured through the sensor connected to the DAS, corresponded to the soil profile reading. The data obtained were entered into spreadsheets.

C ++ language was used for collecting and visualizing the data. The direction control and sensor displacement were considered, in addition to the interaction functions of hardware operational parameters, such as pulses and delay. Calculations generated the pulse ratio, analyzing the operation efficiency and the motor-transmission system. It resulted in 51 pulses per 0.01 m displaced in the transverse direction, equivalent to a speed of 0.14 m s^{-1}.

The driver software recognizes the pulses placed in the programming, transforms them, and sends the signals to the switching of the power components, transferring the current to the motor unit. A delay was determined to control the high and low pulse cycles, i.e., time-on and time-off, respectively. Delays are the time intervals when light is emitted and received by the laser sensor. The time of 0.7 seconds was considered suitable after data collection.

The soil used was a clayey-textured Oxisol (USDA, 1999), collected at a depth of 0.0 to 0.10 m. The soil profiles were evaluated in a pot (Figure 3) with capacity of 168 L, height of 0.08 m, top width of 0.08 m, bottom width of 0.06 m, and length of 3.00 m. Mobilized (0.16 m), original or natural (0.07 m), and cut-out (0.01 m) soil profiles were placed in the pot and then removed. Four soil samples were collected at the working depth during the test to obtain the gravimetric moisture, which resulted in 0.22 kg kg^{-1}.

The rods of the conventional profilometer were carefully arranged along each profile to avoid further damage from contact with the ground (Figure 3A). The soil in the pot was maintained without inclination or height variations, keeping 0.52 m from the reading sensor. The mobilized soil profile was placed at 0.43 m from the sensor, with sharp initial and final inclinations, the same as for the cut-out profile, starting from the removal of soil at 0.59 m from the sensor (Figure 3B).

Determining the mobilized area, elevation area, and soil blistering required obtaining the roughness index and the mobilized soil profile; the electronic profilometer was used for this purpose, with 2.80 m width and reading points every 0.05 m. A previously leveled base transversely to the profile area

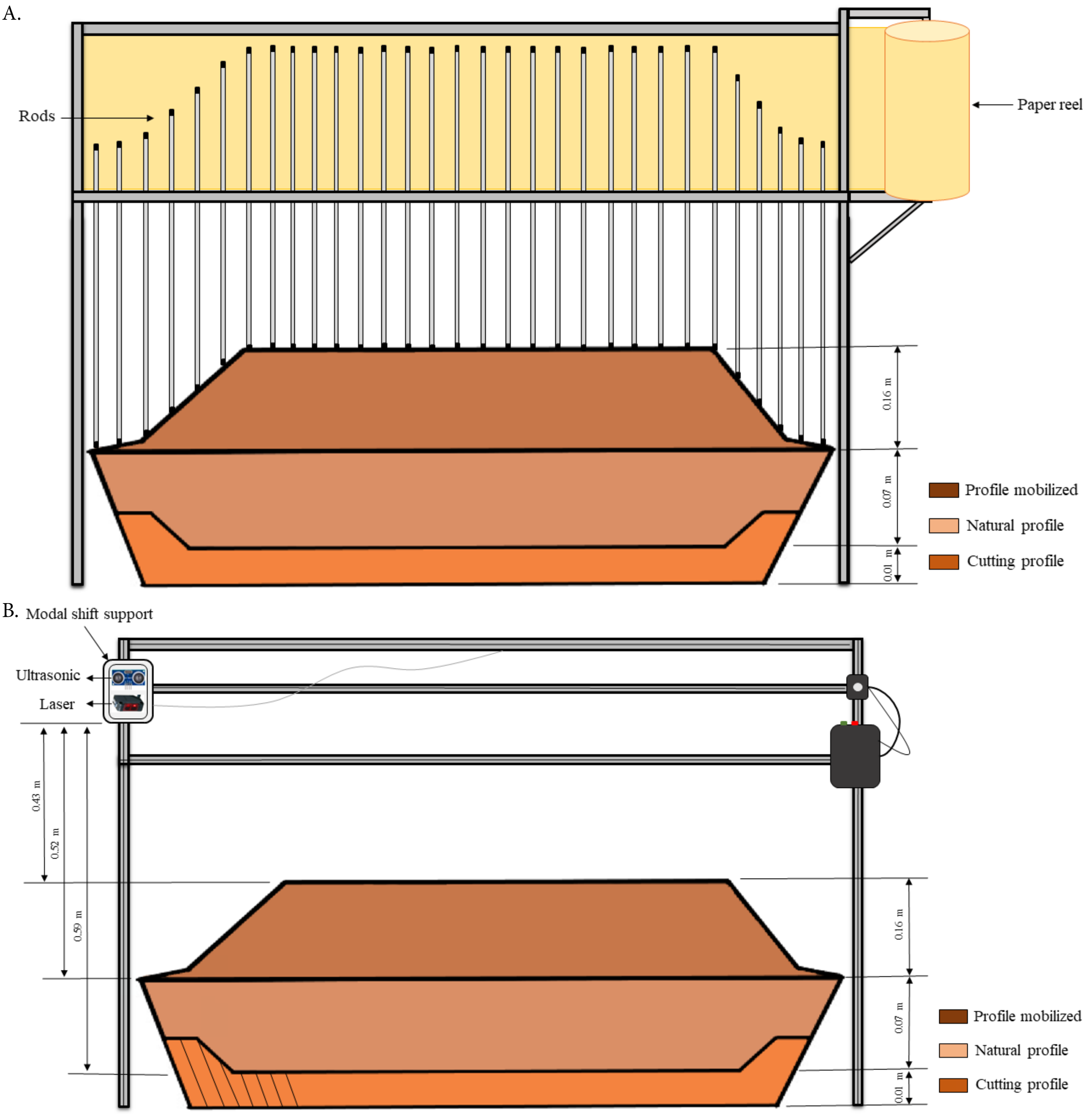


Figure 3. Conventional (A) and (B) electronic profilometers were placed laterally to the pot with the mobilized, original/natural, and cut-out soil profiles

held the devices (Allmaras et al., 1966). The the soil surface was covered with a low-density white paper to raise the laser sensor reading remission above 90%.

According to the methodology proposed by Carvalho Filho et al. (2007), the soil profile should be read before simulating tillage to obtain the non-mobilized profile (natural profile) and after simulating tillage to obtain the soil surface after mobilization (elevation profile) and the internal profile of the mobilized soil (cut-out profile).

The variables analyzed in the profilometry study were: modified roughness, elevated area, mobilized area, blistering, and thickness.

The calculations of the elevation area used the Simpson Rule, given by Eq. 1:

$$\int_{X_0}^{X_n} dx = \frac{h}{3}\left(f_0 + 4f_1 + 2f_2 + 4f_3 + 2f_4 + \ldots + 2f_{n-2} + 4f_{n-1} + f_n\right) \quad (1)$$

where:

$$h = \frac{X_n - X_0}{n}, X_n > X_0$$

where:

n - number of intervals;
f - height of the dimensions (m);
h - distance between heights (m); and,
X - number of height measurements.

The surface roughness index represents the product of the standard deviation between the natural logarithms of the elevation readings by the average elevation height; it is given by Eq. 2:

$$\sigma y = \sigma x \ hm \quad (2)$$

where:

σy - roughness index estimate represented by the standard deviation between heights (m);

σx - standard deviation between natural logarithms of heights; and,

hm - average height (m).

The area between the non-mobilized and cut-out profiles corresponds to the mobilized soil area, whereas the elevation area is between the non-mobilized profile and the soil surface after mobilization. Thus, the mobilized soil profile data provided the average thickness (Eq. 3):

$$T = \frac{MA}{Lp} \quad (3)$$

where:

T - average thickness of the mobilized layer (m);

MA - mobilized soil area (m^2); and,

Lp - profilometer length (m).

Soil blistering is the ratio between the elevation area and the mobilized area, expressed as percentage, according to Eq. 4:

$$B = \frac{EA}{MA}100 \quad (4)$$

where:

B - blistering (%);

EA - elevation area (m^2); and,

MA - mobilized area (m^2).

Finally, the modified roughness of the soil was determined and expressed as percentage; it is the difference between the roughness indexes measured after and before tillage, divided by the roughness index before tillage, according to Eq. 5:

$$MR = \frac{RI_f - RI_i}{RI_i}100 \quad (5)$$

where:

MR - modified roughness (%);

RIf - final roughness index (after soil tillage); and,

RIi - initial roughness index (before soil tillage).

The data collected were subjected to tests of normality (Shapiro-Wilk) and homogeneity of variance (Levene) and, then, to analysis of variance. The statistical program Sigmaplot 12 (Systat Software™) was used; when the F test was significant for a probability value ($p \leq 0.05$), the Tukey's test was applied at $p \leq 0.05$.

Results and Discussion

Table 1 shows the synthesis of the soil profilometry results, with no need for value transformation for all variables studied, denoting normality (Shapiro-Wilk) and homogeneity of variances (Levene). In addition, all coefficients of variation were categorized homogeneously, according to Vanni (1998).

The ultrasound underestimated all variables evaluated (Table 1) when compared to the results obtained with the other devices, showing the most significant differences for modified roughness, followed by elevated area, blistering, and mobilized area.

Modified roughness is the difference between the roughness indexes measured after and before tillage, divided by the roughness index before tillage. According to Correa et al. (2012), the soil surface roughness consists of micro ripples, micro elevations, or micro depressions on the soil surface. The mean test showed that the conventional profilometer provided a modified roughness 13.43% higher than laser, whereas the difference between the conventional and ultrasound devices was 91.59%.

According to Lee et al. (1996), an irregular soil surface strongly affects the detection accuracy of ultrasound sensors regarding measurement distance due to their wide beam width.

When sound waves do not reflect directly back to the sensor, reflected waves may not be captured due to the orientation of the sensor or the object's surface (Yuan et al., 2018). Thus, objects with small surfaces do not emit strong echoes, causing the ultrasound not to consider weak echoes

Table 1. Summary of analysis of variance and mean test for roughness (MR), elevated area (EA), mobilized area (MA), blistering (B), and thickness (T) obtained using conventional, laser, and ultrasound profilometers

Analysis	Variables				
	MR	EA	MA	B	T
Normality (SW)	0.780	0.786	0.731	0.90	0.799
Homogeneity (LEV)	0.081	0.101	0.072	0.10	0.112
F value	270.586**	140.834**	340.412 **	59.826**	1.917**
CV (%)	12.24	3.69	1.33	3.01	1.27
Means test	**(%)**	**(m^2)**	**(m^2)**	**(%)**	**(m)**
Conventional	704.92 a	0.23 a	0.38 a	61.20 a	0.14 a
Laser	610.28 b	0.23 a	0.38 a	59.01 a	0.14 a
Ultrasound	59.28 c	0.17 b	0.32 b	51.58 b	0.12 b

Analysis of variance (ANOVA) F-test: **: ($p \leq 0.01$). CV: coefficient of variation. Means followed by the same lowercase letter in the column are not different from each other by the Tukey's test ($p \leq 0.05$)

as valid signals. These factors probably also interfere with the ultrasound accuracy in reading the soil profile, as highlighted by Li et al. (2018) when considering the irregularity and surface size of soil aggregates under laboratory conditions, in which they smaller than those under field conditions.

The laser sensor was accurate in acquiring the evaluated variables. According to Verhoest et al. (2008), the main advantage of laser profilometers is their accurate measurement of profile roughness, with a sufficient horizontal resolution. Kapłonek et al. (2018) point out that optical profilometers can perform high-precision measurements of surface microtopography at distance from the ground, even under irregularities (Lee et al., 1996), and can reproduce small aggregates and voids between them, generating a very detailed surface, under laboratory conditions (Jester & Klik, 2005).

The conventional profilometer is a contact device (Figure 3A), therefore, it can change the ground surface, affecting the accuracy of profile readings. Thus, the non-contact laser electronic device (Figure 3B) was better in collecting and storing data, as well as more practical and efficient when compared to the conventional device, corroborating with the results found by Laskoski et al. (2017).

Elevated and mobilized areas are obtained from the height, distance, and number of dimensions, adding the number of intervals. The elevated area is between the non-mobilized profile and the soil surface profile after tillage. The differences between ultrasound and conventional device for elevated and mobilized areas were 26.09% and 15.79%, respectively, considering that the soil used was the same for all treatments.

The ultrasound underestimated the elevated area, a variable connected to soil blistering, which is the ratio between the elevated and mobilized areas. The difference between the conventional and ultrasound devices for blistering was 15.72%.

These factors are connected to measurement distance and affect the sensor readings and the consequent electronic representation of the soil profiles (Figure 4). Thus, the extent of the elevated and mobilized areas, heights, and the number of dimensions considerably affect the accuracy of readings, which corroborates with Lee et al. (1996), who reported that the greater accuracy of optical sensors in reading soil profiles is due to its opening angle and the smaller diameter of a point on a target, compared to ultrasound sensors.

During the present experiment, the sensors were subject to slight temperature variations and air currents in the laboratory, which was not hermetically sealed. Environmental conditions, such as temperature, humidity, and presence of acoustic and electronic noises, significantly affect the speed of ultrasonic waves (Sahoo & Udgata, 2020).

Li et al. (2018) emphasized that ultrasonic sensors employ the time of flight (TOF) principle to measure distances. Thus, the sensor performance will depend on reflective characteristics, such as shape and material of the target surface. Moreover, variations in wind, temperature, and humidity affect the speed of sound waves (Kolstad & Shuler, 1980), which can impair the analysis of ultrasonic signals.

Lee et al. (1996) found that ultrasound is strongly affected by temperature, and optical sensor is affected by electrical noise during long-distance detection with presence of a thin water layer on the ground surface.

Ultrasound also underestimated thickness, which was 14.29% lower than that obtained by the laser and conventional devices. This difference can be due to using the same electronic device for acquiring the soil profile with sensors, varying only the length in the conventional device. The accuracy of the readings is also affected by mobilized area, which is connected to soil blistering.

Electronically obtained reference soil profiles were used to assess the differences in soil profile readings between the sensors (ultrasound and laser) and the conventional device (Figure 4). The distances established for the readings were 0.43 m (mobilized profile), 0.52 m (natural profile), and 0.59 m (cut-out profile).

The laser sensor was better than ultrasound for reading soil profiles ((Figure 4). Its vertical distances are closer to those of the conventional profilometer, regarding to manual soil preparation, with the initial and final inclinations in the mobilized and cut-out profiles (Figure 3).

The ultrasound readings differed from those of the others devices, mainly for the cut-out and mobilized profiles; however, its natural profile readings were close to those tajen by laser.

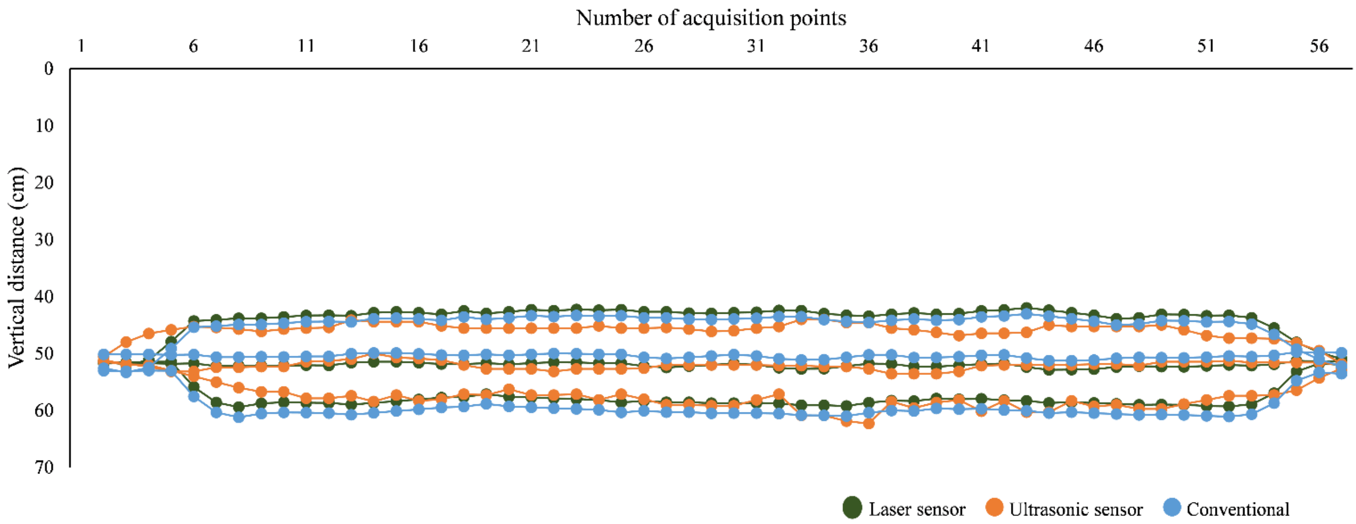


Figure 4. Representation of reference soil profiles (laser electronic profilometer × ultrasound electronic profilometer × conventional profilometer)

The representation of the mobilized profile at 0.43 m distance was significantly different between the sensors, even though it was the shortest distance defined for the readings, which may be due to effects of external factors and not only to vertical distances.

Lee et al. (1996) found variations in ultrasound sensor readings even on a flat reference surface, but it could read irregular surfaces at the shortest measurement distance (0.40 m); the accuracy of the optical sensor decreased as the distance from the surface was increased (up to 0.60 m).

Legg & Bradley (2019) reported that at an established height of the transducer above the ground, the angular beam width decreases along while the spatial and depth resolutions increase, but the sampling area reduces for each ultrasonic pulse. Thus, the laser and ultrasound sensors showed a significant reading difference in the most rectilinear region of the cut-out and mobilized profiles, even on irregular rough surfaces, because the cut-out profile is farther away whereas the mobilized and natural profiles are closer to the ultrasound receiver.

The initial and final sharp inclinations in the mobilized and cut-out profiles affected the accuracy of ultrasound readings. Guck & Magette (1988) used an ultrasound sensor that presented problems during scanning, such as the simultaneous monitoring of an excessive surface to provide the location distance, calculating a height that did not correspond to reality e causing a rebound effect on very smooth surfaces, which were considered slopes.

Thus, ultrasound may present difficulties for an accurate reading due to the waves reflected from inclined surfaces. According to Stiawan et al. (2019), as the waves reach inclined surfaces, some of them deviate from the sensor receiver, consequently reducing the detection accuracy; targets with inclinations greater than approximately 12° from the normal beam axis cause all waves to deviate from them, with no sensor response.

The most rectilinear surface, which corresponds to the natural profile (0.52 m vertical distance), resulted in closer readings between the sensors, probably due to the absence of initial and final inclinations in the profile.

The ultrasound readings were carried out without using any covering material on the surface, whereas the laser sensor readings were taken on soil surface covered with a low-density white paper to raise the reading remission above 90%.

According to Gabriel & Kuria (2020), sunlight or black material does not affect the HC-SR04 ultrasound sensor, but the acoustic detection hinders the readings of soft materials, such as fabrics. In addition, acoustic waves can be reflected by any material of any color (Stiawan et al., 2019) and are not affected by daylight (Azeta et al., 2019).

Šařec et al. (2007) stated the linearity of measurement caused sensitivity of the laser profilometer to the color of the measured surface, and that white surface profiles are closer while those of gray surfaces diverge from reality. Chen et al. (2022) measured objects using a laser scanner at 0.60 m height, under three different lighting conditions, and found the need for applying white paint on the objects' surface before scanning.

Covering the soil surface with a low-density white material allowed the laser sensor to accurately measure the soil profile, even on irregular, rough surfaces. The laser also overcame small aggregates and initial and final inclinations in the mobilized and cut-out soil profiles, which can confuse the signal (Figures 3B and 4).

Conclusions

1. The readings of the analyzed variables by the electronic profilometer assembled with an ultrasound sensor differed significantly from those obtained by the conventional profilometer.

2. The electronic profilometer assembled with a laser sensor did not differ from the conventional profilometer for any of the variables evaluated, except for modified roughness.

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