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Low-cost Terrestrial Photogrammetry as a Tool for a Sample-Based Assessment of Soil Roughness

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Summary: In cooperation with soil experts, a simple and reliable photogrammetric system was developed to acquire three-dimensional data of soil surfaces in sample areas sized 1 m². The work and data flow incorporates the automatic derivation of several soil roughness parameters. The procedure is usable for the in situ quantitative assessment of changes of soil volumes across weather and site conditions. The time- and cost-effective approach is based on terrestrial photogrammetry and meets all performance and accuracy requirements formulated by soil scientists of the Austrian Federal Institute of Land and Water Management Research.

Zusammenfassung: *Preiswerte terrestrische Photogrammetrie als Werkzeug zur Bestimmung der Rauigkeit von Böden.* In Zusammenarbeit mit Bodenfachleuten wurde ein einfaches und zuverlässiges photogrammetrisches Verfahren zur dreidimensionalen Erfassung von Bodenoberflächen mit Hilfe von Probeflächen mit einer Größe von jeweils 1 m² entwickelt. Zusätzlich werden automatisiert geeignete Bodenrauigkeits-Parameter abgeleitet. Das wetter- und ortsunabhängige Verfahren ist auch zur quantitativen Erfassung von Bodenabträgen einsetzbar. Die zeit- und kosteneffektive Methode basiert auf Verfahren der terrestrischen Photogrammetrie und erfüllt alle von Forschern des Österreichischen Instituts für Kulturtechnik und Bodenwasserhaushalt formulierten Genauigkeits- und Performance-Anforderungen.

1 Introduction

Soil erosion is a serious problem in many parts of the world. It decreases the agricultural productivity of soils due to relocation of soil-material (Wegmann et al. 2001, Moritani et al. 2010). Furthermore, the transportation of material into rivers pollutes them with agricultural chemicals and leads to siltation. Therefore, it is a main goal of soil scientists to get knowledge on how to minimize soil erosion.

To investigate the erosion processes, researchers focus their activities by developing proper models. These models, like the revised universal soil loss equation (RUSLE) (Renard et al. 1997) enable the estimation of the amount and the location of soil erosion. Soil erosion models are based on parameters such as soil surface roughness indices, which are also important for other environmental applications (Marzahn et al. 2012).

A broad range of indices were defined for describing the roughness of soil surfaces, e.g. the roughness indices by Taconet & Ciarletti (2007), Planchon et al. (2002), Allmaras et al. (1966) or Linden & Van Doren (1986). Such indices are needed for the calculation of soil erosion with erosion models (Renard et al. 1997). To calculate those indices, three-dimensional data of the soil surfaces is needed. Additionally, the dynamic of soil surfaces (changes) has to be assessed. It is a big challenge for soil scientists to get significant information on all kinds of soils and their development due to the diversity of soils on local level

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(within fields) as well as on regional level (in different areas).

The Austrian Federal Institute of Land and Water Management Research (BAW) has a long tradition and expertise on soil erosion. Based on different datasets, a number of soil erosion models have been developed suitable for multiple spatial scales.

The main objective of this study was to develop and design a method for assessing 3D-data of soil surfaces. Moreover, from the acquired 3D-data, suitable soil roughness parameters were to be derived.

The presented photogrammetric method is a missing link for the characterization of the surface roughness variability (and its changes over time) at field and catchment scale. Necessary is a low-cost photogrammetric method with a high level of automation to enable the complete assessment of soil surfaces and soil roughness parameters in areas sized 1 m² within 15 minutes. In this way, soil characteristics over whole fields and/or whole regions can be assessed by applying the 3D-measurements following a suitable (statistical) sample design.

2 Background and Related Work

Many methods have been developed for the detailed assessment of (micro-)soil surfaces and soil roughness. They can be divided in methods of measurement which have contact to soil (roller chain, pin-meter) and in methods without touching the soil surface (photogrammetry, laser scanning).

The roller chain method, as described by Saleh (1993), is a simple, fast, and inexpensive technique for the quantification of soil roughness. A chain with a known length is placed on a soil. The horizontal distance covered by the chain is a measure for the level of roughness.

Jester & Klik (2005) used pins with a diameter of 1 mm and a spacing of 5 mm to each other. Those pins were mounted on an aluminium frame with the possibility to shift the pins down to the surface of the soil. The final position was registered. This method enabled the measurement of surface profiles of the soil.

According to Mirzaei et al. (2012), high spatial resolution (vertically between ± 0.1 mm and ± 0.5 mm and horizontally between ± 0.1 mm and ± 2.0 mm) can be achieved by laser scanning applications. Haubrock et al. (2009) achieved height accuracies within a grid of 1 mm with an average error of ± 0.19 mm, by mounting the scanning-device on a tripod at a distance of 1.5 m to 2.5 m to the assessed soil surface. However, laser scanner instruments are quite unhandy for in situ measurements and need considerable power supply. Furthermore, they are fragile (Mirzaei et al. 2012) and no laser scanners for the accuracy requirements are provided in the commercial low-price sector (Abd Elbasit et al. 2009).

The increasing performance and usability of digital photogrammetry were the main drivers for the renaissance of image-based methods for soil surface assessment.

Marzahn et al. (2012) describes a photogrammetric soil assessing procedure using a Canon EOS 5D camera in combination with a Canon EF 2/35 mm lens. The dimension of the test sites was 1 m x 2.5 m. Mirzaei et al. (2012) mounted two cameras on a frame to enable stereoscopic measurements in a distance from 1 m to 4 m to the soil surface. Aguilar et al. (2009) also worked with a system of two cameras. The photogrammetric software PhotoModeler Pro 5 was used for camera calibration and OrthoEngine V9.1 for DSM generation to assess an area of 1.2 m x 0.8 m. Gessesse et al. (2010) developed a photogrammetric method to acquire micro-topographic soil surface changes caused by erosion. They also investigated the sediment transport and rill erosion development in the inter-rill areas at storm scale. The method is based on a frame with a movable bar, where two cameras were mounted to assess test site areas with approximately 4 m x 15 m with vertical accuracies between ± 2.8 mm and ± 5.3 mm.

Schneeberger & Willneff (2003), finally, assessed the roughness of soils by using a solid frame as reference for photogrammetric measurements in a local system.

3 Methodology

3.1 *Objectives and Tasks*

The requirements defined by soil scientists of the Austrian Federal Institute of Land and Water Management Research are the following:

- test area of approximately 1 m^2,
- local Cartesian coordinate reference system with height coordinates (z) and plane coordinates (x and y) (the x/y-plane has to be levelled horizontally and the x-axis points to cultivation direction),
- acquisition of a digital soil surface model with a ground resolution less than 1 cm,
- sub-centimetre accuracy (± 3 mm – 5 mm in plane and height),
- time-effective data assessment and post processing,
- low costs,
- equipment easy to handle in the field (one person).

As part of the task, a workflow-integrated derivation of soil roughness indices should be developed with the input of the photogrammetrically assessed 3D point cloud. The BAW predefined the specific indices and the formulas for the calculation of the roughness parameters.

3.2 *Photogrammetry*

The proposed method needs a calibrated camera, i.e. with known interior orientation, and a reference frame, which has to be placed horizontally above a soil surface. For reaching good accuracy of the exterior orientation and for deriving a reliable digital surface model (DSM), photographs have to be taken in oblique and vertical directions. The requirements for this task are low costs for the whole system (camera, software, acquisition time) and a high level of automation.

Camera and interior orientation

To keep the costs low, consumer-level cameras were used instead of high-precision photogrammetric cameras. It is known, that DSM-generation with consumer-level cameras can achieve high accuracy (Marzahn et al. 2012).

The following consumer-level cameras covering different price segments and different qualities were investigated:

- Canon EOS 1100D
- Nikon Coolpix P5000
- Olympus SP-590UZ
- Panasonic Lumix DMC-FS10
- Sony SteadyShot DSC-W380

The above listed cameras are equipped with zoom and autofocus lenses and thus in principle not suited for the type of photogrammetric software that assumes a fixed focus. However, in view of the photoscale of 1:100 or larger and the comparatively low accuracy requirements the slightly changing focal length caused by the autofocus process had no significant influence on the quality of the results. On the other hand, sharp images were important for a reliable identification of the ring codes and sufficient dense point clouds.

The determination of the parameters of the interior orientation of the cameras (focal length, coordinates of principle point, and coefficients of distortion polygon) was performed with the software module 'Camera Calibration Project' of the PhotoModeler Scanner (PMS, EOS Systems Inc.). Photographs of a so called calibration grid (Fig. 1) were taken from four different view angles, each with three different camera rotations (in total 12 photographs).

The coded ring patterns generated as pdf-files by the PhotoModeler Scanner (software)

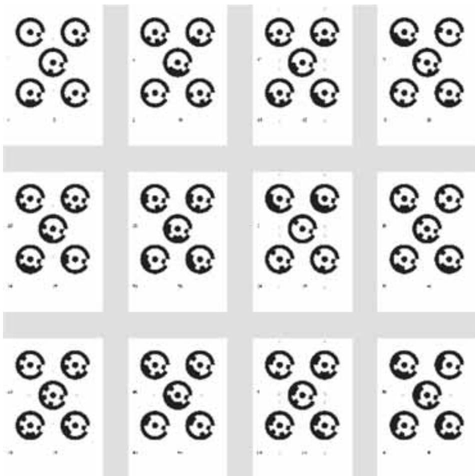

Fig. 1: Calibration grid used to determine the parameters of the interior orientation.

and printed enable an automatic computation of the parameters of the interior orientation. Additionally, the software calculates accuracy measures describing the quality of the camera geometry. The repetition of the interior orientation assessment allowed the estimation of the stability of the investigated cameras.

Regarding the photographic quality of the cameras, photographs from soil samples with different characteristics (roughness, wetness, composition) were visually assessed.

Exterior orientation and reference frame

Control points are used for the calculation of the parameters of the exterior orientation, i.e. position and attitude of the projection centre in a superior coordinate system. The coordinate reference system of the exterior orientation is horizontal realized by a levelled frame.

To support the automated workflow, coded control point marks (RADs – ring automatically detected) are used. The RADs are mounted on a movable frame in a balanced distribution over the test soil area to guarantee accuracies as high as possible. Additionally the reference frame has to fulfil the following requirements:

- easy to transport,
- high stability,
- sufficient size in order to obtain DSMs of an area of 0.9 m x 0.9 m according to Taconet & Ciarletti (2007),
- vertically adjustable up to slopes of 30%,
- enabling an easy mounting of targets.

In an iterative process the frame was developed. The constructed reference frame has a format of 1 m x 1 m. The horizontal alignment is realized by three vertically adjustable piles and by two spirit levels mounted on the frame (Fig. 2).

Fig. 2: Reference frame and levelling facility.

The material of the reference frame is aluminium and has a width of 5 cm. This dimension meets the requirements of being stable and to be handled by only one person. The width also has to be optimized to the size of the mounted control point targets (RADs). Control points have to be detected automatically and this requirement is dependent on the size and colour of the targets, on the quality of the camera, on the photogrammetric set-up, and on the weather conditions during the image acquisition. In a series of tests with various target characteristics (size and colour), with different cameras (Canon EOS 1100D and Nikon Coolpix P5000), and under different weather conditions (bright sky and cloudy), the minimal target size for automatic detection was determined. The size of 5 cm × 5 cm can be seen as a compromise between easy target-detection and handiness of the aluminium frame. Based on these findings further investigations with the developed reference frame were outlined to proof the accuracy of the exterior orientation for specific set-up configurations and for extreme weather conditions.

65 control points (targets) are mounted on the frame. The local coordinates of the control points were determined by conventional geodetic surveying with an achieved accuracy of ± 0.3 mm. As the frame is not perfectly right-angled and the targets are not placed exactly, the axis of the coordinate system fitting best to the frame were determined by adjustment methods.

Photogrammetric set-up

Within this study, investigations were undertaken to optimize the (hand-held) camera positions for both, calculation of the exterior orientation and of the DSM generation, and for minimizing the total number of photographs for each test site and thus the costs. The position of the cameras has to be optimized to enable good geometry for the calculation of the exterior orientation as well as for the generation of the DSM. Photographs with near vertical view directions and high coverage facilitate better results of matching algorithms and thus better surface models. On the other hand, oblique view directions provide better accuracy of the exterior orientation.

Several photographs were taken for several test sites. By varying numbers of photographs and camera positions, the optimal assessment set-up was determined.

Generation of point cloud

The PhotoModeler Scanner software (PMS) generates automatically a point cloud of the surfaces. As the soil assessment system has to be simple as being used not only by photogrammetric experts and the soil conditions can vary within a broad spectrum, e.g. dry to wet, smooth to rough, coarse grained to fine grained, the point cloud extraction in the workflow is proposed to be done with predefined standard parameters, e.g. mean distance of surface grid: 1 mm, chosen pairs of photos have b/h-ratio between 0.1 and 0.6, coordinate reference system attached to targets in the same way for each DSM.

3.3 *Derivation of Soil Surface Parameters*

The PMS software provides an automatic workflow from photographs to point clouds by using RADs. In a post-processing process, a DSM based on the point cloud is calculated. Finally, the average inclinations (in the cultivation direction and rectangular to it), the maximal inclination, and the various roughness parameters of the soil surface are determined. All formulas for the calculation of the DSM were implemented in the software Matlab (MathWorks Inc.).

Grid generation

As a first step, a regular grid has to be calculated. The resolution of the point cloud (close to one point per one mm^2) enables the calculation of the regular grid with a grid size of 1 mm x 1 mm. The reference frame with a dimension of 1 m x 1 m enables the derivation of an area of 0.9 x 0.9 m^2 of the soil surface, which is suitable for soil roughness calculations (Taconet & Ciarletti 2007).

The quality assessment for the digital surface model was performed in two different ways:

- Firstly, the reliability of the method was assessed by analysing photogrammetric time series of the same soil sample.
- Secondly, an accuracy assessment of volume calculations was performed. Soil material with a known volume was deposited on one test site with a photogrammetrically assessed surface. The new surface was determined. The volume of the difference between the new model and the previous one was calculated and compared to the added soil mass.

Inclination

The average inclinations in the cultivation direction and rectangular to it, as well as the maximum inclinations have to be calculated. In a first step, the plane of best fit is calculated for the whole sample by the least-squares method. As the reference frame and its coordinate reference system are placed parallel to the cultivation directions, the adjusted plane provides the desired inclinations in cultivation direction and across.

The maximal inclination (Inc_{max}) is derived from the inclinations in x- (Inc_x) and y-direction (Inc_y) with (1):

$$Inc_{\max} = \sqrt{Inc_x^2 + Inc_y^2} \qquad (1)$$

Roughness indices

The roughness indices calculated in the current study are listed in Tab. 1:

- Random roughness index (RRA) as described in Allmaras et al. (1966). In the calculation of RRA a log transformation is applied followed by a removal of the highest 10 % and lowest 10 % of the values. The height-values are smoothed as proposed in Helming (1992). The RRA is the standard deviation of these values.
- Random roughness (RR) index as described in Planchon et al. (2002).
- RC (roughness overall) index, the RCY (oriented roughness y-axis) and the RCX (oriented roughness x-axis) as described in Taconet & Ciarletti (2007) following Currence & Lovely (1970).

Tab. 1: Calculated roughness indices.

Index abbreviation	Authors	Modification	Basics
RRA	Allmaras et al. 1966	Helming 1992a	standard deviation
RR	Planchon et al. 2002		standard deviation
RC, RCY, RCX	Currence & Lovely 1970	Taconet & Cialetti 2007	standard deviation
LD, LS	Linden & Van Doren 1986		spatial variance analysis
TB	Helming et al. 1992b		total surface area to map area

- Indices based on spatial variability. LD and LS are indices described in Linden & Van Doren (1986).
- The tortuosity-index (TB) is defined as the ratio of the total surface area to the map area (Helming et al. 1992).

The calculation of all above outlined indices was implemented in Matlab software with the input of the DSM. The full data flow from the PhotoModeler Scanner to Matlab is realized.

3.4 *Case Study Application*

Tests of the handling of the photogrammetric method and of the roughness parameter calculations were executed on three different field sites. Field management was done on one field with a cultivator and on two fields with different types of mouldboard ploughs. To calculate mean absolute roughness values per field, replicate measurements were performed on several sample sites (10 replicates for each type of cultivator and 19 replicates for mouldboard plough). In addition, soil texture and organic carbon content were analysed on the field sites.

4 Results and Discussion

4.1 *Selection of a Proper Camera*

Five consumer-level cameras were investigated on their fitness for the outlined task. The applicability of a camera for photogrammetric measurements is given by the pixel resolution, by the geometric accuracy, and by the radiometric quality.

The quality of the camera geometry was evaluated using the calibration results for determining the interior orientation of the PhotoModeler Scanner. In Tab. 2 the 'Total Error' as well as 'Point Marking Residuals' of five tested cameras are listed.

Repetitions of the camera calibration were performed to verify the stability of the cam-

Tab. 2: Results of camera calibration (PhotoModeler Scanner) based on calibration set-up with 12 photographs and 60 reference points per photograph.

Camera	Image format (MPixel)	Total image unit-weight RMSE	Point marking residuals overall RMSE (in pixels)
Canon EOS 1100D	12.2	2.91	± 0.35
Nikon Coolpix P5000	10.0	2.29	± 0.28
Olympus SP-590UZ	11.1	14.98	± 1.76
Panasonic Lumix DMC-FS10	12.0	3.12	± 0.39
Sony SteadyShot DSC-W380	14.0	24.11	± 3.08

eras. As the dimension of the errors is similar to the results outlined in (Tab. 2), all examined cameras can be assumed to be stable.

Based on the calibration results it was decided to continue the investigations with the Nikon Coolpix P5000 and Canon EOS 1100D cameras. These two cameras yield the lowest total error and overall point marking residuals. The total error with below ± 3 pixels as well as the RMSE of the calibration points with less than ± 0.5 pixels is acceptable for zoom and autofocus lenses.

After the camera calibrations, the photographic (radiometric) quality of the two selected cameras was judged visually and by interpreting the results of repeated photogrammetric measurements for different soil conditions and weather conditions (see Fig. 3). The investigations gave satisfactory results independent of the soil characteristics and weather.

4.2 *Configuration of Camera Stations*

To minimize the number of photographs and to optimize the positions of the camera stations several tests were run by varying numbers and configurations of camera stations with a maximum of 12 photographs (8 near-vertical, 4 oblique) as a reference. Fig. 4 outlines the results. The DSM with a grid size of 1 mm derived from all images served as a reference. Good results were obtained using 4 near-vertical and 4 oblique photos. Using this configuration the error was only ± 1.4 mm and hence almost as good as using six near-vertical and 4 oblique directions.

For the practical work a photogrammetric set-up with in total eight photographs was recommended. Four photographs have to be taken in near vertical direction (low angle) with

Fig. 3: Soil samples used for analysing the photographic quality.

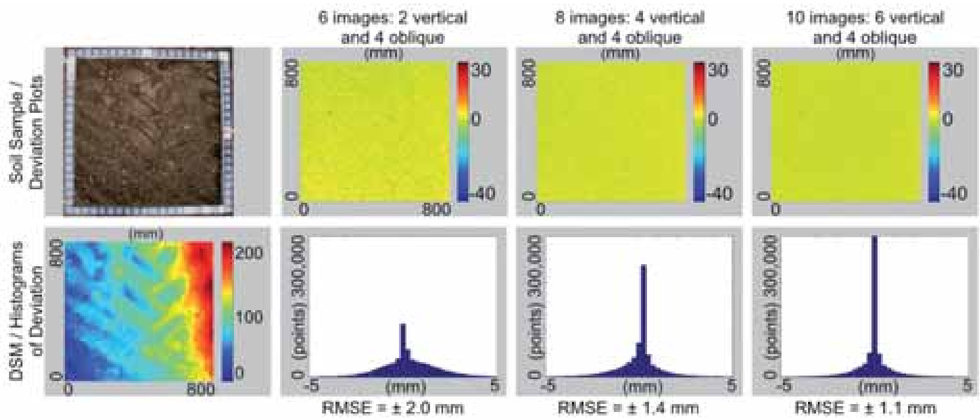

Fig. 4: Accuracies of different configurations of photo stations (same sample plot).

a high overlap (base-to-height ratio between 0.1 and 0.6). These images are important for the point cloud generation. Due to constraints of the PhotoModeler Scanner (PMS) software, only images with near vertical view can be successfully analyzed. The other four photographs have to be taken in oblique direction (angle of approximately 60 degrees to the soil plane and approximately 90 degrees between principal axes) to enable a reliable calculation of exterior orientation parameters.

The outlined RMSE of the exterior orientation lies between ± 0.5 and ± 2.0 pixels (Canon EOS 1100D, 17.8 mm focal length, 5.3 µm pixel size). Assuming an average photo distance from the camera to the frame position of 2 m this measures are equivalent to ± 0.35 mm and ± 1.4 mm in the local coordinate reference system.

4.3 *Accuracy Assessment of DSM*

Comparing DSMs

For seven soil types photogrammetric measurements were performed. For each of the test sites eight photographs (4 near-vertical, 4 oblique) were taken handheld. The measurements were repeated for each test site with similar – albeit not identical – camera stations and with the same position of the reference frame.

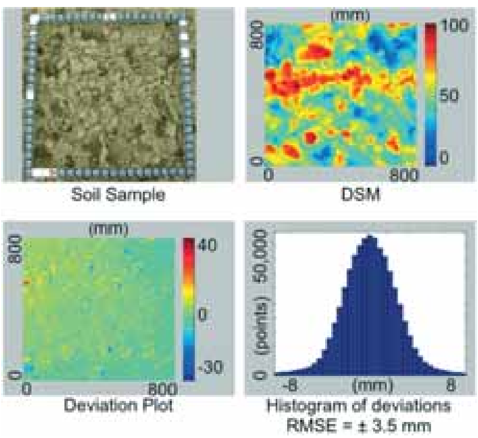

Fig. 5: Results of DSM Analysis of a soil with a high roughness.

The orientation and the generation of point clouds were calculated separately for each of the measurements (7 sites, two set-ups per site) using the PMS software. A Matlab script was used to interpolate a regular grid of all soil surfaces with a grid size of 1 mm x 1 mm based on the generated point cloud. Deviations between the DSMs generated from the same test site were calculated and analysed. Fig. 5 shows the results of one soil sample.

Generally, the investigations pointed out RMSE between ± 2 mm and ± 4 mm between the corresponding surface models. The analysis of the results made obvious, that the biggest errors occur increasingly in soil surfaces with a high roughness and that they are mainly caused by interpolation effects close to sharp edges and steep areas.

Volume determination

One application of the method is to measure the change of volume of a soil during an erosion event such as heavy rainfall. In an experiment, various soil materials (quartz sand) of known volume were added to a soil several times and each time the difference of volume was assessed using the proposed photogrammetric method. This allowed comparing the photogrammetrically measured volume changes against the added volumes.

Seven DSMs with four different volumes were analysed with cross correlation methods. The resulting differences have a mean of 0.4 dm^3, a standard deviation of ± 0.3 dm^3 and a confidence interval ($\alpha = 0.05$) of 0.1 dm^3.

In a second experiment, volumes were removed. Again, the true value – determined by a vessel with a scale – was compared with the one measured photogrammetrically. The results of ten comparisons were surprisingly similar to the one of the first experiment with a mean of 0.4 dm^3 and a standard deviation of ± 0.3 dm^3.

4.4 *Field Observations (Case Study)*

Mean values and standard deviations of various roughness indices (RRA, RR, RC, LD, LS, and TB) for three different field sites are reported in Tab. 3. Additional information about soil conditions and tillage tools for each site is given.

For our test sites, ploughing results in rough and heterogeneous surface conditions were assessed, whereas the use of a cultivator leads to smoother and more homogenous surfaces. During cultivation soil is broken into small and uniform aggregates whereas ploughing turns the soil and results in heterogeneous furrow slices. This is well reflected by all tested roughness indices (Tab. 3). Given the limited number of test sites and the lack of an absolute reference, it was not possible to rank the usefulness of the tested roughness indices. In addition, not all indices are being accepted as relevant for purposes of soil roughness or soil erosion research (Currence & Lovely 1970, Helming 1992, Taconet & Ciarletti 2007).

5 Summary and Conclusions

A method was developed to obtain digital surface models (DSM) and roughness indices from soil surfaces easily, cheaply, quickly and with sufficient accuracy. The proposed method has several characteristics making it appealing for further development:

- The method can be applied easily in the field as only limited equipment is necessary not requiring any sophisticated power supply.
- The use of consumer-level cameras makes the method affordable.
- Merely 15 minutes are necessary in order to get the raw data for about 1 m^2 of soil surface.
- The height accuracy of the soil surface is better than ± 3 mm.
- The processing of the raw data from the PhotoModeler Scanner (PMS) software could be realised quickly and in an uncomplicated way, using scripts from Matlab.

Several other authors, such as Marzahn et al. (2012) or Mirzaei et al. (2012) already worked with similar methods for soil surface assessment. The method developed in this study combines several aspects, resulting in a new approach:

- Only one camera is used, which makes the method cheaper while keeping a sufficient accuracy.
- Only one photogrammetric software program is used for the whole photogrammetric workflow (PhotoModeler Scanner), which also makes the method cheaper and furthermore saves time to convert and transfer the data from the calibration into another program.

Tab. 3: Field site description (texture, humus content and tillage tool), received roughness values and standard deviations for various roughness parameters (RRA, RR, RC, LD, LS, TB).

	Site	Cultivator	Fine mouldboard plough	Rough mouldboard plough
soil and management	management tool	Regent – Tukan FSC	Kuhn – MultiMaster	Vogel&Noot – XM
	(number of samples)	10	19	19
	sand (%)	48.2	16.4	7.0
	silt (%)	35.9	64.0	62.5
	clay (%)	15.9	19.6	30.5
	humus (%)	2.3	1.7	1.9
roughness indices	RRA (mm)	7±2	15±3	20±6
	RR (mm)	11±2	35±5	40±9
	RC (mm)	20±5	42±5	50±11
	LD (mm)	17±3	37±3	41±6
	LS (mm)	1.1±0.5	1.8±0.4	1.9±0.4
	TB (%)	1.5±0.5	3.8±0.8	2.6±0.5

- The reference frame is vertically adjustable which allows an easy application of a coordinate system with a horizontally aligned x/y-plane.
- Taking the photos hand-held instead of using a fixed system makes the method faster and much more applicable in the field. Obviously, a fixed system has the advantage of eliminating the risk of blurred images. However, the tests did not reveal this aspect as a problem.

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