DIGITAL PHOTOGRAMMETRY FOR MEASURING SOIL SURFACE ROUGHNESS

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Abstract

Digital Elevation Models of soil surfaces are used in soil erosion research for a better understanding of erosion processes. Non-contacting techniques are used to avoid disturbance of the soil surface. So called laser scanners are used to obtain high-resolution grids (1 mm²/grid cell) from soil surfaces (up to 16 m²). The scanning devices are moving on a heavy reference frame and are thus not very practicable for field work. The time needed for one scan exceeds hours while soil surfaces may change within much shorter periods of time. For faster data acquisition and better versatility as well as for the coverage of large areas, photogrammetry is proposed to be an ideal surveying method. The system is not in contact with the soil surface, large areas can be covered by a block of images, and temporal resolution is determined by the time to take the necessary number of photographs. A camera can be easily transported on field location. This paper will describe the photogrammetric method under development at the National Soil Erosion Research Laboratory in cooperation with the University of Hanover, Institute for Engineering Surveys. The method is compared to one of the latest laser scanner devices. Results show that the photogrammetric technique is capable of reducing the time for data acquisition, of covering large areas large by combining multiple images, and that it has a better relative accuracy than the laser scanner.

Introduction

Soil erosion is a ubiquitous economical and ecological problem. Detachment and transport of soil particles on a field side degrade the fertility of soil and reduce its productivity. Off-side damages caused by the detachment of soil can be the siltation of ditches, and the input of chemical compounds from agricultural fields into the environment. Runoff material from eroding surfaces is a major contributor of non-point-source (NPS) pollutants that accumulate in surface water bodies. Soil erosion research is mainly concerned about on-side processes. Mathematical models have been developed to gain knowledge of erosion processes, and to better understand soil erosion. Such models are also used to predict the amount of soil loss for planning and consulting purposes. They can be used to understand processes, identify shortcomings of existing models, and help to set new research priorities for a better understanding of soil erosion in general (Nearing et al. 1994). The National Soil Erosion Research Laboratory (NSERL) focuses mainly on soil erosion by water. Erosion processes are studied inside the laboratory as well as on field scales.

The interface between the eroding soil body and the erosive agent is the soil surface. Its behavior has been studied for a long time. Lal and Elliot (1994) defined the most important processes affecting soil erosion to be "infiltration, run-off, detachment and transport by raindrops and overland flow (interrill erosion), and detachment and transport by concentrated flow (rill erosion)." During an erosive event the soil surface is continuously transforming. The behavior of soil surfaces is studied by comparing it before and after experiments. Particles involved in soil erosion processes i.e. raindrops and soil particles, all have characteristic dimensions on a millimeter scale (Huang 1998); thus soil surface data at millimeter scales are needed to study erosion processes. 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.

Laser scanners (Römkens et al., 1986; Khorashahi et al. 1987; Huang et al. 1988; Bertuzzi et al. 1990) are used to generate DEM from soil surfaces. While resolution and accuracy meet the requirements for soil surface studies a long time is needed for each scan. The scan of a 1 m² area at a resolution of 1 mm² needs about 2 hours. The temporal resolution of the laser scanner devices is not sufficient to produce time sequences of rapidly changing surfaces.

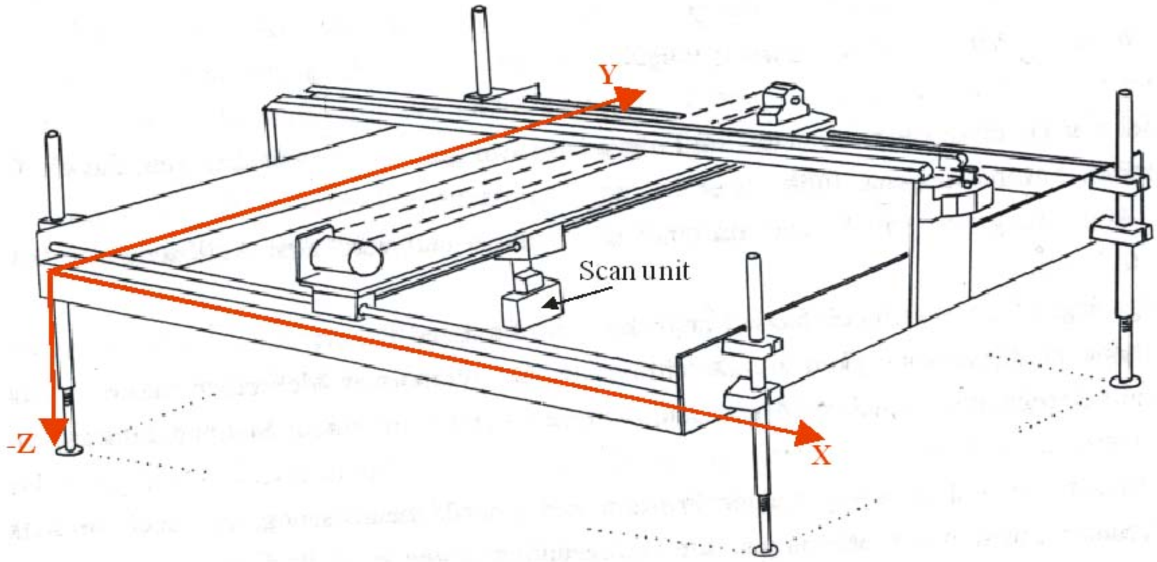

Figure 1. Laser scanner with the scan unit mounted on a frame (Helming 1993, edited). The scan unit is moved in a XY-plane by stepping motors; elevation (Z) is determined by triangulation at each XY location.

The scan unit is moved on a frame by stepping motors in X and Y direction (figure 1). While field plots for erosion experiments exceed areas of 30 m², classic scanners cover an area up to 16 m², portable devices up to 3 m². The limitations of the laser scanners are size and portability, as well as the time needed for each high-resolution scan. To be able to cover larger areas and to increase the temporal resolution of DEM, the authors propose a photogrammetric technique using stereo images. Accuracy, and resolution of this technique should match laser scanner standards.

Photogrammetry has already used for some applications in the field of geomorphology and soil erosion research. In 1983 Welch and Jordan used analytical photogrammetry to monitor stream channel erosion. Kirby (1991) described the advantages of photogrammetry for geomorphological studies emphasizing the quick data acquisition, the portability of a camera-based system, the high accuracies accomplished with metric cameras, and the easy coverage of areas with a block of images as major advantages. At the same time one million of coordinate points have to be measured to create a grid of just 1 m² at a resolution of 1 mm². Only with the availability of algorithms for automated matching of homologous points, and since computers can handle large digital images, photogramnmetry became practical for the generation of so many points. Algorithms were developed for the automatic detection of homologous points in images. Helming (1993) used a matching procedure to create soil surface DEM. She concluded that computing power and resolution of digital cameras did not suffice at that point of time. Stojic et al. (1998) used a commercially available matching program for their analysis of a laboratory flume with an area of about 33 m² with encouraging results. Since 1999, the NSERL, in cooperation with the Institute of Photogrammetry and Engineering Surveys (IPI – University of Hanover, Germany), has been developing a completely digital photogrammetric set up for the creation of soil surface DEM on a regular basis (Wegmann et al. 2001). This paper will present first results, and compare the properties of DEM surfaces generated by photogrammetry to DEM created by the laser scanner method.

Materials and methods

The soil surface under investigation was prepared in a laboratory flume with dimensions of 4.18 m, 2.21 m and 1.30 m length, width, and height, respectively (figure 2). A 31 % steep surface was created with sand beneath the soil material. Soil material from the B_t horizon of a Camden soil (Typic Hapludalfs) containing 23 g/Kg sand, 864 g/Kg silt, and 113 g/Kg clay, was passed through an 8 mm sieve, air dried, and a 20 cm thick layer of soil was filled in the box. A rainfall simulator was used to simulate rainstorm events. For more details refer to Santel (2001).

Figure 2. Experimental set up. A 31 % slope was created. Control points have been fixed around the flume. The camera was moved parallel to the soil surface with the apparatus seen above the flume. A rainfall simulator is located further above the flume. Deep and narrow rills formed on the soil surface.

After each rainfall experiment the surface was scanned with a laser scanner device and stereo photographs were taken. The scanner is a new development by C. Huang at the NSERL. Instead of tracking a point on the surface, a laser line is projected on the soil surface, and its signal is tracked on a CCD (charge-coupled device) sensor in a camera pointing at the soil surface (figure 3).

The distance between camera and laser, as well as the angle between the camera and the laser source is fixed. The signal at each location on the CCD sensor is converted into an elevation reading by triangulation (after correction with the calibration file). The scan unit travels on a 4 m long beam and scans 0.6 m wide profiles along track. Directly after scanning the surface a regular grid of elevation data is available, the datum is established relative to the beam. For calibration, 200 target points with known object coordinates were arranged in the vertical projection plane of the laser line with the camera directed at it.

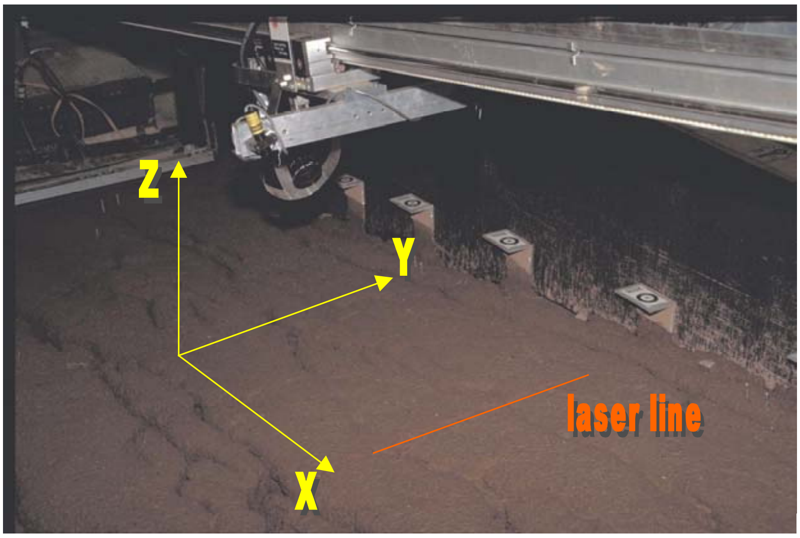

*Figure 3. New laser scanner at the NSERL tracking a laser line on the soil surface. A 4 m * 0.6 m long strip is covered by the laser scanner*

The points were signalized by LED (light emitting diode). The x, y locations of each control point was measured on the sensor and fourth order polynomials were used to relate the sensor coordinates to object coordinates; an approach quite often used in image analysis (x, y coordinates are related to the Y and Z coordinates in object space, while the X coordinate is determined by the position of the laser scanner on the beam; compare figure 3). The scan unit was only calibrated at one position on the beam. Beam deflection, the accuracy of the stepping motors, or the deviations due to the movement of the system were not accounted for. For the laser scanner DEM, presented in figure 4, a two week old calibration was used.

About 1 hour was needed for each 4 * 0.6 m² scan. Six strips were needed to cover the whole flume. They were mosaiced together to build one DEM of the soil surface after an experiment. For a common datum each strip was registered to control points (figure 2) that were measured with a total station to an accuracy of 0.3 mm.

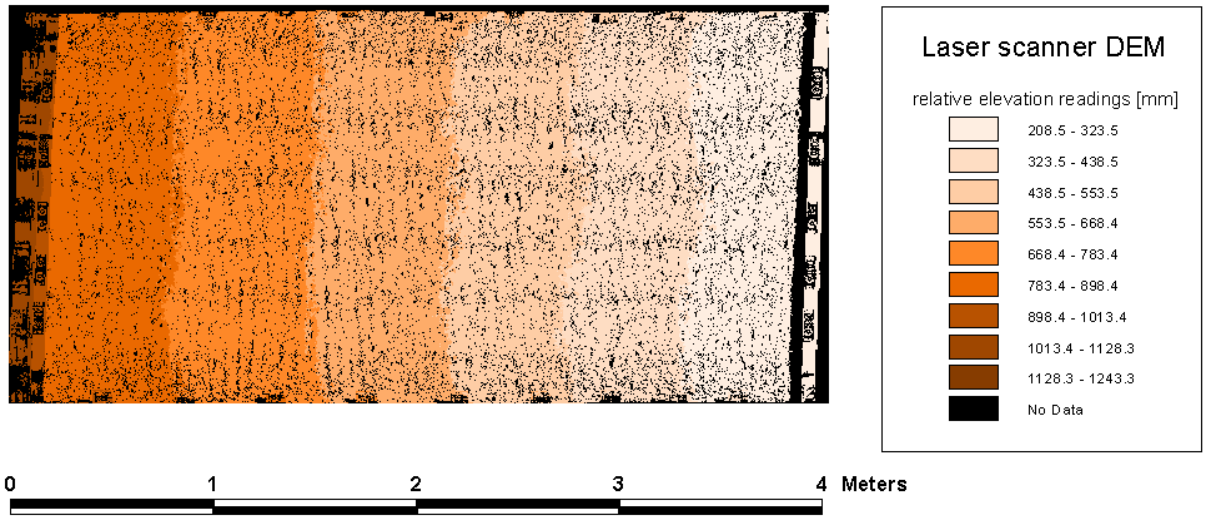

Figure 4. Laser scanner DEM. Elevation units in mm relative to individual vertical datum. While the DEM from photographs was interpolated, the laser scanner DEM was not, thus all the no data readings can be seen in the raster (continued on next page).

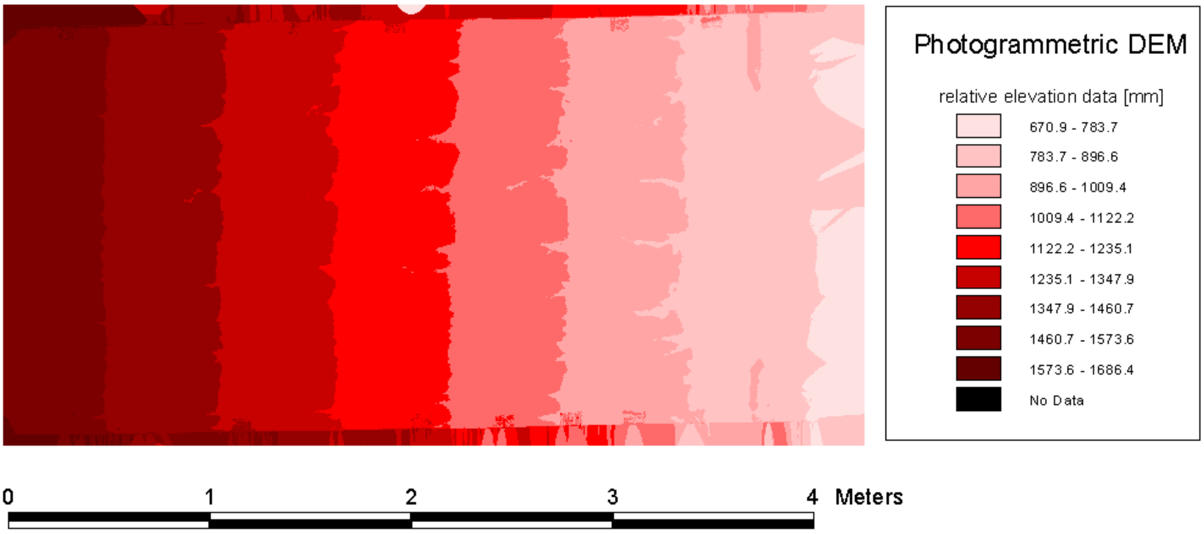

Figure 4 (continued). Laser scanner DEM. Elevation units in mm relative to individual vertical datum. While the DEM from photographs was interpolated, the laser scanner DEM was not, thus all the no data readings can be seen in the raster.

For the photogrammetric survey a Kodak DCS 1m (monochrome) with a Leica Elmarit R 19 mm lens was used (focal length multiplier due to the ratio of 35 mm film size compared to chip size is 1.3). On the basis of the well-known instable interior orientation (Maas et al. 1999), the CCD sensor (3060 x 2036 pixel; 9 * 9 µm²/pixel) was stabilized by removing it from the Kodak camera back, and attaching it to the camera body. The lens was converted to fit the camera mount of the DCS 1m, and focus stops were fitted to it. Images are stored on PCMCIA III cards. The images have a radiometric resolution of 8 Bit and require 6 MB diskspace. For coordinate measurements the software DPLX (Pollak et al. 2000) was used; the camera system was calibrated with the bundle block adjustment program BLUH (Jacobsen 2000), both programs were developed at the IPI. A three-dimensional testfield with 161 well-distributed control points known with an accuracy of 0.3 mm was used for camera calibration. Five images were taken for each calibration. A relative accuracy compared to the format of the CCD of 1: 35,000 (σ_0 of the block adjustment was 0.8 µm) was accomplished. It was not practical to calibrate the camera simultaneously on the box due to the experimental set up. Therefore, the camera was calibrated in two steps. In the first step the camera was calibrated to determine the interior orientation and additional parameters accounting for systematic image errors using the testfield. Then, a strip of 7 vertical images with 60% forward overlap at an average scale of 1:88 of the box was taken. Tie points were manually measured on the soil surface in the images and a second calibration only with additional parameters was carried out with BLUH, after applying the first calibration for initial correction of systematic image errors. The relative accuracy accomplished within the box was about 1:12,000 (σ_0 = 2.6 µm); conjugate points could only be identified in 3 images at the most. The time needed for image acquisition was about 10 min. The same control points that were utilized for the registration of the laser scanner data were used to establish the exterior orientation of the images. Target points were located only around the flume edges to avoid disturbance of the soil. DPCOR (IPI Hanover) software was used for the matching of conjugate points. The program uses a least squares matching algorithm. The user can identify up to 49 pairs of homologous points in both images as start points. The algorithm follows the region growing principle (Heipke and Kornus 1993; Otto 1989) to match conjugate points in stereo image pairs. Matching was carried out in image space, no orientation parameters are required. A pixel matrix in the left scene is compared to a matrix of pixels in the right scene by means of a local 6 parameter affine transformation after adjusting for contrast and brightness differences. A least squares adjustment leads to sub pixel accuracy for the matched coordinates. Object coordinates of matched points were imported into ArcView GIS and a regular raster surface with cell size of 3 * 3 mm² was interpolated.

Analysis

Figure 4 shows two DEM of a soil surface after experiments. One model was generated from photo and one from laser scanner data. While the photo-based grid was interpolated from the object coordinates, the laser grid still includes no data readings where the laser line could not be detected. In these areas the laser line was not visible to the camera. Especially deep and narrow rills cannot be detected by the laser scanner technique. About 18 % of the laser DEM shows no data readings. The individual strips are registered applying target point information and when mosaiced to one DEM that covers the whole flume. The photogrammetric technique is less affected by obstructed areas (10 % no data for the whole model).

The object of interest was the soil surface. No points were known with their absolute accuracy on the surface, thus making an absolute comparison of the laser scanner to the photogrammetric technique difficult. To overcome this, and to have at least a relative measure of the accuracies within the DEM, overlapping areas of photogrammetric stereo models and overlapping areas of laser scanner strips were compared. For this purpose adjacent laser scanner strips were registered on each other using a 6 parameter affine transformation. 4 corresponding target points in two strips were measured and the six parameters of the transformation were calculated by a least squares adjustment. The results for the individual transformations are given in table 1.

Table 1. Registration of laser scanner strips.

Strip #	σ_z [mm]	max. deviation [mm]	MSE of transformation parameters	
			x-direction	y-direction
1-2	2.53	22.24	0.367	0.380
2-3	2.45	21.57	0.384	0.017
3-4	2.73	23.24	0.373	0.125
4-5	2.72	18.52	0.375	0.0
5-6	2.47	20.89	0.001	0.0
average	2.55	21.29		

The standard deviation in Z varied between 2.35 mm, and 2.73 mm. Since the strips were scanned parallel to each other, this deviation does not account for any beam deflection, or scale errors along track that were also not accounted for during calibration. Calibration was done about 10 days before the experiment. Comparing two laser scanner strips that used a 5 week old calibration a deviation in Z of 33 mm was found, clearly indicating that calibration should be done more thoroughly, and more often.

The photogrammetric DEM in figure 4 was interpolated from about 4,5 million points by the means of an inverse distance weighted interpolation technique with 4 neighbors. Object coordinates of points in the overlapping areas were compared with PIDENT a program of the BLUH system. Points with a maximum position difference of 0.4 mm (half the distance covered by a pixel on the ground) were assumed to represent the same location in overlapping models. If there was more than one hit in that area the nearest point was used. The results are presented in table 2.

Table 2. Deviations in areas of overlapping photogrammetric model.

Models	σ_z [mm]	max deviation [mm]
12-23	n/a*	n/a*
23-34	2.86	18.24
34-45	1.51	26.78
45-56	1.32	59.62
56-67	1.13	24.17
average	1.705	32.20

**overlapping area does not cover soil surface*

Deviations in the overlapping areas vary between 1.13 mm and 2.86 mm. Figure 5 shows a hillshading model of the photogrammetric DEM in figure 4 in the background, one can clearly identify where rills have developed. Comparing the deviations in areas of overlapping models, one can see that in downslope direction (left to right in figure 4; model 56 is furthest to the left, model 12 furthest to the right) where more rills cut into the surface, the deviations increase in the overlapping areas.

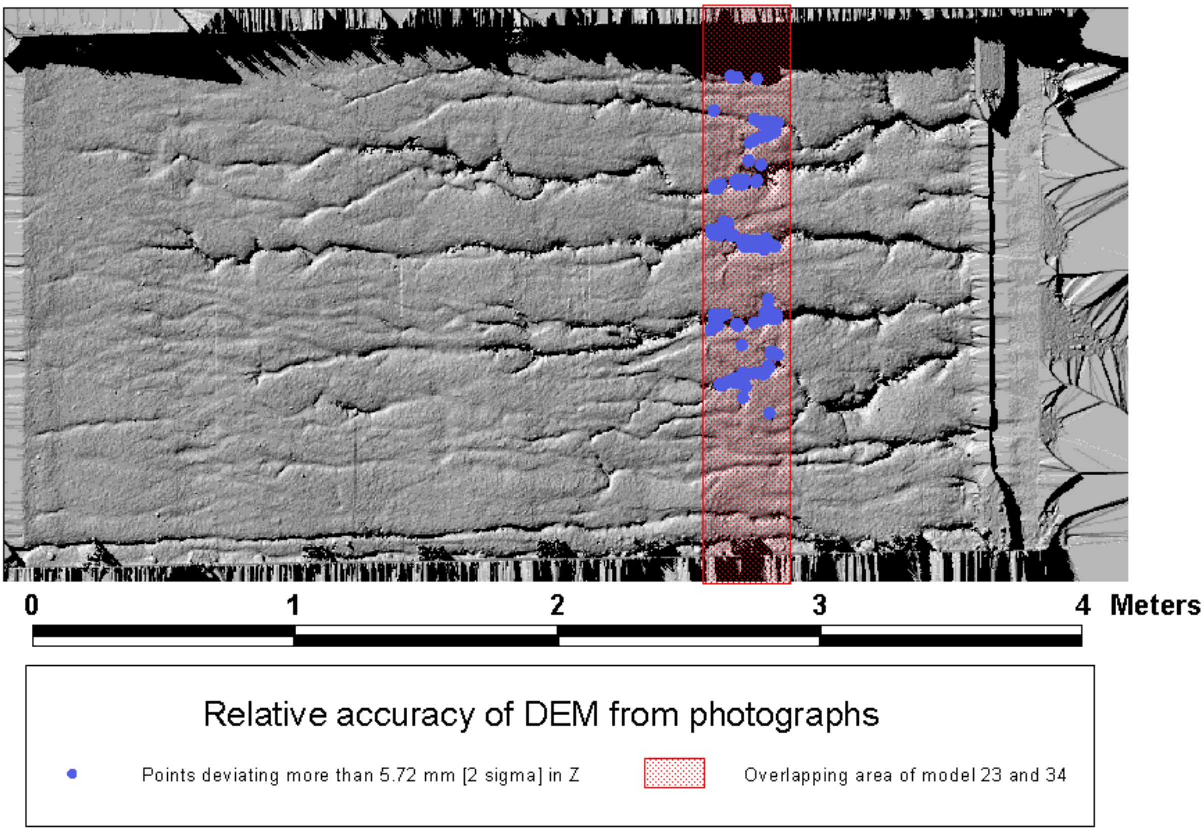

Figure 5. Shown is the overlapping area of model 23 and 34. Points deviating more than 2 σ are plotted on a hillshading model of the DEM to emphasize rills. Deviationd occur mostly in rill areas.

The photogrammetric technique matches many more points within rills than the laser scanner does. At the same time mismatches happen especially in rill areas. Figure 5 presents all the points that deviate more than 2 standard deviations (5.72 mm) from the mean in the overlapping area of models 23 and 34. Almost all of those points are found in rill areas. Eliminating those points from the statistical analysis leads to a standard deviation in Z of only 1.31 mm compared to 2.86 mm including the mismatches (about 1 % of all points identified by PIDENT deviated by more than 2 standard deviation). The maximum absolute deviations are larger for the photogrammetric technique, but represent extreme outlier. Such mismatches can be reduced by setting stricter parameter limits for the matching procedure, Although adjusting the boundary limits of matching parameters reduces the number of points successfully matched within rills, and this may affect the analysis of the DEM later on. An acceptable project dependent balance has to be found.

Conclusion

Considering the fact that both methods were used to generate DEM of a highly erodible soil surface, with a steep slope, and after simulating extreme rainfall events that formed deep and narrow rills, the results are good enough for further analysis of the microrelief. The photogrammetric technique is less affected by obstruction because the camera is pointing vertically down on the surface; thus more points inside rills can be detected. Mismatches occurred, but did not affect the overall performance significantly as compared to the laser scanner technique. A simultaneous calibration on the soil box would improve results. The relative accuracy of the photogrammetric technique was superior to the laser scanner technique. For the laser scanner beam deflection, the movement of the system during scans, and the accuracy of the stepping motor are not included in the calibration and could lead to significant additional deviations on an absolute scale. Calibration should be done more thoroughly and more often for the laser scanner. For the photogrammetric technique only 10 minutes were needed for data acquisition, covering an area of about 8 m². The temporal resolution of DEM generation was significantly improved. The camera can be easily transported and large areas can be captured for DEM generation. At the same time relative accuracy was better than for the laser scanner. The resolution matched the resolution of the laser scanner.

Digital close-range photogrammetry is a very useful technique for DEM generation of soil surfaces. Improving computer hardware, and larger imagers will make this technique even faster and more efficient in the future. The use of a multi-image matching technique, and additional constraints like information of epipolar geometry might be implemented for better accuracies and faster matching. The versatility of the system was appreciated and it will be used for further research projects inside the laboratory and for field experiments.

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