Evaluation of digital terrain models derived from data collected with RTK-GPS based automatic steering systems using a high precision laser scanner

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Abstract

RTK-GPS receivers on tractors and combine harvesters are being introduced with automated steering systems. The position and height data provided by these systems is very accurate and can be collected in the field for the computation of digital terrain models (DTM) at very low or no additional cost. Digital terrain models allow deriving secondary terrain information such as slope and aspect which then may be combined with soil information and measured or predicted precipitation for optimising the management of crops with respect to economic and ecological aspects. It is important to understand the accuracy and reliability of DTM derived from RTK-GPS data in order to adequately apply this information when modelling surface runoff, interflow, plant available water capacity and the influence of slope and aspect on global radiation and the local microclimate. Data collected with a high-precision laser system and a RTK-GPS based automated steering system recorded during subsequent operations has been investigated. The focus was to evaluate the accuracy of height measurements from RTK-GPS receivers and to better understand the impact of different interpolation methods on the resulting DTM. The results indicate that the accuracies, with respect to standard deviations, of the digital terrain models obtained from RTK-GPS data were in the same range as the standard deviations between different digital terrain models from laser data created with different interpolation methods. The initially required accuracy of better than 25 cm for modelling surface runoff can be well obtained when using RTK-GPS data collected during field operations such as sowing and tillage.

Keywords: DTM, RTK-GPS, laser

Introduction

Plant available water is the limiting factor for plant growth in many parts of Europe. All applications, especially seeding density and fertilizer application should therefore account for the availability of water in a given time period and within management zones which have been defined at the sub-field level.

The Geostep project (www.geostep.org) aims to develop models that allow the availability of water at sub-field scale to be estimated. The model predicts the microclimate based on a global circulation model and data from local weather stations. Soil information is derived from remote sensing data acquired during specific levels of plant development. Remote sensing is being used to determine the surface temperature which correlates to plant assimilation. The degree of assimilation is again closely related to the amount of plant available water in the root zone.

Predicting the local micro-climate as well as modelling surface runoff and interflow relies on accurate information on slope and aspect. Both parameters can be derived from digital terrain models.

Schmidt (2003) proved that height measurements from RTK-GPS are usable for creating digital terrain models and that these digital terrain models are usable to derive the above parameters.
With the growing use of automated steering systems in crop production, highly accurate GPS position data from dual frequency GPS receivers can be obtained during field operations at no or very low cost. Most navigation controllers feature a sensor fusion concept using gyroscopes, accelerometers and GPS data in order to compensate for roll, pitch and yaw of the tractor. Therefore the resulting height measurements are even more reliable than those obtained with GPS sensors only (Westphalen *et al.*, 2004).
In order to evaluate the reliablity and accuracy of height measurements provided by automated steering systems several field trials have been undertaken with data from a 3D laser scanning system being used as a reference.

Materials and methods

The field under investigation, covering 27.5 ha, is located in Bavaria, Germany. Data have been collected during tillage and sowing operations between October 24 and October 26, 2006.

Instrumentation

A Trimble AgGPS RTK Autopilot system steered an Agco Challenger MT 765 tracked tractor was steering the tractor during all operations. The system consists of a GPS receiver, a navigation controller, a CAN bus interface to the tractor's steering controller and a display unit. A Gregoire-Besson Discodent disk harrow with 4.35 m working width has was for tilling. The average speed was 10 km/h. Winter wheat was sown shortly after tilling using a 6 m Vaederstadt Rapid seeder at an average speed of 14 km/h.
Position and height data as well GPS quality parameters (number of satellites, DOP, correction status) were logged at 0.2 Hz on a Trimble AgGPS Fieldmanager Display in ESRI Shape file format. The Fieldmanager Display was connected to a Trimble AgGPS Navigation Controller (Generation II) integrating three gyroscopes and three accelerometers and thereby accounting for pitch, roll and yaw of the vehicle. The navigation controller was supplied with position data from a Trimble AgGPS 252 RTK receiver. RTK corrections were transmitted with a VHF radio from a Trimble MS 750 receiver from a building less than 1 km from the edge of the field. The GPS receiver is specified to determine its position with an accuarcy of 2.5 cm.
About two weeks after sowing, the field was scanned with an Optech Ilris 3 D Laser scanner (http://www.optech.ca/i3dtechoverview-ilris.htm). The system is specified to measure distances at 7 mm and relative position at 8 mm accuracy. Data was collected from 10 different locations around the field with a density of 18 cm in 400 m distance. Overall, 12.4 million positions with relative x, y and z co-ordinates were logged during two subsequent days.

Data processing

The RTK-GPS data was stored on a CF Card on a FieldManager Display in ESRI Shape file format. All relevant data (position, height, GPS quality parameters) were contained in the attribute table (dBase file). dBase files from different jobs were merged and imported into a MS Access database table. During sowing 3,653 data points were recorded. Data logging during tillage produced 6,039 data points.The data was filtered by applying an SQL query based on the following criteria:
- correction status = 4 (RTK fix);
- DOP < 3;
- number of satellites > 4.

2.5% or 91 record sets were filtered from the data collected during sowing, 1.3% or 77 record sets were removed from the data recorded during tillage operations. Filtered and merged RTK-GPS raw data were exported into single dBase files for further analysis.

The ten laser data sets were aligned and georeferenced using static RTK-GPS measurements of the different laser locations. Data outside the field was clipped and data density was reduced to 11% (668,525 data points).

All steps described above were performed with the Polyworks IM Align module (http://www.innovmetric.com/Manufacturing/what_inspector.aspx).

Data analysis

Four RTK-GPS data sets (sowing and tilling, both raw and filtered) and the laser data set were exported from the respective data sources into either dBase or ASCII files. In the following, all data files were imported into SAGA GIS (http://www.saga-gis.org) software (Conrad, 2006) for the creation of grid files with different interpolation methods.

Grids with a raster cell size of 2.5 m were created from RTK-GPS data using inverse distance interpolation (power: 1.5, search radius: 25 m, maximum number of points: 10) and multi-level B-spline Interpolation with B-spline refinement as suggested by Lee *et al.* (1997). The ten grid entities (5 data sets, 2 interpolation methods) were spatially joined and all datasets without missing values were exported into one single ASCII file containing the position of the grid cells as well as all grid values.

The resulting file was imported into R (R Development Core Team, 2006) for further statistical analysis. Mean differences as well as the standard deviation of grid differences have been calculated for all pairs of grid data.

Results

Table 1 shows the grid differences for all pairs of grids. The mean difference between the grids created from laser data with inverse distance (IDW) and multi-level B-splines (MBS) is 0 whereas the difference between grids from laser data and grids from RTK-GPS data ranges from 2.91 to 3.08

Table 1. Mean difference between grid values of 2.5 m grids calculated from laser data and RTK-GPS data obtained during tillage and sowing operations using multi-level B-spline algorithm and inverse distance to a power.

	ZI	ZS	SIR	SIF	TIR	TIF	SSR	SSF	TSR
ZS	0.00		-3.08	-3.08	-2.92	-3.08	-3.08	-3.08	-2.92
SIR	-3.08	-3.08		0.00	0.17	0.01	0.00	0.00	0.16
SIF	-3.08	-3.08	0.00		0.17	0.01	0.00	0.00	0.17
TIR	-2.91	-2.92	0.17	0.17		-0.16	-0.16	-0.17	0.00
TIF	-3.07	-3.08	0.01	0.01	-0.16		0.00	-0.01	0.16
SSR	-3.08	-3.08	0.00	0.00	-0.16	0.00		0.00	0.16
SSF	-3.08	-3.08	0.00	0.00	-0.17	-0.01	0.00		0.16
TSR	-2.92	-2.92	0.16	0.17	0.00	0.16	0.16	0.16	
TSF	-3.06	-3.06	0.02	0.02	-0.14	0.02	0.02	0.02	-0.14
∅	-3.03	-3.04	0.05	0.05	-0.04	0.00	0.00	0.00	0.10

Annotation:

Z. Laser data
S.. RTK-GPS data collected during sowing
T.. RTK-GPS data collected during tillage
∅ mean

.I. Inverse Distance Interpolation
S. Multilevel B-Spline Interpolation
R Raw RTK-GPS data
F Filtered RTK-GPS data

m (mean 3.03. m). This indicates a systematic offset between the laser grids and the data collected with RTK-GPS system on the tractor.
Comparing the difference between grids derived from laser data and RTK-GPS data a substantial deviation can be observed for those grids which have been interpolated from raw data during tillage operations. This is mainly due to some data points recorded during tillage with low GPS quality and/or missing or erroneous height values. The mean differences between all other grids created from laser data and RTK-GPS data are very much on the same level with very little deviation (range 3.06 to 3.08 m).
The mean differences between grids created from RTK-GPS data also show a very small deviation (range 0.00 to 0.02 m) when excluding raw data collected during tillage. The mean difference between the latter grids and all other grids generated from RTK-GPS data is between 0.14 and 0.17 m. The difference between the two grids created from the same data set (tillage, raw) using two different interpolation methods again is zero / very small (0.00 m).
The standard deviation of differences between grid cell values is summarized in Table 2. Looking at the standard deviations between grids created from laser data and RTK-GPS data, it is apparent that the values differ most for grids from raw RTK-GPS data collected during tillage operations. However, the standard deviations differ about 60% (3.85 m, 6.46 m) when comparing differences of grids calculated with IDW and MBS. It seems that MBS is more sensitive when interpolating datasets containing erroneous measurements.

Table 2. Standard deviation of differences between grid values of 2.5 m grids calculated from laser data and RTK-GPS data obtained during tillage and sowing operations using multi-level B-spline algorithm and inverse distance to a power (see annotation in Table 1 for acronyms).

	ZI	ZS	SIR	SIF	TIR	TIF	SSR	SSF	TSR
ZS	0.08		0.22	0.20	3.85	0.20	0.24	0.20	6.46
SIR	0.20	0.22		0.05	3.84	0.09	0.06	0.07	6.46
SIF	0.19	0.20	0.05		3.84	0.07	0.10	0.05	6.46
TIR	3.85	3.85	3.84	3.84		3.84	3.84	3.84	3.36
TIF	0.19	0.20	0.09	0.07	3.84		0.12	0.08	6.46
SSR	0.23	0.24	0.06	0.10	3.84	0.12		0.09	6.46
SSF	0.19	0.20	0.07	0.05	3.84	0.08	0.09		6.46
TSR	6.46	6.46	6.46	6.46	3.36	6.46	6.46	6.46	
TSF	0.25	0.25	0.18	0.17	3.84	0.12	0.20	0.17	6.46
Operation									
Ø S..	0.20	0.21	0.06	0.07	3.84	0.09	0.08	0.07	6.46
Ø T..	2.69	2.69	2.65	2.64	3.68	3.48	2.66	2.64	5.43
Interpolation									
Ø .I.	1.11	1.12	1.33	1.32	3.84	1.33	1.03	1.01	5.69
Ø .S.	1.78	1.79	1.69	1.70	3.72	1.70	2.25	2.24	6.46
Filter									
Ø ..F	0.20	0.21	0.10	0.10	3.84	0.09	0.13	0.10	6.46
Ø ..R	2.69	2.69	3.46	2.61	3.68	2.63	3.46	2.61	5.43

The standard deviation of differences between grids created from laser data applying IDW and MBS is 0.08 m whereas the standard deviation of differences between grids generated from laser and RTK-GPS data is in the range of 0.19 to 0.25 m (excluding RTK-GPS data collected during tilling). So the standard deviation between grids from RTK-GPS data and laser data is about two to threefold larger.
The standard deviation of grid value differences between grids created with RTK-GPS data ranges between 0.05 and 0.20 m when excluding the grids created from raw RTK-GPS data during tillage. The standard deviation between grids created from RTK-GPS data collected during sowing and tillage (filtered, IDW, 0.07 m) is even lower than the standard deviation between grids generated from laser data with different interpolation methods (0.08 m). The standard deviation between grids created from the same RTK-GPS data set (sowing, filtered) with different interpolation methods (0.06 m) also falls below the standard deviation of differences between the laser data grids calculated with IDW and MBS.
When grouped by operation, the RTK-GPS data recorded during sowing operations is clearly superior with respect to standard deviation to the data collected during tillage. The standard deviations for the latter datasets is 10- to 20-fold higher. It has been discussed above that this is due to some erroneous GPS measurements during the tillage operation. When comparing the standard deviations grouped by interpolation method the grids derived from filtered data are clearly superior to the grids created from raw RTK-GPS data with respect to standard deviation. The erroneous data collected during tillage operations obviously has a strong effect on the comparison of the interpolation methods. When only comparing single value pairs which are not affected the by these measurements (difference between filtered data from sowing and tillage operations) it becomes clear that the standard deviation of grid differences still substantially differs depending on the interpolation method (Table 2: SIF-TIF 0.07 m, SSF-TSF 0.17 m). This difference is most probably due to spline interpolation producing odd results at the edges of datasets (see also Figure 1b, western edge).
Arranging the standard deviations of grid differences by filter status clearly reveals that the standard deviations are substantially reduced by filtering. The standard deviation of grid differences is reduced by a factor of more than 10. The standard deviation of grid differences from laser and filtered RTK-GPS data is 0.20 m. The standard deviation of grid differences between grids created from filtered RTK-GPS data is in the range of 0.09 m to 0.13 m.
Figure 1 shows a set of grid difference maps. The classification has been chosen to show deviations of less than 0.20 m, less than 0.50 m and more than 0.50 m. Figure 1a shows the difference map for filtered RTK-GPS data collected using sowing and tillage interpolated with IDW. In the centre of the field and at the northern and southern edges, the deviations are generally less than 0.20 m. Higher deviations (0.20 to 0.50 m) are only observed at the western edges and at small parts of the eastern edge. This means that the standard deviation of grid differences between these grids (0.07 m) is not due to noise equally distributed over the whole area covered with data but at least partially caused by high deviations at the edge of the field.
Figure 1b shows the difference between grids created with IDW and MBS from filtered RTK-GPS data collected during sowing. The value of all grid cells differs less than 0.20 m except parts at the eastern edge. This may be due to spline interpolation producing odd estimates at the edge of datasets.
The differences between grid cells calculated from laser data interpolated with IDW and filtered RTK-GPS data during sowing is shown in Figure 1c. Apart from artifacts at the edge of the field which have been observed in all grid difference maps described above, higher differences (0.20 m to 0.50 m) are scattered across the eastern and southern parts of the field. The concentric distribution indicates that these deviations are more likely due to biased laser measurements than due to errors in the RTK-GPS data which has been collected in north-south direction. Hence, part of the standard

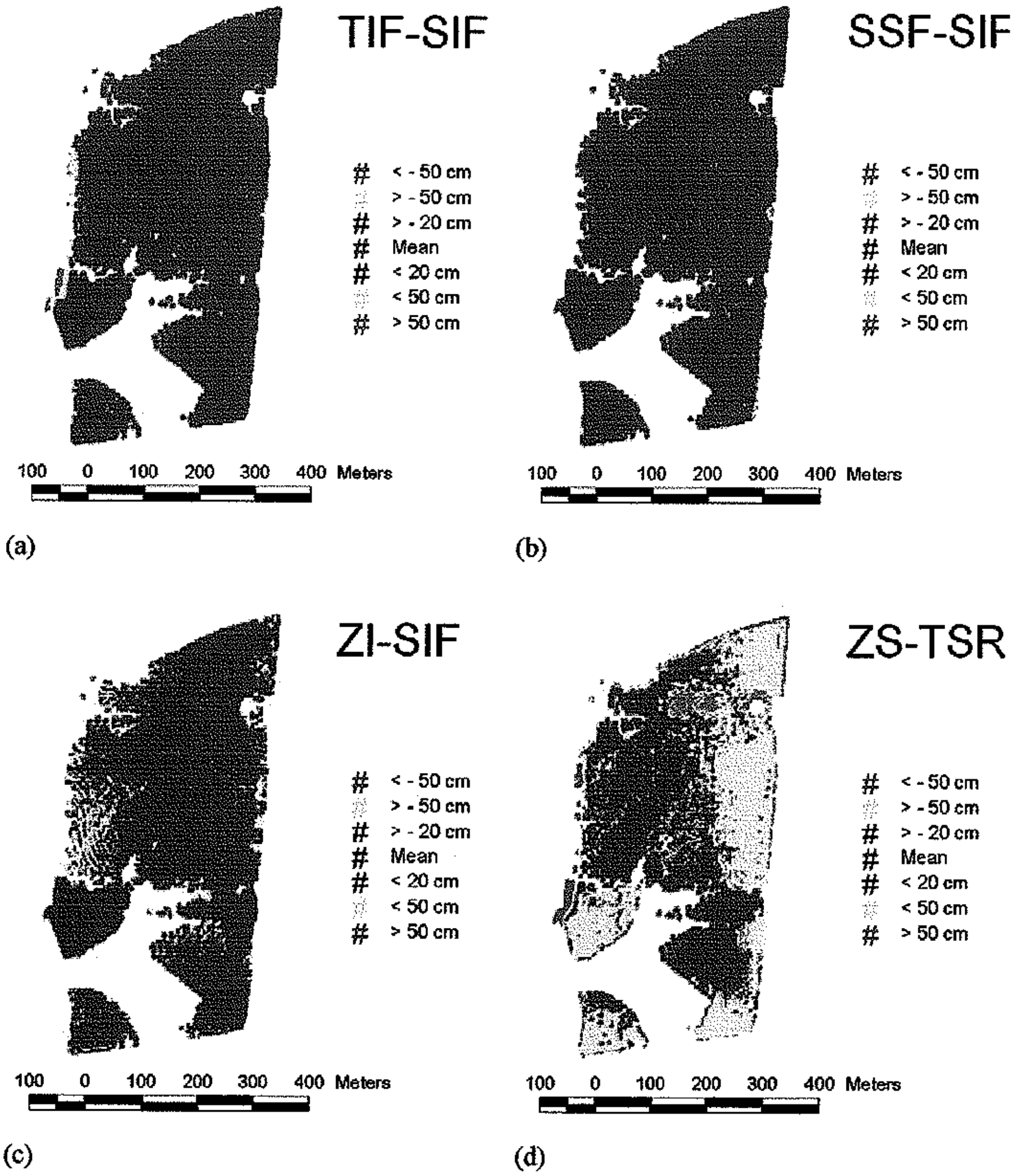

Figure 1. Grid difference maps: (a) Tillage vs. sowing, both inverse distance from filtered GPS data, (b) B-spline vs. inverse distance, both RTK data collected during sowing, (c) Laser vs. GPS (both inverse distance, GPS data from sowing, filtered), (d) Laser vs. GPS (both B-spline, GPS data from tillage, raw).

deviation between laser data and RTK-GPS data can be explained by erroneous laser measurements rather than inaccurate RTK-GPS height measurements.

Figure 1d shows the differences between the grids created from laser data and raw RTK-GPS data collected during tillage using MBS interpolation. Large deviations of more than 0.50 m are found at the edges of the field. Also two spots in the central northern region contain grids were the difference is larger than 0.50 m. Large areas with grid differences of 0.20 m to 0.50 m are covering the eastern and southern part of the field. The map emphasizes the importance of filtering for creating suitable digital terrain models from RTK-GPS data. When comparing this map with a map of differences between the same datasets interpolated with IDW (not shown) it is clear that the spline interpolation of datasets with erroneous values results in larger grid deviations than interpolation with IDW. This is especially the case for grids on the edge of an area.

Discussion

The mean offset observed between laser data and RTK-GPS data is not relevant for the application in focus. Modelling surface runoff and exposition of plants does not depend on absolute but on relative height measurements (see also Schmidt, 2003).
The deviation between grid cell values derived from laser and RTK-GPS data was mainly due to GPS positions logged with low GPS quality (no corrections, low number of satellites, poor satellite geometry). Filtering RTK-GPS data with a simple quality filter vastly improved the consistency of digital terrain models when comparing grid values from laser data and RTK-GPS data. It can be safely assumed that the standard deviation of differences between grids created from laser data and RTK-GPS data is partially influenced by erroneous laser measurements far off the laser location (concentric patterns in difference maps).
Taking into account the errors inherent in the data collected with the reference system, the standard deviations observed in this trial match with the results obtained in similar scenarios by Clark and Lee (1998) and Westphalen *et al.* (2004). It is noteworthy that the standard deviations between the digital terrain models derived from RTK-GPS data on different occasions are lower than the deviation between these datasets and the terrain models derived from laser data. Hence, the repeatability or long-time accuracy of height measurements obtained with RTK-GPS appears to be in the same range as the accuracy of the reference system used in this trial and seems to be appropriate for deriving secondary terrain parameters such as slope and aspect for the intended use in the Geostep project.
Several authors (Saraswat *et al.*, 2003; Schmidt *et al.*, 2003) have discussed the potential use of L1-DGPS data collected during field operations such as sowing and tillage as well as GPS height measurements obtained while collecting yield data for creating digital terrain models. The results indicate that height data collected during a single operation will deviate 1 m or more from the true height. Using data collected during different operations over the year decreased the RMSE error to approx. 0.30 to 0.40 m. This accuracy is not considered to be acceptable.
After more height data has been collected with RTK-GPS systems on different fields during subsequent operations in different years, further analysis should reveal the long term repeatability of height measurements obtained from RTK-GPS receivers.
It is also being considered to conduct trials where RTK-GPS position data is not only logged after the positions have been corrected for pitch, roll and yaw by a navigation controller but to also to collect data where these factors have not been accounted for. In parallel, data will be sourced directly from the RTK-GPS receiver supplying position information to the navigation controller in order to understand in which respect roll, pitch and yaw compensation helps to improve the accuracy of digital terrain models. Position data from a DGPS receiver will also be logged in parallel in order to be sure that the accuracy of height data from L1-DGPS receivers does match the needs defined within the Geostep project.

Conclusions

First results of the investigation of the accuracy of digital terrain models obtained from RTK-GPS data indicate that the accuracy specified for the estimation of secondary terrain parameters within the Geostep project (0.25 m) was well achieved. The accuracy was only maintained when data was filtered based on GPS quality indicators such as correction status, number of satellites and satellite geometry. Applying a filter for eliminating outliers may help to further improve the accuracy of digital terrain models.

A high precision laser system was found to be not accurate enough under the given circumstances (long range measurements at low angles) for benchmarking digital terrain models created from RTK-GPS data. The standard deviation of differences between two digital terrain models created from RTK-GPS datasets collected on different occasions was less than the standard deviation of differences between the two datasets and a digital terrain model derived from laser data.

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