Monitoring the planarity and subsidence of a motorway using kinematic laser scanning

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ABSTRACT

Mobile Mapping is extensively used for the fast and accurate acquisition of the transportation infrastructure. Regarding this, the inspection of the road surface is important, because deficiencies caused by non-planarity and subsidence pose a risk to the traffic. Recently, a scan-based Mobile Mapping System (MMS) has been developed at the University of Bonn. The goal of this paper is to evaluate this MMS, where the height component is of main interest. Following this, the applicability of the MMS for monitoring the planarity and subsidence of road surfaces is investigated. The test area is a 6 km long section of the A44n motorway in Germany. For the evaluation of the MMS, leveled control points along the motorway were utilized. The control points are provided with physical heights, thus, undulations from a geoid model were used for the transformation of the ellipsoidal heights of the MMS. Moreover, a tilt correction for the geoid was determined based on GNSS measurements and leveling. This correction improves the accuracy of the MMS by 40 %, leading to physical heights with an accuracy of < 10 mm (route mean square error). The height precision of the MMS was found to be 5 mm (standard deviation). As a result, a potential subsidence of the road surface in the order of a few cm is detectable. In addition, the cross fall of the motorway was extracted from the point clouds describing the planarity of the road surface. In this respect, no deficiencies of the motorway were detected.

I. INTRODUCTION

An intact road infrastructure is crucial for a modern society. In this context, highways and motorways play an important role, because great quantities of freights are transported via these traffic routes every day. For instance, in 2016, almost 2.5 trillion tonne-kilometers of freights were transported overland in the European Union. In this respect, road transport, at 72.8 %, was the largest contributor (European Commission, 2018). This volume of traffic exposes the roads to enormous loads, damaging the road surface in the form of ruts, cracks and bumps. Especially ruts are a problem due to the risk of aquaplaning.

In addition to this, road surfaces can be affected by local subsidence caused by an unstable underground. Reasons for instabilities in the underground are, e. g., geological irregularities or deficiencies in construction. This is particularly problematical in case of abrupt or irregular subsidence leading to bumps and cracks. Furthermore, subsidence can cause depressions, again leading to the risk of aquaplaning. As a result, both loads due to traffic and environmental phenomena pose a danger to the road surface.

Therefore, the monitoring of the planarity and the subsidence of road surfaces is of great importance. Classical instruments for measuring subsidence are levels or total stations; the planarity can be measured by special devices like measuring rods, planographs and profilographs (FGSV, 2017) or laser triangulation sensors with integrated inclinometers (FGSV, 2009).

In addition to this, Mobile Mapping has widely been used for the acquisition of the road infrastructure in recent years. The applications range from inventories to challenging tasks like road monitoring. However, in contrast to classical measuring techniques, typically poorer accuracies can be reached. But the advantage of Mobile Mapping is that the acquisition of road corridors can be accomplished much faster and with higher temporal and spatial resolution. Moreover, the condition of the road can be analyzed in more detail and on a bigger scale.

In recent years, a Mobile Mapping System has also been developed at the University of Bonn, consisting of a high-quality GNSS/IMU unit and a high-speed 2D laser scanner (Heinz *et al.*, 2017). Applying commercial and customized sensor components, the system setup was built in-house, hence, providing full access to all components. The system is calibrated in a proprietary plane-based calibration field. The trajectory estimation is performed using a Kalman filter toolbox developed at the Univsersity of Bonn, soley utilizing observations from RTK-GNSS and the inertial sensors. No control points or loop closures are required. Nevertheless, the tests within this work demonstrate that high-quality georeferenced point clouds are obtained.

In the light of this, the goal of this paper is twofold: Initially, an evaluation of the precision and accuracy of the Mobile Mapping System is performed. The focus of this investigation is on the height component. On the basis of this and as motivated in the beginning of this paper, the applicability of the Mobile Mapping System for monitoring the planarity and subsidence of road surfaces is studied at the A44n motorway in Germany. In this respect, the quality of the height component is important. In this context, several research questions arise that are addressed in this paper:

- How precise is the Mobile Mapping System when measuring the road surface multiple times? This is important for monitoring a possible subsidence of the road surface in two epochs.
- How accurate can physical heights be determined from the point clouds when utilizing undulations from a geoid model? This is of interest when comparing or combining the results with other measuring techniques, e. g., leveling.
- In which order of magnitude potential subsidence of the road surface can be detected applying the Mobile Mapping System?
- How accurate can descriptive parameters for the planarity of the road surface be extracted from the point clouds, e. g., cross fall?

This paper is organized as follows: Section II surveys the related literature. Sections III and IV describe the test area and the measurements. Section V discusses details on data analysis. The results are presented in Section VI. A conclusion is drawn in Section VII.

II. Mobile Mapping for Applications in Transportation Infrastructure

As introduced, Mobile Mapping is utilized for many applications in transportation infrastructure. Reviews can be found in, e. g., Williams *et al.*, 2013 or Guan *et al.,* 2016. A common application of Mobile Mapping is the acquisition of buildings and road furniture for inventories. Objects of interest are, e. g., curbs and road markings (Yao *et al.*, 2018) or pole-like objects such as road signs, traffic lights and trees (Li *et al.*, 2018). In addition to this, safety-relevant applications can also be solved by Mobile Mapping. This includes the measuring of clearances for power lines, bridges and tunnels (Gräfe, 2007; Mikrut *et al.*, 2016).

This paper addresses the monitoring of the road surface and the determination of descriptive road parameters from the point clouds. Also for this, examples from the field of Mobile Mapping can be found, generating digital road surface models (Gräfe, 2007), detecting cracks, ruts or potholes (Miraliakbari *et al.*, 2014), measuring cross fall and longitudinal slope (Wang *et al.*, 2017), evaluating the drainage conditions of the road surface (Lantieri *et al.*, 2015) or determining descriptive parameters for the planarity of the road surface (Reiterer *et al.*, 2013).

In Germany, the Road and Transportation Research Association (FGSV) officially regulates the inspection of the planarity of road surfaces using optical instruments by a technical guideline (FGSV, 2009). This guideline regulates the preparation, execution, processing and quality assurance of the measurements and results, including tolerances for accuracy and repeatability. These tolerances are in the mm to sub-mm range and, thus, quite challenging. According to the guideline, the inspection of the planarity of road surfaces in cross direction has to be carried out by means of a special measuring rod equipped with laser triangulation sensors. The measuring rod is attached to a vehicle in such a way that the sensors are mounted a few cm above the road surface. Simultaneously, the inclination in the cross direction is measured by an inclinometer. Different measuring principles are permitted if their equivalence has officially been proven.

The measuring system as described in the guideline (FGSV, 2009) does not correspond to classical Mobile Mapping. However, Reiterer *et al.*, 2013 demonstrate that the requirements of the FGSV can also be met by a Mobile Mapping System consisting of georeferencing sensors (GNSS, IMU, odometer) as well as a specialized 2D laser scanner purpose-built for this application.

The investigations of this paper are oriented towards the FGSV guidelines (FGSV, 2009) with respect to data processing and calculation of descriptive parameters for the planarity of the road surface. The focus is on the calculation of the cross fall. However, it is explicitly emphasized that the results of this paper are not an official road inspection according the FGSV guidelines. For this purpose, an evaluation of the Mobile Mapping System on a test track against a reference system is required (FGSV, 2009). It is clear even without such an evaluation that our Mobile Mapping System does not meet all requirements of the FGSV. For instance, the accuracy of the 2D laser scanner is the range of a few mm and, thus, above the required accuracy of some tenth of a mm.

III. Test Area

According to Section II, kinematic laser scanning is a very promising technology for the monitoring of road surfaces. In order to examine this in more detail, a measurement campaign was carried out on a 6 km long section of the A44n motorway in Germany, which was newly built between 2012 and 2018 (Figure 1). The investigated section of the motorway is located approximately 35 km northwest from the city of Cologne and was opened for traffic in July 2018. The measurements were performed in December 2017 and, thus, without any interference by moving traffic. However, in some parts of the motorway construction site operations were in progress.

Figure 1. Investigated section of the A44n motorway in North Rhine-Westphalia, Germany (Source: GoogleMaps).

IV. Measurement Campaign

The measurement campaign can be subdivided into three main steps, which are discussed in more detail in the following, i. e.:

- installation of control points for the evaluation of the Mobile Mapping System
- static GNSS measurements as well as leveling for analyzing the undulations between the ellipsoidal and physical heights in the test area
- kinematic acquisition of the road surface using the Mobile Mapping System

Please note that the Mobile Mapping System provides ellipsoidal heights w. r. t. the GRS80 ellipsoid due to the use of GNSS, but the coordinates of the control points are given with physical heights in the German height system DHHN2016. Thus, undulations for the transformation between the height systems are required.

A. *Installation of Control Points*

Control points are a state-of-the-art method for the evaluation of Mobile Mapping Systems. Examples can be found in, e. g., Barber *et al.*, 2008; Kaartinen *et al.*, 2012 and Kukko *et al.*, 2012. Therefore, eight control points were marked in the road surface of the A44n motorway (Figure 2, blue circles). Four control points were installed at the roadside of each lane (western lane: 208, 220, 253, 265; eastern lane: 201, 213, 244, 258). The coordinates of the eight control points were determined using leveling and a total station. In this way, coordinates in the German reference system for both horizontal position (ETRS89/UTM) and physical height (DHHN2016) were derived, having an accuracy of 1-2 cm for the position and 1-2 mm for the height. Please note that the height is by far more important for this application. Hence, the poorer accuracy for the horizontal position is acceptable. For the evaluation of the Mobile Mapping System, the control points were signalized with targets (Figure 2).

Five additional points P1 - P5 (Figure 2, red triangles) were determined in the same way. These points were not utilized for the evaluation of the Mobile Mapping System, but serve as the basis for the analysis of the undulations between geoid and ellipsoid in the test area. Section IV.B addresses this in more detail.

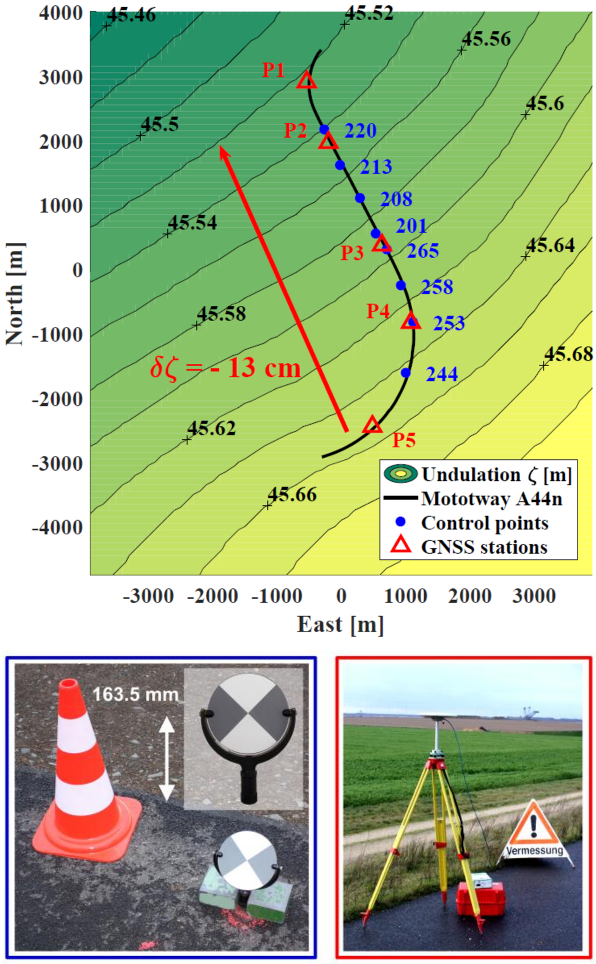

Figure 2. German Combined Quasi Geoid 2016 (GCG16) at the A44n motorway (change of undulation in northwest direction: $\delta\zeta$ = -13 cm). Five GNSS stations were set up to measure a tilt correction for the GCG16. Eight control points were installed to evaluate the Mobile Mapping System.

B. *Static GNSS Measurements and Leveling*

The coordinates of the control points as introduced in Section IV.A are given with physical heights H in the German height system DHHN2016, but the Mobile Mapping System provides ellipsoidal heights h w. r. t. the GRS80 ellipsoid due to the use of GNSS. Therefore, undulations ζ are needed in order to connect the two height systems:

$$H^{DHHN2016} = h_{GRS80} - \zeta_{\,GRS80}^{\,DHHN2016}. \tag{1}$$

In order to transform ellipsoidal heights into physical heights, the GCG16 quasi geoid model can be used (German Combined Quasi Geoid 2016), which provides undulations with an accuracy of < 1 cm in lowlands (BKG, 2017). However, the uncertainty of the GCG16 affects the evaluation of the Mobile Mapping System. Thus, an in-depth analysis of the quality of the GCG16 was carried out before performing the measurements with the Mobile Mapping System.

The connection between GRS80 ellipsoid and GCG16 quasi geoid model at the A44n motorway is mainly characterized by an offset of about 45.5 m (Figure 2). Yet, a slight inclination exists, leading to a continuous change of the undulation.

For reducing the uncertainty of the GCG16 as much as possible, static GNSS measurements and levelings were carried out at five stations P1 - P5 (Figure 2, red triangles). The physical height differences ΔH between the stations were accurately measured by leveling. In addition to this, ellipsoidal height differences Δh were determined using static GNSS measurements. Station P3 was chosen as master station and four baselines to the remaining stations were observed for 2.5 h using high-quality GNSS equipment. The antenna heights were determined by leveling with sub-mm accuracy. GPS and GLONASS carrier phase observations on two frequencies were post-processed using state-of-the-art software and techniques leading to mm accuracies.

By comparing the physical height differences ΔH with the ellipsoidal height differences Δh, the relation between ellipsoid and quasi geoid can be investigated. In this case, the comparison allows for the calculation of a tilt correction for the GCG16. However, both GNSS baselines and leveling are relative measurements. In consequence, a constant height error of the GCG16 is not detectable. In order to eliminate such a potential error, station P3 as used for the determination of the height differences was also utilized as GNSS master station for the Mobile Mapping System (Figure 3). The ellipsoidal height of station P3 was derived by adding the undulation of the GCG16 to the accurate physical height of station P3 as known from the installation of the control points. The antenna height was again determined by leveling. In this way, a constant height error of the GCG16 can be eliminated.

Please note that the undulations are only relevant for the evaluation of the Mobile Mapping System using the control points. For monitoring the subsidence of the road surface in two epochs, the undulations are irrelevant. The same applies to the inspection of the planarity of the road surface, because the variation of the undulation in small areas of up to 25 m is below 1 mm and, thus, neglectable. However, the study of the undulations and the evaluation using the control points indicate how accurate physical heights can be determined with the Mobile Mapping System. This is relevant when measurements of the Mobile Mapping System are compared with the results from different techniques such as leveling or total station.

C. *Kinematic Acquisition of the Road Surface*

The acquisition of the A44n motorway was carried out by using a Mobile Mapping System, developed at the University of Bonn (Figure 3). This system consists of commercial and customized sensor components. But the system setup was built in-house and, thus, we have full access to all system components. For the estimation of the trajectroy a navigation-grade inertial navigation system iMAR iNAV-FJI-LSURV (IMAR, 2016) is utilized, consisting of fiber-optic gyroscopes, servo accelerometers and a multi-frequency RTK-GNSS. The accuracies are specified with < 0.025° for the attitude and a few centimeters for the position. The trajectory is estimated using a Kalman Filter toolbox developed in-house at the University of Bonn and soley using observations from RTK-GNSS and the inertial sensors. Control points or lopp closures are not required. Nevertheless, the tests within this work prove that high-quality georeferenced point clouds are obtained.

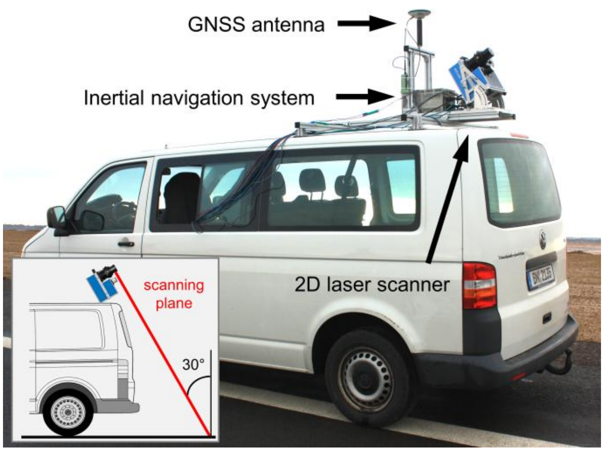

Figure 3. Mobile Mapping System for the acquisition of the road surface of the A44n motorway.

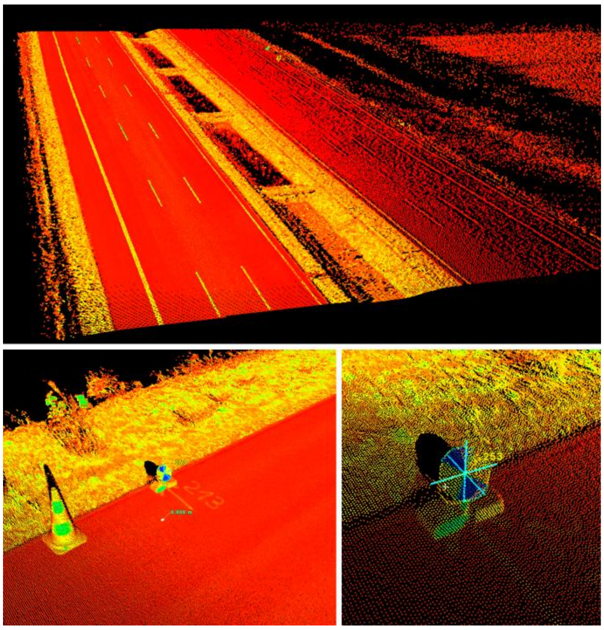

Figure 4. Point clouds of the Mobile Mapping System with a detailed view of a scanned control point (ID 253).

For scanning, a high-speed 2D laser scanner Z+F Profiler 9012A (ZF, 2018) is used having a maximum profile rate of 200 Hz and a scan rate of up to 1 MHz. A particular feature of this 2D laser scanner is a special close-range optimization, improving the precision of the distance measurements in the range between 1 m and 5 m making it suitable for precisely measuring the road surface (Heinz *et al.*, 2018). The lever arm and boresight angles between the 2D laser scanner and the GNSS/IMU unit were accurately calibrated by means of a plane-based approach (Heinz *et al.*, 2015; Heinz *et al.*, 2017) in a proprietary calibration field.

Both the western and eastern lane of the motorway were scanned twice with the Mobile Mapping System. Hence, four measurement runs were carried out. The distance was around 6 km for each run and took 7-8 minutes at an average speed of about 50 km/h. The master station for the RTK-GNSS was set up at station P3 (Figure 2, red triangle), where accurate coordinates for both horizontal position (ETRS89/UTM) as well as physical height (DHHN2016) are given. The ellipsoidal height of the master station was derived by adding the undulation of the GCG16 model to the given physical height (Section IV.B).

The control points were also scanned twice. The Mobile Mapping System passed the control points at walking speed to generate a sufficient point density on the targets. During data processing, the target center coordinates were automatically extracted from the point clouds. Figure 4 shows one of the measured point clouds with a detailed view of control point 253. Visually, the point clouds look high quality.

V. Data Analysis

In Section V, details regarding the data analysis are presented. Section V.A addresses the calculation of a local tilt correction function for the GCG16 quasi geoid, improving the determination of physical heights from the point clouds of the Mobile Mapping System. This is relevant for the comparison at the control points. Sections V.B demonstrates how the cross fall of the road surface as descriptive parameter for the planarity can be extracted from the point clouds.

A. *Local Tilt Correction for the GCG16*

The reference heights of the control points are given in the form of physical heights H in the German height system DHHN2016. In contrast, the point clouds of the Mobile Mapping System provide ellipsoidal heights h w. r. t. the GRS80 ellipsoid. Thus, undulations ζ of the GCG16 model are needed to make a connection. The undulations are specified with an accuracy of < 1 cm in lowlands (BKG, 2017). However, the actual accuracy in the area of the A44n motorway is unknown.

A constant height error of the GCG16 was eliminated by setting up the GNSS master station of the Mobile Mapping System on station P3 with known physical height (Section IV.B); the static GNSS measurements and levelings along the A44n motorway (Section VI.B) can be used for checking the inclination between quasi geoid and ellipsoid. The basic equation is given by:

$$\Delta\zeta_i^{i+1} = \Delta H_i^{i+1} - \Delta h_i^{i+1} + (\zeta_{i+1} - \zeta_i) \stackrel{\text{def}}{=} 0. \qquad (2)$$

In accordance with theory, the difference between the physical height difference ΔH and the ellipsoidal height difference Δh between two points i and $i+1$ is compensated by the associated undulations ζ. If this is not the case, an unmodeled discrepancy $\Delta\zeta$ exists.

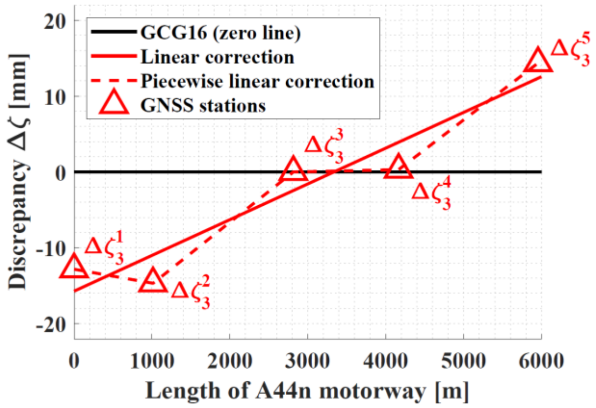

Figure 5. Linear and piecewise linear correction function for the GCG16 quasi geoid as a funtion of the length of the A44n motorway. The slope of the linear function is 4.9 mm/km.

In the course of the processing of the levelings and the GNSS measurements the discrepancies $\Delta\zeta$ w. r. t. station P3 were determined. The results are visualized in Figure 5. As can be seen, the discrepancies $\Delta\zeta$ are negative in the north and positive in the south, which indicates a tilting error. Due to the fact that the height differences ΔH and Δh can be determined with an accuracy of a few mm, the deviations from the black zero line of the GCG16 were found to be significant.

Two different approaches were applied to derive a correction function for the GCG16. In the first case, the data were approximated with a linear function. In the second case, a piecewise linear function with changing slope was selected. The piecewise linear function was chosen due to the limited number of data points for a regression. Furthermore, the piecewise linear function allows for a correction on a smaller scale.

Both approaches were used to correct the heights of the control points as extracted from the point clouds of the Mobile Mapping System (Section VI.A).

B. *Calculation of the Cross Fall*

According to the FGSV, various parameters are used to describe the planarity of road surfaces in both cross and longitudinal direction (FGSV, 2009). We focus on the calculation of the cross fall. The cross fall indicates the inclination of the road surface w. r. t. the horizon in cross direction and serves: (i) draining of the road surface; (ii) reduction of centrifugal forces in turns.

For the calculation of the cross fall, cross profiles of the road surface are required. These cross profiles are directly provided by the Mobile Mapping System. Due to the adaption of the 2D laser scanner to the moving platform (Figure 3), a cross profile of the road surface is scanned for each revolution of the 2D laser scanner. When operated with a maximum profile rate of 200 Hz at a driving speed of 50 km/h, cross profiles with a longitudinal spacing of 7 cm are recorded.

In order to separate the road surface from the soft shoulders of the road, a RANSAC approach is utilized (Fischler and Bolles, 1981). Moreover, the width of the driving lanes is known and the road markings can be detected in the cross profiles using the intensity values of the 2D laser scanner. Following this, the cross fall is estimated by a linear regression of all points within a cross profile w. r. t. the horizontal plane. The slope of the regression indicates the cross fall, which is counted positive to the right in driving direction. Finally, the values are smoothed in longitudinal direction using a moving average of 20 m length (FGSV, 2009).

VI. Results

In the following, the results are presented. In Section VI.A, the Mobile Mapping System is evaluated. The cross fall of the motorway is analyzed in Section VI.B.

A. *Evaluation Based on Control Points*

In order to evaluate the height component of the Mobile Mapping System, the heights of the control points were extracted from the point clouds and compared to the reference heights. In the course of this, undulations from the GCG16 quasi geoid model (BKG, 2017) were used in combination with the linear tilt corrections from Section V.A.

The results are shown in Figure 6. The statistics are listed in Table 1. In addition to minimum, maximum, mean and median error, we also estimated the RMS (Route Mean Square Error) and a standard deviation STD (σ_h) from the double measurements of the control points j according to:

$$\sigma_h = \sqrt{\frac{\sum_{j=1}^{n}\left(h_j^{(II)} - h_j^{(I)}\right)^2}{2 \cdot n}}, \tag{3}$$

where $h^{(I)}$ and $h^{(II)}$ denote the height values from first and second measurement, and $n = 8$ is the total number of control points.

When using the GCG16 quasi geoid model without any tilt correction, a maximum error of 31.9 mm can be detected. Especially the control points 220 and 213 in the northern part show bigger errors of more than 20 mm, whereas the errors at the remaining control points are all below 10 mm and rather spread around zero. The bigger errors at the control points 220 and 213 lead to an increased RMS of 14.1 mm as well as mean and median values of several millimeters.

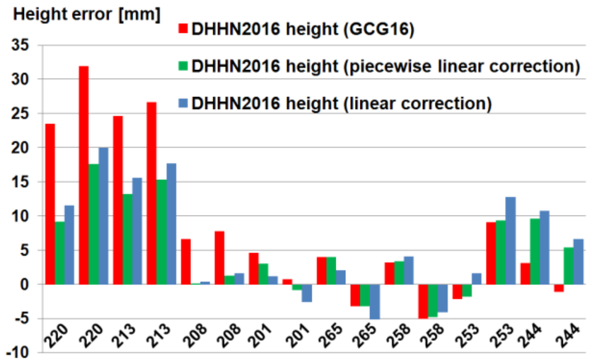

Figure 6. Errors at the control points between the reference heights and the measured heights from the point clouds.

Table 1. Evaluation of the height component based on eight control points (each scanned twice, i. e., total number is 16).

	Height GCG16 [mm]	Height Linear [mm]	Height Piecewise [mm]
Minimum	-5.0	-5.1	-4.8
Maximum	31.9	20.0	17.6
Mean	8.4	5.9	5.1
Median	4.3	3.1	3.7
RMS	14.1	9.7	8.2
STD (σ_h)	4.7	4.7	4.7

However, the standard deviation of 4.7 mm, which is only one third of the RMS, is noticeable. This becomes clear when having a closer look at Figure 6. Though the magnitudes of the errors differ from one control point to another, the errors of repeated measurements of the same control point are mostly similar indicating a high precision of the Mobile Mapping System.

A possible explanation for the poorer accuracy of 14.1 mm, as compared to the precision of 4.7 mm, is the uncertatinty of the Mobile Mapping System, which is primarily defined by the systematics of GNSS. Due to the fact that there is a completely free horizon at the A44n motorway (Figure 1), we assume that the GNSS conditions are basically not changing during a single measurement run with a duration of 7-8 minutes. As a consequence, we expect that errors caused by the Mobile Mapping System should lead to a systematic error mostly similar at all control points. Since this is not the case (Figure 6), we assume that the increased errors in the north are probably not caused by the Mobile Mapping System. This leads to the conclusion that the increased errors are more likely caused by the uncertatinty of the GCG16 quasi geoid model.

The assumption that the errors can be attributed to the GCG16 is confirmed by the results obtained when using the tilt correction for the GCG16. Regardless of whether the linear or the piecewise linear correction approach is selected, the errors at the control points 220, 213 and 208 can considerably be reduced. The piecewise linear correction performs even better than the linear correction leading to an RMS of 8.2 mm. The linear correction leads to an RMS of 9.7 mm. However, a certain amount of the increased errors at the control points 220 and 213 remains, even after the correction. It is possible that our simple linear correction function does not fully compensate for all errors of the GCG16. Nevertheless, the results confirm the high quality of the GCG16 model, which allows for a determination of physical heights with cm to mm accuracy. According to the results, the height accuracy of the Mobile Mapping System can be specified with an RMS of < 10 mm when using the tilt correction and a precision of about 5 mm standard deviation.

B. *Analysis of the Cross Fall*

In addition to the evaluation of the Mobile Mapping System, the cross fall as descriptive parameter for the planarity of the road surface was extracted from the point clouds. In the following, the results for the first run on the eastern lane are presented. The remaining runs gave similar results.

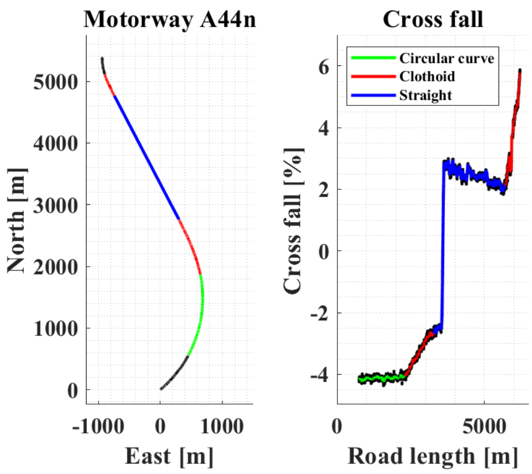

Figure 7. Cross fall of the eastern lane of the A44n motorway. Different draft elements can be distinguished.

Figure 7 shows the cross fall of the eastern lane of the A44n motorway as a function of the length of the road. Clearly, the draft elements of the motorway can be distinguished from each other, i. e., circular curve (green), clothoid (red) and straight (blue).

In the southern part, the road has a constant cross fall of about -4 % to the left corresponding to a circular curve. Following this, the cross fall linearly decreases to about -2.5 %. This corresponds to the draft element of a clothoid transferring the circular curve into a straight. The draft element of a clothoid is defined by a linear decrease of the curvature, leading to a smooth transfer between a circular curve and a straight. The clothoid is followed by a straight having a cross fall of about -2.5 %, which rapidly changes to about +2.5 % on average. This is due to the fact that the cross fall switches from the left to the right side of the road. This change is permissible, because on the straight no compensation of centrifugal forces is required like in turns. The reason for reversing the cross fall is that on the straight the water now runs to the outside of the road (i. e., to the east), avoiding a much more complex drainage in the middle of the motorway between the western and the eastern lane (FGSV, 2008). Following the straight, the cross fall again increases linearly up to 6 %, which indicates the next clothoid.

The values for the cross fall as extracted from the point clouds provide plausible results. On motorways in Germany, a minimum cross fall of 2.5 % is required. In circular curves, the cross fall can be increased up to 6 % depending on the radius of the circular curve and the speed limit (FGSV, 2008).

We clearly emphazie that the results are not an official road inspection according the FGSV guidelines due to the reasons described at the end of Section II.

VII. Conclusion

Coming back to the questions raised in Section I, the following conclusions can be drawn from our tests:

- According to the evaluation based on the control points, the precision of the height component of the Mobile Mapping System can be specified with a standard deviation of about 5 mm.
- According to the evaluation based on the control points, physical heights can be measured with an accuracy of 14 mm RMS when using the GCG16 quasi geoid model; by using a tilt correction for the GCG16, the accuracy can be improved to an RMS of < 10 mm. This indicates the high quality of both the GCG16 quasi geoid model and the Mobile Mapping System.
- Based on the results of the evaluation, a potential subsidence of the road surface could significantly be detected in the order of a few cm.
- The investigations demonstrate that it is basically possible to extract descriptive parameters for the planarity of road surfaces from the point clouds; though the characteristics of the Mobile Mapping System do not fully meet the requirements of the FGSV, a basic analysis can be performed.

In summary it can be stated that the applicability of the proposed Mobile Mapping System for monitoring the planarity and subsidence of road surfaces can be certified based on the presented pilot study. However, some limitations have to be taken into account.

Future research should focus on the calculation of additional parameters describing the planarity of road surfaces, e. g., rut depth and fictive water depth. In addition, investigations in longitudinal direction are of interest. Moreover, it would be reasonable to compare the road parameters with values from construction. In addition to this, the Mobile Mapping System could be applied on older or potentially damaged roads. In this respect, the A44n motorway should be scanned again in its current status after several months of traffic.

VIII. ACKNOWLEDGEMENTS

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