EVALUATION OF A LASER LAND-BASED MOBILE MAPPING SYSTEM FOR MONITORING SANDY COASTS

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ABSTRACT:

The Dutch coast is characterized by sandy beaches flanked by dunes. Its morphology is essential for the defense against flooding of the hinterland. Therefore it is monitored on a yearly basis by Airborne Laser Scanning (ALS). However, it is recognized that most erosion of the beach and first dune row takes place during storms. To assess the state of the coast immediately after a storm with ALS is expensive and difficult to organize. Here, the performance of a Land-based Mobile Mapping System (LMMS) is evaluated. A test data set was obtained by Geomaat using the StreetMapper LMMS system, employing three individual line scanners. Both the relative quality of laser point heights and of a derived Digital Terrain model (DTM) are assessed. In the first analysis height differences between close-by points are considered. Except for arbitrary close-by points, also close-by points obtained from different scanners and from different drive-lines are analyzed. It is shown that on a flat beach a precision of 3 mm is achieved and that almost no internal biases exist. In the second analysis a DTM with a grid size of 1 m is obtained using least squares. Each grid point height includes a quality description, which incorporates both measurement precision and terrain roughness. Although some problems remain with the low scanning height of 2 m, which causes shadow-effect behind low dunes, it is concluded that a laser LMMS enables the acquisition of a high quality DTM product, which is available within two days.

1 INTRODUCTION

The Dutch coast typically consists of a relatively flat sandy beach lined on a side by the dunes, which are partly covered by marram grass. This coastal area is important for the Netherlands for many reasons, e.g. as recreational and nature area, and as protection against a sea flood and storms. The last usage is especially crucial, because the most densely populated areas in the Netherlands are located just behind the coastal defense and are partly below the mean sea level. Therefore, it is essential to continuously monitor and maintain the coast in order to protect the Dutch hinterland from the sea. In 1990 a national coastal policy was adopted, with the aim of maintaining the seaward position of the coastline, as it was on January 1, 1990. To successfully maintain this so-called Basal Coast Line a suitable acquisition technique to measure beach morphology and its changes needs to be employed. Because high energy events like storms may cause large changes, as for example shown in Fig. 1, the main interest is to monitor coastal topography on the temporal and spatial scale of storm impacts. Therefore, a flexible system is needed that can access a damaged area immediately after the storm and provide the results of morphologic changes as quickly as possible (in one day). Besides, to estimate in detail the beach erosion caused by heavy storm events, high spatial resolution measurements are needed.

Since 1996 the Dutch Ministry of Transport, Public Works and Water Management (RWS, Rijkswaterstaat) annually measures the beach topography by means of Airborne Laser Scanning (ALS). The ALS technique has limitations in case of projects that include cost effective capturing of 3D data or when dense point coverage of the vertical features is required (e.g. steep dune slopes). Besides, the ALS data in general can not be provided on demand. First, because flying permissions are needed and secondly

Figure 1: A real example of a dune erosion on the Dutch coast and the possible consequence [GoogleEarth].

after-storm weather conditions may hinder or prevent the acquisition. To summarize, the ALS method offers good results in terms of quality and reliability, but is not flexible. One of the potential alternative techniques is a Land-based Mobile Mapping System (LMMS). LMMS is a complex real-time, multi-tasking and multi-sensor system, which integrates (i) a number of line scanners and/or digital cameras for surface mapping, (ii) GNSS for positioning and (iii) additional sensors like for example INS to monitor the vehicle motion. Those sensors are usually mounted on a rigid platform, placed on the roof of a vehicle. The LMMS mapping sensors can be of different type and orientation, which makes every LMMS system unique in terms of performance and thus quality. For an overview of the early LMMS see (Ellum and El-Sheimy, 2002). More recent LMMS and system providers are described in (Shan and Toth, 2008, Vosselman and Maas, 2010, Petrie, 2010). In this research the LMMS, employing a laser scanner as a mapping sensor and integrated GPS/INS system as a main navigation sensor is discussed.

Using laser LMMS it is in principle possible to quickly obtain 3D geo-referenced data of a large extended area, such as a beach. High frequency laser pulse measurements enable high spatial resolution. Besides, higher point density is expected, because the measured ranges are smaller than in case of ALS. On the other hand, more data voids might occur behind elevated features when measuring from the ground. Besides, attention must be paid to the intersection geometry of the laser beam with the relatively horizontal beach. If scanning a horizontal surface, the geometry gets poorer further away from the trajectory. This decreases the laser point positioning quality. In order to test the laser LMMS performance on the Dutch coast RWS initiated a pilot-project. Particular interest of the RWS is the level of obtainable accuracy and processing time of a final topographic product, which is a Digital Terrain Model (DTM). The RWS requirements are twofold. First a vertical DTM accuracy of at least 10 cm at a grid spacing of 1×1 m is required, and, second, it is required that the results are available close to real-time. In this research the quality of derived LMMS laser point cloud and DTM is analyzed.

In general it is important to know the laser point quality, prior to using points in further processing, like computing a DTM. In quite some researches the theoretical or overall expected (a-priory) quality of the derived 3D laser point cloud is estimated by linearizing the geo-referencing equation. For equations of the first order error model see e.g. (Ellum and El-Sheimy, 2002, Glennie, 2007, Barber et al., 2008). The random errors of the LMMS measurements (i.e. range, scan angle, IMU angles and GPS position) and calibration parameters (i.e. lever-arms and boresight angles) are propagated to obtain a-priori 3D laser point precision. To verify those theoretical models and estimate an empirical (a-posteriori) quality of a laser point positioning, a proper Quality Control (QC) is needed. In (Habib et al., 2008) the existing QC procedures are explained in detail. However, standard and efficient procedures for validating the quality of derived laser points and further on the DTM are still missing.

In the following a procedure to evaluate the laser LMMS measurements of sandy Dutch beach morphology is described. In Section 2 the methodology to estimate both the relative quality of the LMMS laser point heights and the derived DTM is described. In Section 3 the methodology is applied on the real data and results of both quality evaluation procedures are presented. In Section 4 conclusions, which include recommendations for further work, are given.

2 METHODOLOGY

In this section first the scanning geometry at the time of each laser point acquisition is reconstructed by applying simple geometrical rules. The intersection geometry in general influences the laser point positioning quality. Thus, this influence is considered further on to compute the theoretical height precision. Here, also the random errors of LMMS measurements and calibration parameters specified for a LMMS are included.

Next, the methodology to evaluate the relative quality of LMMS laser point heights is described. The relative quality describes the relation between two points acquired in the same region in a short time period (point-to-point quality) (Kremer and Hunter, 2007). As stated already in the introduction, the quality of the whole LMMS data depends on the quality of the system measurements and calibration. The latter one varies depending on the experience of the data processor. It is therefore impossible to give a-prior relative quality quotes (Cox, 2009). For this reason here a real laser LMMS data set is used and the empirical quality of point heights is estimated employing a QC procedure.

Terrain laser points, which were extracted from the raw data by provider Geomaat, are used to interpolate the DTM. The importance of DTM applications makes it inevitable to provide DTMs with adequate quality measures at a high level of detail, as it is for example described in (Kraus et al., 2006). The idea is to inform the user about the DTM quality and warn them of weakly determined areas. Thus, in the following an approach to evaluate the quality of each grid point height is described.

2.1 Reconstructing the scanning geometry

The instantaneous scanning geometry of a laser point can be described by the range and the incidence angle, which besides influence the footprint size. Those geometric attributes are computed for each measured laser point using point position and the trajectory position. Both data sets include the X, Y and Z coordinates and the acquisition time.

The range R is the length of the vector $\vec{p}$ from the laser scanner position at time t to the laser point. It can be computed for each laser point once the sensor position at the time t of the laser point acquisition is known. The laser scanner position is linearly interpolated using the consecutive trajectory positions. Here it is assumed that the trajectory position directly represents the laser scanner position.

The incidence angle α is the angle between the laser beam $\vec{p}$ and the upward normal ($\vec{n}$) of the surface at the laser point position. When a beam hits a surface perpendicular to it, the incidence angle is $0°$ and when a beam is parallel to a surface the incidence angle is $90°$. The normal vector $\vec{n}$ is computed as follows. For each laser point the closest 4 points are determined using a k Nearest Neighbor algorithm (Giaccari, 2010). A plane is fitted to all 5 points using Least Squares. The result is the normal $\vec{n}$ of a plane at a laser point. The number k = 4 of neighboring laser points participating in plane fitting is chosen such that the computed normals reflect just a local surface.

The laser footprint is the area of an illuminated surface and is approximated by a circle. Thus, its diameter D_{fp} is computed in terms of the laser beam-width β and changing incidence angle α and range R, as written in Eq. 1:

$$D_{fp} = \frac{R \cdot \beta}{\cos \alpha} \qquad (1)$$

2.2 Theoretical quality of laser points

The theoretical models of error propagation through the geo-referencing equation are used to estimate an expected precision of each laser point height σ_{Zi}. First the specified random errors of LMMS measurements and calibration parameters are inserted in the first order model of error propagation. Besides, the real measurements as range, scan angle and the IMU angles are considered in the computation. The result is the height precision of laser point i due to L-MMS measurement errors $\sigma_{Zi,m}$ (measuring precision). The value for the random range error used here is valid when the laser beam falls perpendicular to the target (Schwarz, 2009). In practice the incidence angle is changing over the acquisition area and is usually non-perpendicular as shown in Fig. 2. High incidence angles result in poor intersection geometry and affect the range measurements, (Soudarissanane et al., 2009, Lichti and Gordon, 2004, Schaer et al., 2007, Alharthy et al., 2004). For pulse laser scanners, which are used in this research, the approach in (Lichti et al., 2005) is used. At a given

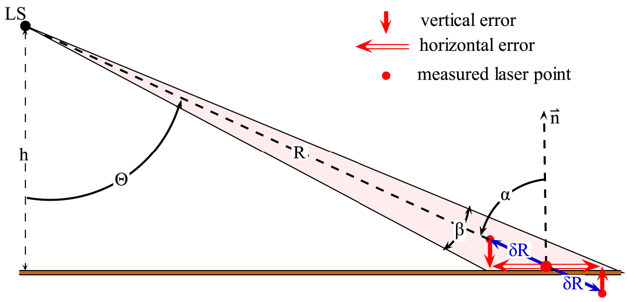

Figure 2: The range error δR due to the non-perpendicular scanning geometry and the influence of δR on vertical and horizontal laser point positioning error.

range R and knowing the beam width β from the laser scanner specifications, the range error δR is parameterized in terms of incidence angle α as given in Eq. 2 (Lichti et al., 2005):

$$\delta R = \frac{R \cdot \beta \cdot \tan\alpha}{2} \tag{2}$$

This range error δR is then propagated through the geo-referencing equation and the height precision of laser point i due to the (non-perpendicular) scanning geometry $\sigma_{Zi,\delta R}$ (geometrical precision) is computed.

Finally, the allover theoretical height precision of point i is written as Eq. 3:

$$\sigma_{Zi} = \sqrt{\sigma^2_{Zi,m} + \sigma^2_{Zi,\delta R}} \tag{3}$$

2.3 Empirical relative quality of laser points

In general the idea of validating the relative quality of laser data is based on checking the compatibility of laser points in areas, where data overlap (Kremer and Hunter, 2007). In (Habib et al., 2008) some QC procedures are explained. However, the acquisition area discussed in this research, i.e. the sandy beach, does not include (many) steady points or lines, that are sufficiently well defined in the laser LMMS point cloud. In other words, the beach area lacks artificial sharp edges or planes, which could be extracted from the laser points and used in a relative QC procedure. Besides, the terrain on the beach is changing smoothly. Thus finding and aligning breaklines of beach morphology is not a promising method either. Instead, the advantage of high LMMS laser point density is used and a point-to-point comparison is made. Namely, the height differences between laser points that lie so close together that their footprints partly overlap, i.e. the height differences between so-called identical points, are analyzed. Not all measured laser points are considered in the process of finding those identical points. The next two conditions are set for laser points:

- The footprint diameter might be unreasonably big in case the incidence angle is close to 90°. Therefore, just laser points that have an incidence angle less than 89.9° are considered: $\alpha_P < 89.9°$.
- Because just the vertical component Z of the two points is compared, points should lie on an almost horizontal plane in order to avoid the influence of surface slope on the height difference. This requirement is considered to be fulfilled, if the z-component of the normal N_z, computed at each laser point as explained in Section 2), is: $N_{Pz} \approx 1$.

Now pairs of closest points in 3D are found using the kNN algorithm (Giaccari, 2010), where k = 1. The closest point pair enters the set of identical point pairs, if the 3D distance $d_{i,j}$ between laser point P_i and its nearest neighbor P_j is smaller then the minimal size of their footprint radii. At the same time the 3D distance $d_{i,j}$ should be smaller than 5 cm, thus:

$$d_{i,j} \leq \text{Min}(\min(r_i, r_j), 5\ cm), \tag{4}$$

where $i, j = 1 \ldots n$ & $i \neq j$ and n the number of laser points. The height differences ΔZ between identical points are considered as an empirical quality measure. It is expected that the mean of signed height differences ΔZ equals approximately zero.

LMMS is characterized by a high laser point density, compared to ALS. This high point density has several reasons. First, from an operational viewpoint, the drive paths can be arbitrary close together, resulting in overlapping drive-lines, while the vehicle can also scan at low driving speeds. Besides, usually more laser scanners are mounted on a vehicle and measure at the same time. It is not clear a-priori that points from different drive-lines can have the same quality. That is because the acquisition time is different and the configuration of GPS satellites may have changed. Also different scanners may result in points of different quality. Therefore the height differences ΔZ of identical points are investigated for three different cases:

1. Identical points (IP) from the complete data set.
2. Identical points (IP) belonging to different scanners (scanner overlap).
3. Identical points (IP) belonging to overlapping drive-lines (drive-line overlap).

For each case the height differences of identical points are analyzed in order to estimate noise levels and possibly identify systematic errors. Besides, the correlation with geometric attributes, i.e. the range and incidence angle, of laser points is investigated.

2.4 DTM interpolation and quality

There are many different algorithms to interpolate a DTM. The more common are Nearest Neighbor, Inverse Distance Weighting, Moving Least Squares and Kriging (Shan and Toth, 2008). Many researches and books exist on those topics, however they are not discusses further in this research. The main emphasis is on the DTM quality estimation.

In general the quality of a DTM depends on a number of individual influencing factors, see (Li et al., 2005, Huaxing, 2008). The ones investigated here are: the number of terrain points (FD1), height precision of individual terrain point (FD2), terrain point distribution (FD3), the terrain roughness (FR) and interpolation method (FI). When the DTM is constructed from the existing laser data, the first three influencing factors (FD1, FD2, FD3) are usually known or can be estimated. The fourth influencing factor, the terrain roughness (FR), is related to the interpolation method (FI).

Following the research in (Kraus et al., 2006), a grid point elevation and its precision are estimated by linear interpolation (FI). Rules of error propagation based on variances and co-variances of the original terrain laser points are applied, to estimate the quality of the grid points. The output is then strictly speaking the precision of a grid point, which is denoted by a standard deviation σ_{DTM}. In other words, the systematic errors are assumed to be zero (Kraus et al., 2006). First a grid of 1×1 m size is laid over the terrain laser points. For grid cells, which include 4 or more terrain laser points, a tilted plane is modeled in a Least Square sense by a first order polynomial as given in Eq. 5:

$$Z = a_0 + a_1X + a_2Y. \tag{5}$$

Here X, Y, Z are the coordinates of the terrain laser points (observations) that are included into the plane computation and a_0, a_1 and a_2 are the unknown plane coefficients. The graphical representation of each term in Eq. 5 is shown in Fig. 3. To make the

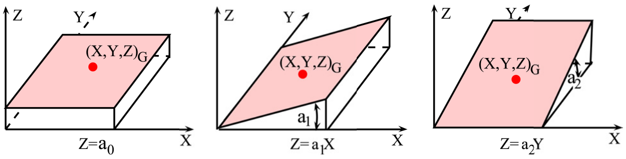

Figure 3: A graphic representation of terms given in Eq. 5; after (Li et al., 2005)

least squares computation more efficient, a new coordinate system is used with the interpolation grid point (X_G,Y_G) as the origin; therefore the method is called Moving Least Squares (MLS) adjustment (Karel and Kraus, 2006). The equation of a plane (Eq. 5) simplifies, so the plane coefficient a_0 becomes the elevation of the grid point itself, as written in Eq. 6:

$$Z_G = a_0 \tag{6}$$

The mathematical model of Moving Least Squares for linear surface fitting is then given in matrix vector notation as in Eq. 7b:

$$y \approx A \cdot x \tag{7a}$$

$$\begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_n \end{bmatrix} = \begin{bmatrix} 1 & X_1 - X_G & Y_1 - Y_G \\ 1 & X_2 - X_G & Y_2 - Y_G \\ \vdots & \vdots & \vdots \\ 1 & X_n - X_G & Y_n - Y_G \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} \tag{7b}$$

Where X_i, Y_i, Z_i for $i = 1 \ldots n$ are the coordinates of the n original laser terrain points included in the plane computation. Then the unknowns in vector $\hat{x}$ and their variance-covariance matrix $\Sigma_{\hat{x}\hat{x}}$ are computed in a least squares adjustment as written in Eq. 8 and Eq. 9 respectively:

$$\hat{x} = \left(A^T \Sigma_{yy}^{-1} A\right)^{-1} A^T \Sigma_{yy}^{-1} y \tag{8}$$

$$\Sigma_{\hat{x}\hat{x}} = \left(A^T \Sigma_{yy}^{-1} A\right)^{-1} \tag{9}$$

Where Σ_{yy} is the variance matrix of observations. Here, the theoretical height precision of the laser points σ_{Zi} computed in Section 2.2 is used. Besides, the vertical distances between the original terrain points and the modeled plain, are computed. Those residuals e are applied to calculate the Root Mean Square Error (RMSE) as written in Eq. 10 for each plane:

$$RMSE = \sqrt{\frac{e^Te}{n}} \tag{10}$$

To finally predict the DTM quality σ_{DTM}, a mathematical model after (Li et al., 2005) as written in Eq. 11 is used.

$$\sigma_{DTM}^2 = \sigma_{a_0}^2 + \sigma_e^2 \tag{11}$$

Here the standard deviation of the constant plane coefficient σ_{a_0} represents the quality of the original data and accounts for the precision of the original laser points (FD2), their density (FD1) and distribution (FD3). The second term σ_e^2 represents the quality loss due to the representation of the terrain surface. In this research the RMSE is considered as a measure of the terrain surface roughness (FR) with respect to the plane modeled by the chosen random-to-grid MLS interpolation (FI). Therefore σ_e simply equals the RMSE as computed in Eq. 10.

3 RESULTS AND DISCUSSION

In this section the results of the quality evaluation of both LMMS laser point heights and a derived DTM are discussed for a LMMS data set representing a stretch of Dutch coast. Before these results are given, first this data set is described in more detail.

3.1 Data description

The LMMS data set was acquired on the Dutch coast near Egmond aan Zee using the StreetMapper system owned by provider Geomaat (StreetMapper, 2010, Geomaat, 2010). The acquisition took place on November 27, 2008 at the time of low tide. Within 2 hours a stretch of beach of 6 km long and 180 m wide was covered. The point cloud consists of about 56 million laser points. As experienced by Geomaat, the 3D laser point coordinates and the classification into terrain and non-terrain points can be done within 2 days. In this research a smaller representative test area of 213×101 m was chosen, which is covered by 8 drive-lines, see Fig. 4. The data set consists of 1 220 825 laser points. Each record of a laser point has 15 attributes, which are: 3D laser point position X, Y, Z, intensity I, class number C, scanning angle Θ, time of point acquisition T, drive-line number DL and scanner number SC, range R, incidence angle α, footprint diameter D_{fp}, range error due to scanning geometry δR, measuring precision $\sigma_{Z,m}$ and geometrical precision $\sigma_{Z,\delta R}$. The second data set used in this research composes of eight trajectories positions within the test area (black lines in Fig. 4).

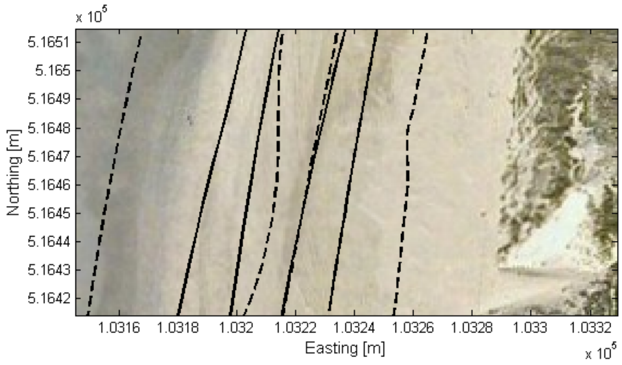

Figure 4: The digital photo of the test area [GoogleMaps]. The black dashed lines mark the trajectories driven downward i.e. from the north to the south and the solid lines mark the trajectories driven in the opposite direction.

3.2 Results of height differences of identical points

By analyzing the attributes of the identical point pairs, i.e. the scanner and drive-line number, it is concluded that the majority of identical point pairs belongs to the same scanner and the same drive-line. Fewer identical point are found in the scanner overlap and drive-line overlap (see Table 1). In Table 1 the results of height differences for the three cases are presented. The mean (avg) of height differences ΔZ is very close to zero for the case ALL-N_z and scanner overlap. In the latter case the offset of 0,2 mm from the expected zero mean could indicate the scanners calibration error, which is in any case very small. In case of drive-line overlap the average of height differences ΔZ as expected equals to zero, thus it can be assumed there is no offset between drive-lines. In other words there is no systematic error in GPS/INS positioning. The standard deviations (std) are equal or smaller than 3.5 mm, which denotes the relative precision of LMMS laser points. Analyses of the correlation between height

		ALL-N_z	Scanner overlap	Drive-line overlap
No. of ident. point pairs		17 754	608	5 473
Height difference ΔZ [mm]	min	-47	-20	-47
	max	46	36	46
	avg	0.1	0.2	0.0
	std	3.1	2.5	3.5

Table 1: Statistics of the height differences of identical points.

differences of identical points lying on a horizontal surface and the geometric attributes, i.e. range and incidence angle, do not show a clear trend.

3.3 Results of DTM interpolation and precision estimation

Within the test area the terrain laser points, as classified by Geomaat, are used in the following DTM analysis. In Fig. 5 a 3D surface of the interpolated DTM is shown. In this raster image each pixel represents an 1×1 m grid cell and the pixel color shows the corresponding grid point height. The grid point elevation is changing from -0.19 m at the coastline to up to 22 m in the dunes. The white holes in the DTM are results of the shadow-effect (white holes in green area) and most probably of the presence of water-bodies on the beach (white holes in blue area).

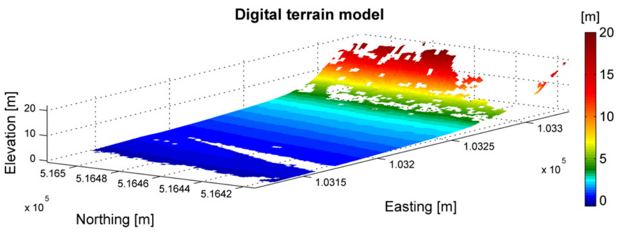

Figure 5: Raster image of interpolated DTM grid points visualized in 3D.

The height precision σ_{DTM} of the grid points, as computed by Eq. 11, varies between 0.0018 and 2.9 m. The average precision of grid points σ_{DTM} equals to 4.7 mm. For comparison, the precision of the observations σ_{Zi} is on average 2.4 cm.

In Fig. 6 the relation between the height precision of grid points σ_{DTM}(y-axis), the number of points n (x-axis) and data quality component σ_{a0} (colorbar), is presented. Comparison of the colorbar and the y-axis scale shows, that the size of the grid point height precision σ_{DTM} depends mainly on the data quality component σ_{a0}. Besides, one can observe that, if approximately 50 or more points are included in the grid point computation, the standard deviation of grid point heights σ_{DTM} drops below 1 cm.

In Fig. 7 the spatial variation of standard deviation σ_{DTM} over the test area is shown. Green color shows grid points having a

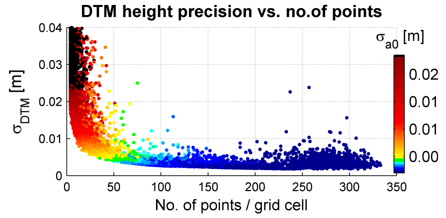

Figure 6: Correlation between the grid point height precision σ_{DTM} and the number n of terrain laser points; color-coded by the data quality component σ_{a0}.

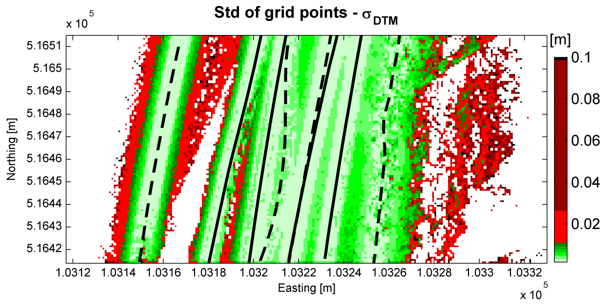

Figure 7: Grid point height precision σ_{DTM}.

height precision σ_{DTM} smaller than 1 cm. Most of the beach area has good DTM quality, which decreases with the distance from a trajectory. For example, the precision at the edges of the drive line DL11 (most left one) decreases and is at some point worse than 2.56 cm, mostly due to the lower point density. The DTM quality gets worse also in the dune area, due to the low point density, low theoretical precision of terrain laser point heights and high terrain roughness.

4 CONCLUSIONS AND FUTURE WORK

In this article most important results are the empirical laser point height precision assessed by the QC of identical points and the precision of the grid point heights estimated my a mathematical model employing results of MLS adjustment. Both values are surprisingly small.

Firstly, the empirical relative precision of laser points is around 3 mm. Besides, it was concluded there is almost no bias in the StreetMapper system. However, it is recommended to analyze bigger number of identical points. Within the QC of identical points an attempt was made to show the influence of the scanning geometry on the laser point quality. Results show that height differences between identical points do not depend neither on the range neither on the incidence angle. To verify the influence of the scanning geometry on the laser point quality it is recommended to additionally measure control points across the drive-line and compare them with the point cloud.

Secondly, the average precision of grid point height equaled to 4.7 mm. The computation was performed within the weighted MLS adjustment, using the theoretical height precision of terrain laser point as weights. It was found that the main influencing factor on the grid point height precision is the density of terrain laser points. That is, because a higher number of observations (i.e. terrain laser points) enabled partly elimination of the observation noise. The consequence is, that the precision of grid point height improved with an increasing number of terrain laser points and exceeded the theoretical height precision of the individual terrain laser points. Rijkswaterstaat required a 1×1 m DTM having a precision better then 10 cm. Thus, it was concluded that those requirements can be easily met employing laser LMMS.

The adjustment method for the DTM quality estimation includes just the grid cells with more than 3 terrain laser points and gives strictly speaking the precision of the grid points. Using another method would allow to compute the precision for all grid cells and would result in a slightly higher coverage. To optimally profit from the available data it is recommended that this method is adaptive to both point density and surface relief. Besides, areas without any terrain laser points, resulting from the shadow-effect or surfaces covered with a water, must be separately analyzed, e.g. see (Kraus et al., 2004). On the other hand, to asses the absolute positional and height accuracy of the DTM product, external reference data of higher accuracy should be used.

A last recommendation for further projects, assessing sandy beach morphology, is to place laser scanners on a higher platform. The StreetMapper platform of 2 m above the ground resulted in quite some data gaps due to occlusions behind the pre-dunes. Based on the DTM visibility analysis, as given in (Li et al., 2005), for a particular area of interest the optimal height of the laser scanner(s) above the ground could be calculated.

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