ASSESSMENT OF LIDAR DTM ACCURACY IN COASTAL VEGETATED AREAS

J. Göpfert, C. Heipke

Institute of Photogrammetry and GeoInformation
University of Hanover
(goepfert, heipke)@ipi.uni-hannover.de

Commission III, WG III/3

KEY WORDS: lidar, vegetation, accuracy, feature extraction

ABSTRACT:

Digital terrain models (DTM's) are widely used in coastal engineering. Reliable height information is necessary for different purposes such as calculating flood risk scenarios, change detection of morphological objects and hydrographic numeric modelling. In this specific field light detection and ranging (lidar) replaces step by step other methods such as terrestrial surveying. However, some new problems are associated with lidar technology. For instance, in vegetated areas the accuracy of the lidar DTM decreases.

In this paper the influence of different types of coastal vegetation on the accuracy of the lidar height information is investigated. For that purpose this research starts with a comparison of terrestrial control measurements and the lidar data in order to detect problematic areas with respect to the accuracy of the DTM. Based on the resulting height differences the influence of different attributes of the vegetation, i.e. type, height, density, is analysed. In the next step typical features, which are able to describe the attributes, are extracted from the available remote sensing and GIS data (ranging from laser heights and intensity information to multispectral images and biotope mapping). These features were used to perform a classification of the lidar data in different categories of accuracy. Finally, first results for two test areas are presented.

1. INTRODUCTION

Various agencies operating in the field of coastal management require reliable area-wide height information for the transition zone between land and water, in dunes and for their protection facilities, in order to detect important changes with regard to the safety of the coastal area. In former times terrestrial surveying was used to collect this information. However, these methods are very time and cost consuming as well as difficult to perform in coastal areas with dense vegetation and frequently flooded terrain. Therefore, the lidar technique replaces more and more the traditional methods. However, new problems related to the application of the lidar data have to be solved. The influence of vegetation on the quality of the lidar DTM is one of these problems. The laser beam is not able to fully penetrate dense vegetation surfaces such as shrubberies in dune valleys. Thus, the laser pulse is often reflected before hitting the bare ground or a mixed signal (surface as volume scatterer) generates a certain height off-set. Common filter algorithms are able to remove points reflected from higher vegetation. If there are only a few or no ground points in the analysed area caused by the dense vegetation the filter methods fail. Additionally, low vegetation which is not significantly higher than the surrounding bare ground is difficult to detect. Figure 1 demonstrates the circumstances on the basis of a valley in the dunes (East Frisian Island Juist) with dense standings of Japanese rose and creeping willow. The digital surface model (DSM) from the unfiltered lidar data is illustrated on the left side (a), whereas the figure in the middle depicts the lidar DTM (b) and the DTM of the control points is displayed on the right (c). Obviously, some vegetation points are still present in the dataset after the filtering process. This paper investigates the described influence of the vegetation on the accuracy of the lidar DTM for typical plant population in the coastal area of Northern Germany.
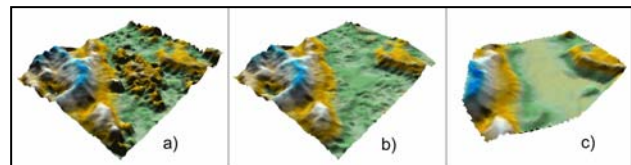

Figure 1: a) lidar DSM, b) lidar DTM, c) DTM of control points

Additionally the potential of different attributes (vegetation height and density) for the description of the height discrepancies caused by the vegetation are analysed. These attributes have to be connected to features extracted from the available remote sensing data in order to perform a classification of the lidar data in different accuracy levels. Finally, the presented approach generates a lidar quality map depending on the vegetation.

2. STATUS OF RESEARCH

Before choosing attributes which influence the lidar quality in vegetated areas, it is necessary to understand the basic principles of the interaction between the laser beam and the reflecting surface. Wagner et al. (2004) discussed physical concepts for understanding how distributed targets such as trees or inclined surfaces transform the emitted laser pulse by using the radar equation. Additionally, they pointed out the advantages of full-waveform scanners in the analysis of the backscattered laser pulse. Pfeifer et al. (2004) considered the influence of different parameters such as flying height, footprint size, echo detection and selection as well as pulse width on the laser measurement over vegetation.

After understanding the basic principle an analysis can be performed by using ground truth measurements in comparison to the lidar height. In this manner several studies investigated

the influence of different vegetation types on the quality of the lidar DTM. Elberink and Crombaghs (2004) found a systematic upwards shift of up to 15cm for low vegetated areas (creeping red fescue). Ahokas et al. (2003) evaluated the lidar accuracy for asphalt (standard deviation 10 cm), gravel (4cm), grass (11cm) and forest ground (17cm). Pfeifer et al. (2004) investigated the influence of long dense grass (+ 7.3cm), young forest (+ 9.4cm) and old willow forest (+ 11.6cm) on the accuracy of lidar data. Hodgson and Bresnahan (2004) used the horizontal coordinates of the irregularly distributed lidar points for the measurement of the ground truth in order to avoid an interpolation influence during the calculation of an error budget for a lidar data set. They found a standard deviation of 17cm for evergreen and 26cm for deciduous forest, however in contrast to other studies only low shifts (-4,6 cm for evergreen, + 1,0cm for deciduous) occurred.

Only a few researchers investigated object or data driven parameters with an influence of the laser measurement except the vegetation type. Hopkinson et al. (2004) presented a method to identify the relationship between the standard deviation of pre-processed laser heights (the ground elevation was subtracted from the first and last pulse measurement) and vegetation height itself for low vegetation (<1,3m). They found the following expression,

$$\text{vegetation height} = 2.7 * \text{standard deviation},$$

and determined the r.m.s.e. of the predicted vegetation heights with 15cm. Pfeifer et al. (2004) and Gorte et al. (2005) used also the variation of the laser heights in order to detect relations to the height shift in low vegetated areas. Instead of the standard deviation they defined texture parameters and showed their potential for correction.

In (Moffiet et al., 2005) the capabilities of classified returns (ground and vegetation, first, last and single pulse) as well as the returned intensity were investigated to distinguish different tree types. The authors pointed out that the average and the standard deviation of the intensity values are affected by the forest structure as well as the reflective properties of the vegetation, whereas the information content of a single intensity value is difficult to interpret.

In different studies a combination of height and multispectral data is used in order to detect and classify vegetation types. For example, Mundt et al. (2006) explored the potential of this combination for mapping sagebrush distribution; and Straub and Heipke (2001) determine tree hypothesis using geometric and radiometric features from height and image data.

3. DATA

This research is mainly based on two test flights. Most of the investigations were carried out using data collected by the company Milan-Flug GmbH covering the region of the East Frisian Island "Langeoog" in the leaf-off period (April 2005). During the campaign a LMS Q560 system of the company Riegl was used. Flying at a height of 600m the system provided an average point density of 2.9 points/m^2. The following data were collected:
- RGB – Orthophotos (resolution: 0,2 m)
- maximum of three pulses per laser beam
- unfiltered raw data (x, y, z, intensity)
- points (x, y, z), separated into ground and vegetation

Supported by biologists various control areas for typical vegetation types were defined. Within a few days of the flight campaign ground truth data for these regions were collected including the height of the ground and the vegetation as well as a verbal description of the vegetation. For each of the following vegetation types two test fields were chosen:
- Japanese rose (Rosa rugosa) (vegetation heights up to 1,3 m)
- Beach grass (Ammophila arenaria) (<1,0m)
- Crowberry (Empetrum nigrum) (<0,4m)
- Creeping willow (Salix repens) (<1,6m)
- Common seabuckthorn (Hippophaë rhamnoides) (<1,4m)
- Common reed (Phragmites australis) (<2,2m)
- Sand couch grass (Agropyron pungens) (<0,5m)

Furthermore, two mixed habitats (rose/seabuckthorn (<2,6m) and seabuckthorn/willow (<1,6m) were investigated. Additionally, some fisheye photos taken from the ground to the zenith were acquired in order to quantify the vegetation density (Figure 3). Four bare ground areas in the immediate vicinity of the vegetated test region were surveyed to check the general quality of the data.

The data for the second test flight were collected during a measurement campaign of the company TopScan with an ALTM 2050 scanner from Optech covering the East Frisian island Juist (March 2004). The flying altitude was 1000m and the system provided an average point density of 2 points/m^2. The following data were used for the analysis:
- CIR – Orthophotos (resolution: 0,2 m)
- last pulse data
- unfiltered raw data (x, y, z, intensity)
- points (x, y, z), separated into ground and vegetation

A test area called "Dunes" consisting of 696 control points within a mixed population of Japanese rose and willow was surveyed in the same way as described above. Vegetation heights of up to 2,8m occurred.

Finally, a biotope mapping performed on aerial photos taken in 2002 and 2003 with a HRSC-AX and a DMC camera was used as input for the distinction of different predominant vegetation types.

4. METHODS

In this paper we analyse the relationship between different object as well as data driven features and the accuracy of the lidar DTM in vegetated areas. We combine image, lidar and GIS data to accomplish this task. In contrast to the above mentioned work our aim is not to do vegetation classification Initially, section 4.1 investigates the characteristics of vegetation with respect to the lidar measurement. The next section connects the analysed vegetation attributes to features generated from remote sensing data. Finally, in 4.3 the workflow to classify the lidar data into different accuracy levels using the extracted features is discussed.

4.1 Characteristics of vegetation in lidar data

For an assessment of the influence of vegetation attributes on the quality of the lidar height information we use ground truth measurements. In order to compare directly terrestrial and lidar data it is necessary to interpolate the heights obtained by one of the methods from the surrounding measurements. One argument for the interpolation of the lidar data is the higher point density (~3 points/m^2 in comparison to ~0.5 points/m^2 for the ground truth measurements). Additionally, the topographic features of

the surface are not reflected in the point distribution of the terrestrial data due to the difficult measurement conditions, i.e. dense vegetation and rough terrain. For these reasons we compute a DTM from the filtered lidar data and interpolate the lidar height information for the control points using their x- and y-coordinates. Then the mean height discrepancies (lidar-DTM minus reference height) and their standard deviation were determined.

Initially the height discrepancies (lidar DTM minus reference height) depending on one parameter are analysed. The influence of the following parameters is investigated:
- vegetation type
- vegetation height
- vegetation density

Many related studies found that the surface type is one of the crucial factors for the accuracy of the DTM derived from lidar data (see also status of research). For that reason the first parameter which has to be analysed is the vegetation type.
Laser pulses do not penetrate every layer of the vegetation in a similar way. Therefore, the laser beam is very often reflected above the bare ground or a mixed signal from ground and vegetation returns to the scanner. Thus, an upwards shift for the lidar heights is expected in vegetated areas. Caused by the different structure the influence of several vegetation types on the lidar accuracy should vary.
The research focuses on typical vegetation for coastal areas, beginning with layers of biomass covering the ground in spring, produced by felted mulch or bear leaves during winter times. For example dense standings of beach grass and shrubberies in dunes as well as common reed and sand couch grass in the transition zone between land and water belong to the monitored vegetation types.

The vegetation height is the next analysed parameter. With higher vegetation the distance of the laser beam through the different layers of organic material becomes longer. Therefore, assuming a uniform vegetation structure in every layer the probability that a part of the laser energy is absorbed or reflected before reaching the ground is higher.
In order to investigate the influence of the vegetation height the parameter is divided into regular intervals. The height discrepancies at the control points are assigned to the related interval. For every related interval the mean and the standard deviation of the height shift are determined and plotted over the vegetation height.

Subsequent, the influence of the vegetation density is studied. The vegetation density can not be measured directly. Therefore, suitable values which are able to describe the characteristics of the vegetation density must be defined. One method to quantify this parameter determines the ratio of the classified ground points to all lidar points in the analysed test field. This idea assumes that in dense vegetation less laser pulses penetrate the canopy and more vegetation points are filtered. For that reason a larger ratio implies a lower vegetation density and can potentially act as an indicator for higher accuracies of the lidar DTM. However, the filter result may be wrong, and thus the definition of vegetation density breaks down in very dense vegetation surfaces which are hardly penetrated by the Laser beam.
The analysis of the fish eye photos offers another method to define the vegetation density (figure 2). An algorithm to calculate the coverage with organic material depending on the zenith angle was developed based on the rectified image (for

the rectification process see r. g. Schwalbe, 2005). The images are segmented into vegetation and background using simple thresholds which are calculated from the minima of the grey value histogram. Finally, the correlation between the degree of coverage and the height discrepancies is investigated.
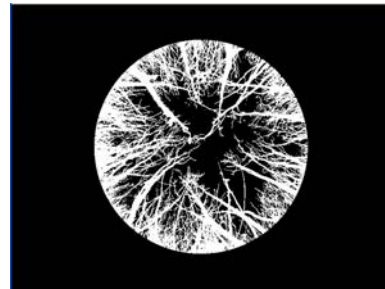

Figure 2: Segmented fish eye photo (rosa rugosa)

Note that the term "dense vegetation" is also related to the size of the lidar footprint: lasers with smaller footprints are able to penetrate vegetation with higher density in a more undisturbed way. The impact of the size of the lidar footprint on the penetration rate, however, is not subject of this research.

Finally, the parameters vegetation height and density are also analysed with respect to only one vegetation type, in order to describe a more complex model of the influence of the vegetation on laser heights.

4.2 Features for classification

In the next step features have to be determined which are able to represent the vegetation attributes in the remote sensing data. The mean value and the standard deviation of the multispectral, lidar height and intensity channels and some texture parameters derived from the co-occurrence matrix (i.e. contrast and homogeneity) are investigated. The co-occurrence matrix contains the spatial dependencies of the grey values for certain directions and distances (see e. g. Haralick, 1979).
Considering one vegetation type we assume that the mean values of the Normalized Difference Vegetation Index (NDVI) correspond to the vegetation density: The leaf area index (LAI) is one of the most important parameters for characterising the structure of canopy. Many studies such as (Pandya, 2004) found a strong positive correlation between the LAI and the NDVI calculated from remote sensing data. Therefore, if the NDVI increases, the amount of active organic material and the vegetation density in the pixel should be higher. For the test flight in the area of the island Langeoog the near infrared channel is not available. Thus, the Degree of Artificiality (DoA) as defined in (Niederöst, 2000) is used instead of the NDVI.
Next, we relate lidar intensity to vegetation density: Every layer of the vegetation where the laser pulse is reflected decrease the intensity value for the following echoes. For that reason a lower intensity indicates a higher vegetation density under the assumption of a similar reflectivity observing only one kind of vegetation and the same beam direction. However, very dense vegetation surfaces which can not be penetrated by the laser pulse yield higher intensity values. But the cross section of the illuminated area is not as homogeneous as the footprint hitting bare ground. Therefore, the average returned intensity in vegetated areas should be lower. Thus, for pre-defined neighbourhoods we compute the mean and the average of the lidar intensity (also motivated by Moffiet et al. 2005).
Furthermore, features have to be defined for the vegetation height. On one side we can use the contrast of the height image

derived from the co-occurrence matrix to describe height differences in the local neighbourhood of a pixel. A higher contrast is equivalent to larger differences of grey values, and we assume a correlation with higher vegetation. On the other side for vegetation heights larger than 0.5m different pulses can be detected by the Riegl scanner. In this case we use the differences between the first and the last pulse of lidar raw data to define the vegetation height.

Finally, instead of extracting features for the distinction of different vegetation types we use the biotope mapping in order to limit the research area to one predominant plant population.

The capabilities of extracted features to describe the characteristics of the vegetation and their influence on the accuracy of the lidar DTM are tested using the height discrepancies at the control points.

4.3 Classification

Based on the different data sources (multispectral image, lidar data, biotope mapping) a supervised classification is performed in order to divide the lidar data into different levels of accuracy depending on the predominant vegetation. Figure 3 depicts the workflow of the classification.
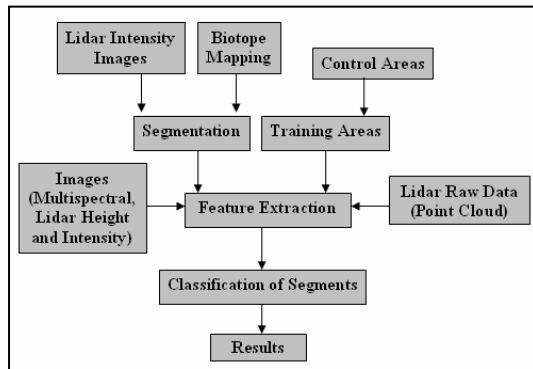

Figure 3: Classification workflow

A segment based approach for the classification was chosen in order to consider the local neighbourhood of the laser pulse and to define mean values and standard deviation as well as other texture parameters.

Initially, a DSM is calculated using the unfiltered lidar data in order to preserve texture information stemming from the vegetation. Subsequently, this DSM is transformed to a greyscale image in order to use the data in combination with the multispectral images for an image based classification. The same procedure is accomplished for the intensity values of the returned laser pulses.

The segmentation is performed using a region growing method applied to the low pass filtered lidar intensity image. Starting with the local grey value minima as seed regions (corresponds to areas with low lidar accuracy), the analysed pixel is assigned to the current segment if the difference of the average grey value of the segment and the grey value of the pixel is smaller than a certain threshold.

Previous work indicates that the vegetation type is an important factor for the accuracy of the lidar DTM and for the applicability of the discussed features. Thus, the extension of the segments and, consequently, the area of the following classification are limited to one predominant vegetation type using the borderlines of the biotope mapping.

Training areas are generated by using the height discrepancies from the control points. For that purpose a difference model is calculated and transformed into an image, so that the grey values correspond to the height discrepancies. This image is segmented into different accuracy levels. These segments are used as training areas for the classification.

In the last step the feature vectors derived for the training areas and the segmentation are used to classify the lidar height data into different levels of accuracy. In this paper the Euclidian distance between the feature vectors is used to classify the current segment. For this method the features are normalised to the same overall value in order to weight the features equally.

5. RESULTS

5.1 Characteristics of vegetation in lidar data

The influence of the vegetation type on the lidar accuracy is illustrated in figure 4. Obviously, the lidar DTM is higher than the related control points for each vegetation type (8 – 24 cm). This finding corresponds to the theoretical consideration that laser pulses do not penetrate all vegetation. For each type the standard deviation of a single measurement is only in the range from 5 up to 15cm. The highest height shift was detected for beach grass (+19.3cm), seabuckthorn (+18.4cm), sand couch grass (+20.1cm) and the mixed area seabuckthorn/willow (+23.2cm).
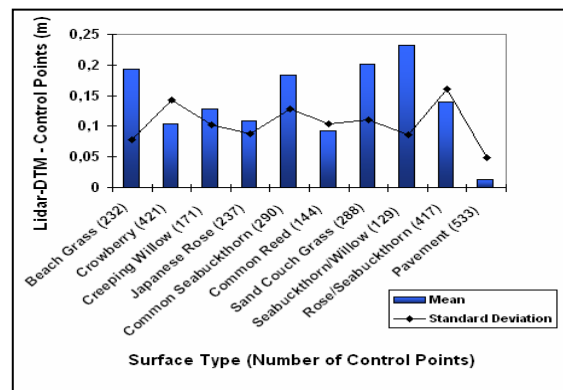

Figure 4: Height shift for different surface types (Langeoog, Riegl scanner)

Figure 5 illustrates the accuracy of the lidar DTM depending on the vegetation height. The relatively large discrepancies for the vegetation heights of 0.5 – 1.0m are caused by the beach grass belonging to this range. Various standings of beach grass produce a height shift up to 0.38m. In contrast many values obtained by the control area in the reed lead to lower discrepancies in the diagram for vegetation heights between 1.7 and 2.0m. Due to the vertical plant structure without ramifications in the leaf-off period the influence of the reed on the quality of the lidar DTM is low. In summary, the diagram demonstrates that the vegetation height without considering other parameters does not suffice in order to describe the height discrepancies in the vegetated areas.

However, considering only one vegetation type some plant heights show a strong correlation with the height discrepancies (see figure 6). Obviously, the filtering process influences these dependencies. If some points of the higher vegetation are filtered, the accuracy for the related interval increases.
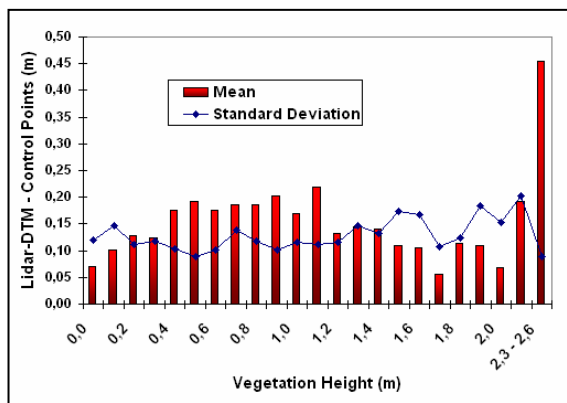
Figure 5: Height shift plotted over vegetation heights for all vegetation types (Langeoog, Riegl scanner)
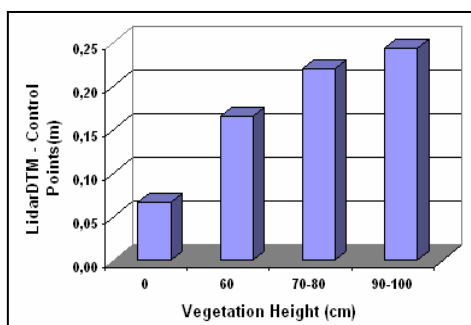

Figure 6: Height shift plotted over vegetation heights for beach grass (Langeoog, Riegl scanner)

In figure 7 the correlation between the vegetation density calculated from the fisheye images and the height discrepancies is visualised. Only a low correlation (0.19) was found considering all vegetation types. However, for several lower vegetation types a high correlation was detected, e.g. for beach grass and Japanese rose. Therefore, for certain vegetation types the defined vegetation density seems to correspond to the height shift. The two negative values are caused by some outliers which occurred due to the filtering process, as was determined by a detailed analysis of the data.
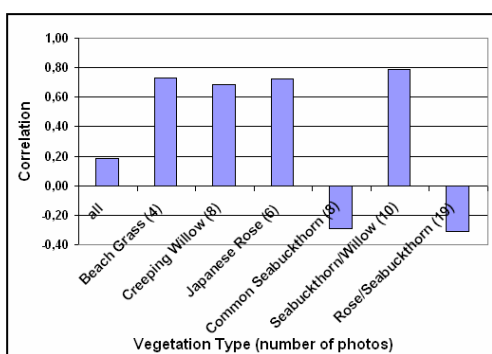

Figure 7: Correlation between the degree of coverage of the fisheye photos and the height shift (zenith angle up to 40°)

5.2 Features for classification

Figures 8 and 9 show the height discrepancies depending on the lidar intensity for some vegetation types. A high negative correlation can be detected for the intensity values (-0.51 for beach grass, see figure 8), and especially for the lidar DSM (-0.92 instead of -0.6 for the DTM, see figure 9). Thus, whereas the filtering process eliminates higher vegetation and therefore

increases the accuracy of the lidar result, it unfortunately also renders lidar intensity less useful as an indicator for the lidar DTM accuracy, because the darker points potentially belonging to the upper vegetation are filtered out.
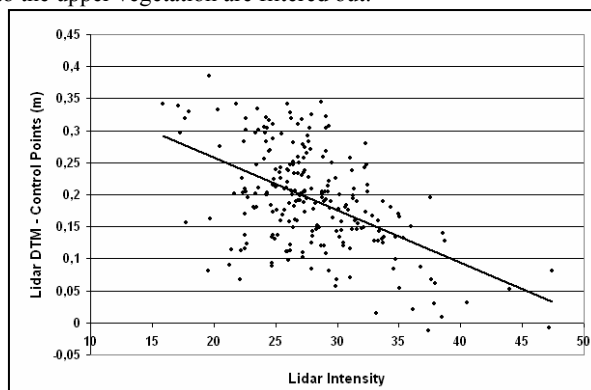

Figure 8: Height shift plotted over lidar intensity for beach grass (Langeoog, Riegl scanner)
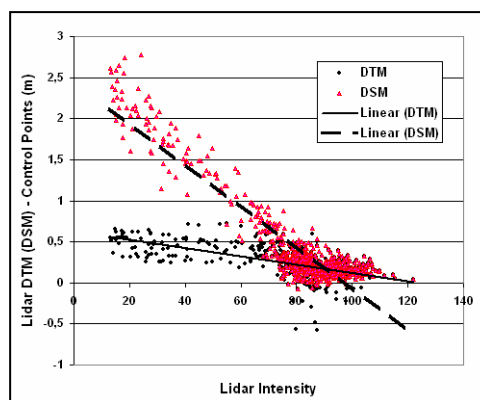

Figure 9: Height shift plotted over lidar intensity for Japanese rose/willow (Juist, ALTM scanner)

Figures 10 and 11 illustrate the height discrepancies depending on the DoA and NDVI. Only a low correlation (0.39 for beach grass (DoA), 0.23 for Dunes (NDVI)) between the height shift and the indices could be identified. Due to the fact that the measurement campaign was conducted in spring, the plants in the test area Dunes (rose, willow) had just started their activity. Therefore, in general only low NDVI values occurred. Obviously, the correlation for active vegetation such as beach grass is higher.
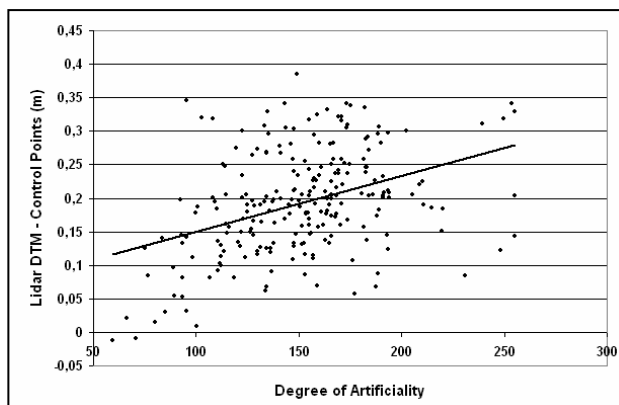

Figure 10: Height shift plotted over DoA for beach grass (island Langeoog, Riegl scanner)
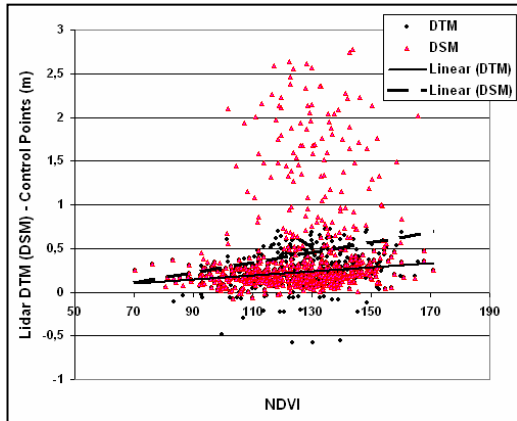
Figure 11: Height shift plotted over NDVI for the test area dunes (Japanese rose/willow, island Juist, ALTM scanner)

In summary, lidar intensity as well as vegetation indices show potential for the distinction of different accuracy levels in the lidar DTM. Additionally, a negative correlation between the height shift and the values of the channels in the visible spectrum was also detected. However, all values vary strongly in a single accuracy interval. Therefore, mean values for segments are more suitable for classification purposes.

5.3 Classification

Finally, first classification results for beach grass and the test area Dunes are presented. Tables 1 and 2 summarise the extracted features for different accuracy levels, while figures 12 and 13 illustrate the results graphically. In addition to the features discussed in 5.2 the contrast of the height image was also used (see also chapter 4.2).

In the first example two different training areas of beach grass are used to classify the same region. If the algorithm works correctly, the extracted features for the accuracy intervals in table 1 and the classifications on the left and the right side of figure 12 have to be the same. However, comparing these features and classifications some differences can be identified. The problems are associated with the different range of the height shift (table 1 second row) and the varying size of the control areas related to the accuracy levels for the two test fields. The latter one has a strong influence on the extracted height contrasts.

Table 1: Extracted features for the accuracy levels of beach grass (not normalised)

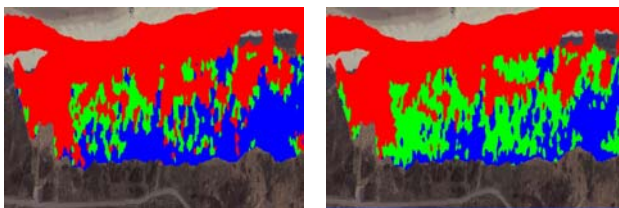| Parameter	Beach Grass 1			Beach Grass 2		
Area Height Shift (cm)	(+5,7) – (+34,5)			(-1,2) – (+38,5)		
Class (Height Shift)	<+13	<+26	>+26	<+13	<+26	>+26
Mean Blue	88,5	83,6	82,5	86,4	83,0	80,6
Mean DoA	79,5	89,0	92,7	76,1	89,2	94,5
Mean Intensity	70,0	69,6	65,1	83,6	67,7	60,8
Height Contrast	0,20	0,21	0,24	0,13	0,30	0,33

Figure 12: Classification result using two different control areas of beach grass (red = height shift up to +13cm, green = +26cm, blue = >26 cm)

Due to the completely different size and form of the training areas and the segments it is also possible to compare the classification result within the training areas in order to assess the applicability of the segmentation process and the practicability of the classification using the extracted features. A good match can be detected in the second example for the test area Dunes (figure 13).

Table 2: Extracted features for the accuracy levels of the test area Dunes (not normalised)

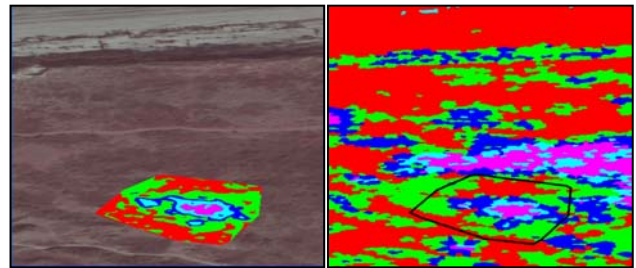| Parameter	Test Area Dunes				
Area Height Shift (cm)	(-7,7) – (+72,0)				
Class (Height Shift)	<+15	<+30	<+45	<+60	>+60
Mean Green	84,7	81,1	77,3	76,7	76,5
Mean NDVI	129,0	136,9	146,0	145,6	149,2
Mean Intensity	88,5	81,6	62,0	40,5	38,3
Height Contrast	0,28	0,34	0,68	0,62	0,50

Figure 13: Left: training area from control points, Right: Classification result for a part of the island Juist (red = height shift up to +15cm, green = +30cm, blue = +45 cm, cyan = +60cm, pink = >+60cm)

6. CONCLUSION AND OUTLOOK

This paper discusses an approach for mapping the quality of lidar heights in vegetated areas using a combination of various data sources. Some features (lidar intensity, height contrast, vegetation indices) show capabilities in order to classify lidar data in vegetated areas into different accuracy levels. However, attributes and features are strongly correlated to the vegetation type. Therefore, a biotope mapping or a multispectral classification of the vegetation has to be used in conjunction with the lidar data.

The vegetation attributes, such as the height and density, as well as some extracted features, such as lidar intensity, show a better correlation to the height discrepancies using unfiltered lidar data. Only the height contrast is related to the filtering process. Therefore, the presented method should be applied to unfiltered lidar data in order to assess the quality of the height information in vegetated areas, and the filtering process has to be modelled as well. For example, a simple method can be designed using a difference model between the unfiltered and the filtered lidar heights. This difference model can then be subtracted from the predicted height shift.

The transferability of the features extracted from the lidar data to other scanners, flight conditions and regions seems to be difficult. For instance, lidar intensity values depend on many parameters (i.e. the scanner type, echo detection methods and intensity determination, characteristics of the emitted pulse, flight date, surface type etc.). For the general transferability of the method this approach uses ground truth data which adapt the features to the current conditions.

ACKNOWLEDGMENTS

REFERENCES

Ahokas, E., Kaartinen, H., Hyyppä, J.(2003): A quality assessment of airborne laser scanner data. The International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3/W13, Dresden, Germany.

Gorte, B., Pfeifer, N., Oude Elberink, S. (2005): Height texture of low vegetation in airborne laser scanner data and its potential for DTM correction. The International archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVI, Part 3/W19, pp. 150-155.

Haralick, R. M. (1979). Statistical and structural approaches to texture. Proceedings of the IEEE 67(5), 786–804.

Hodgson, M. and P. Bresnahan (2004). Accuracy of Airborne Lidar-Derived Elevation: Empirical Assessment and Error Budget. Photogrammetric Engineering & Remote Sensing, Vol. 70, No. 3, March 2004, pp. 331-339.

Hopkinson, C., Lim, K., Chasmer, L.E., Treitz, P., Creed, I.F., Gynan, C. (2004): Wetland grass to plantation forest – estimating vegetation height from the standard deviation of lidar frequency distributions. The International archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVI, Part 8/W2, pp. 288-294.

Moffiet, T., Mengerson, K., Witte, C., King, R., Denham, R. (2005): Airborne laser scanning: Exploratory data analysis indcates variables for classification of individual trees or forest stands according to species. ISPRS Journal of Photogrammetry & Remote Sensing 59 (2005), pp. 289-309.

Mundt, J. T., Streutker D. R., Glenn N.F. (2006): Mapping Sagebrush Distribution Using Fusion of Hyperspectral and Lidar Classifications. In Photogrammetric Engineering & Remote Sensing, Vol. 72, No.1, January 2006, pp. 47-54.

Niederöst, M. (2000): Reliable Reconstruction of Buildings for Digital Map Revision. The International Archives of Photogrammetry and Remote Sensing, ISPRS, Amsterdam, Netherlands, Vol. XXXIII, Part B3, pp. 635-642.

Oude Elberink, S. and M. Crombaghs (2004). Laseraltimetrie voor de hoogtemetingen van de kwelders Waddenzee. Technical Report AGI-GAP-2003-50 (in Dutch), AGI, RWS, The Netherlands.

Pandya, M.R. (2004): Leaf Area Index Retrieval Using Irs Liss-iii Sensor Data and validation of Modis Lai Product Over India. The International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, Part B7, pp. 144-149.

Pfeifer, N., Gorte, B., Oude Elberink, S. (2004): Influences of Vegetation on Laser Altimetry – Analysis and Correction Approaches. The International archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part 8/W2, pp. 283-287.

Straub, B., Heipke, C. (2001): Automatic Extraction of Trees for 3D-City Models from Images and Height Data. Automatic Extraction of Man-Made Objects from Aerial and Space Images. Vol. 3., eds. Baltsavias, Gruen, van Gool, A.A.Balkema Publishers. Lisse Abingdon Exton(PA) Tokio. pp. 267-277.

Schwalbe, E. (2005): Geometric Modelling and Calibration of Fisheye Lens Camera Systems. The International archives of Photogrammetry, Remote Sensing and Spatial Information Sciences.Vol. XXXVI, Part 5/W8.

Wagner, W., Ullrich, A., Melzer, T., Briese, C., Kraus, K.(2004): From single-pulse to full-waveform airborne laser scanners: Potential and practical challenges. The International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, Part B3, pp. 201-206.