Aspects of Lidar Processing in Coastal Areas

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ABSTRACT:

The coastline of the North Sea is characterized by a large number of different morphological structures like dikes, dunes, and tidal creeks. Due to the tidal effects and other natural forces like wind the shape, size and position of such objects may change rapidly over time. In order to securely protect shorelines and coastal areas, a permanent monitoring has to be performed.
In the past, mainly terrestrial surveys and photogrammetry have been used to obtain information about changes in time. In general these surveys included morphological features like form- and breaklines. Important changes of the monitored objects can be detected by comparing identical morphological features of different time epochs. Unfortunately the terrestrial surveys include a lot of disadvantages like high costs, sometimes very difficult or even impossible to perform and very time consuming.
Concerning the aspects of the frequency of surveys and the accessibility to tidal areas Airborne Laserscanning (Lidar) is perhaps more adopted to map changes of morphological objects. However the use of Lidar data gives some new problems, three of them will be shown here together with attempts for their resolving.
In many cases especially in flat tidal lands water does not vanish totally during low tide, but areas of water coverage remain and the boundary of tidal land to water can not be extracted accurately from the height data of the Lidar systems. This is especially important, because the Lidar data will be intersected with regular echo sounder data to yield a 3D topography of the coastal area of the German Bight. An approach on how to tackle this problem is shown in this paper.
Especially on the islands, but also on the coast side the accuracy of the laser heights sometimes is not very high, because vegetated areas, which have not been found by the filtering processes being applied to the data by the surveying companies. This is due to the fact that recognition of these types of vegetation is very difficult. Because of the density and type of this typical vegetation even ground truth measurements within these areas are very difficult to perform. Therefore it is desirable to have an indication of the error magnitude at these sites which can be stored together with the height data as quality information. Attempts to do this by using structural information derived from height textures together with Lidar intensities and/or simultaneously imaged multispectral data are investigated.
Because of the amount of data, the use of the total number of measured laser points in performing change detection mapping is very time consuming. This can be improved by an prior extraction of morphological features, like breaklines. Their extraction can be done by fitting suitable functions into the 3D-Points of the object. Due to the fact that the properties of used functions are known à priori, form- and/or breaklines may be modelled from the estimated parameters of the function.

1. INTRODUCTION

For some years Lidar Data has been extensively used for topographic mapping in areas such as islands, tidal flats and coastal areas with special respect to detailed morphology and change detection. These changes result in morphological modifications of the terrain structure (Breaklines, tidal creeks and other structures) together with erosion and sedimentation processes. The mentioned changes are of extreme relevance since they immediately have an impact on constructions for coastal protection and their functionality in different time scales and hence result in an endangerment of the area and the people living there. Therefore the rapid and accurate detection and documentation of such changes is an important task of coastal protection. Furthermore these changes have an immediate influence to the security of shipping traffic in tidal regions.

Following a constant improvement of the Lidar technology and an increase in the economy of the procedure the possibilities of partly replacing in particular the methods of sounding or terrestrial measurements of difficult to access tidal areas is being considered by using laser scanner methods.

The mapping of morphological changes is a permanent task of the Federal Waterways Administration, who recently enforced the use of Lidar technology in the framework of conservation of evidence to determine morphological variations in the Jade estuary and the estuary mouths of the rivers Weser and Elbe. By using laser scanning technology in combination with high resolution soundings from vessels morphological data for numerical modelling of estuaries are obtained which serve to assess the impact of planned expansion constructions (Jade, Weser, Elbe) or to assess the optimization of flood barrage systems, such as those of the river Ems.

The data as obtained from the contracted Lidar survey companies are pre-processed according to geometry and removal of non-topographic objects (filtering) in order to obtain a Digital Terrain Model (DTM). It could be shown, that these data is partly erroneous. In some parts vegetated areas have not been detected and remain in the filtered data. As an example the heights of abundantly covered troughs do not differ from heights in the surrounding area of these objects and hence do not represent the actual terrain. Further problems remain in the distinguishing of the border between land and water (waterline), which can not be detected accurate enough by using common procedures.

Generally break- and formlines are not computed and are missing in order to do morphological and topographic accurate terrain mapping. First approaches to this problem have been developed and tested, but difficulties remain for an operational use, such as missing density of the data or the fact, that the signal is close to the noise level (in terms of height variations).

One important goal of the use of Lidar technology is the establishment of high accurate Digital Elevation models (DEM) of tidal flats and coastal areas. By an analysis of these DEM and a comparison to surveys of prior epochs important insights can be gained, like possible changes of objects like dikes, dunes, structural changes of the land- water boundaries, tidal channels and foreland edges. Because the point density of Lidar is much higher than that of multi-beam echo sounders, coastal areas are surveyed by Lidar at low tide. Although the time of survey is during the minimum water level, part of the water remains within tidal creeks, extending through the area similar to a river delta. Frequently water can be found also in small depressions and hollows of the tidal flats, which never get dry. These areas, which belong also to the DEM, have to be filled with height data from other sources like echo soundings. Therefore the extent of these areas has to be mapped. One method of using the intensity data of Lidar systems is shown in the next chapter.

The results shown in this paper are the preliminary findings of a research project on the “Development of regionally adapted procedures and tools for the processing of Lidar Data from island, tidal and coastal areas”, being funded by the Federal Ministry of Education and Research (BMBF) under project no. 03KIS050.

2. AN ATTEMPT TO MAP THE LAND WATER BOUNDARY BY LIDAR

In order to calculate an accurate DTM in coastal areas, water covered regions, which do not belong to the terrain surface, within the surveyed area have to be estimated and eliminated from the calculation process. This can be done by using common classification techniques like maximum likelihood, if digital imageries, which have to be taken at the same time as the Lidar measurement, are available. Due to the fact that the collection of laserscan data and digital imagery is more cost consuming, a suitable approach has to be developed to divide the originally laser points into water and non water points. For this purpose only the original Lidar data including height and intensity can be used.

2.1 Basic principles

To develop a suitable algorithm which divides laser points into water and non water points the physical characteristics of the reflection of water and land areas has to be considered.
Like any other liquid substance water tries to keep the smallest possible amount of potential energy E_{pot}. Furthermore the potential energy of all water molecules at the surface of a plane water area is the same. Due to these facts calm water areas are always surrounded by land having a higher potential energy (as well as a larger height value).

Generally the amplitude of the intensity of a returned laser beam echo for an illuminated water area is lower than the intensity echo of an illuminated land area within the survey area. This is because a vast part of the emitted radiation energy E_{emi} is absorbed by the water (Figure 1). Additionally water surfaces generally do not behave like a Lambertian emitter. As a result of the Rayleigh Criteria (Pedrotti and Pedrotti 1987) the calm water surface behaves like a mirror. Thus directed reflexion occurs. Depending on the spatial orientation of the aircraft and the emitted laser pulse and the water surface with respect to each other only a small part of the emitted radiation E_{emi} comes back to the detector (Frauendorfer 2002). Often a distance measurement can not accomplished successfully because the received radiation energy E_{rec} is not distinguishable from background noise.

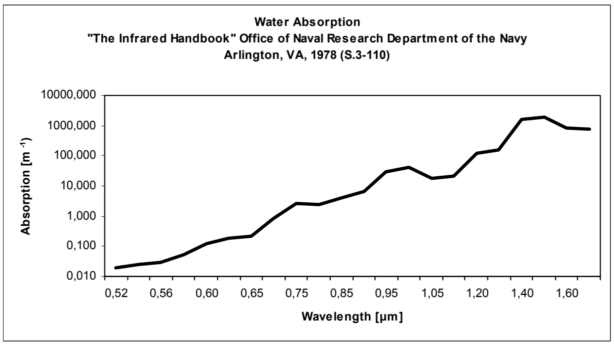

Figure 1: Absorption coefficient of pure water (Wolfe et al 1989)

2.2 Segmentation attempt for water and non water areas

Taking the basic principles elucidated in 2.1 into account, following approach is made:

At first a Digital Surface Model (DSM) is calculated from all laser points. The DSM is smoothed by using lowpass filtering. Then local height minima are extracted from the DSM. This is followed by a region growing using height and intensity data. The local minima represent the potential seed zones of the searched water areas.
The local height minima are sorted in relation to their mean height. Only local height minima below an empiric determined height threshold are used to perform the region growing. Then the first region is checked whether it is a water region or not. If the mean intensity value of the region is lower than an empiric given intensity value, the region is classified as water area (otherwise as a land region). In this case an adjusted height plane using all region pixels is calculated. Due to stochastic measurement errors and the influence of tide and wind the local minima do not match the searched water area completely. Thus the region is expanded by performing a dilation using a circle as structure element in that way, that the region grows in all direction by one pixel. Consecutively every boundary pixel is checked by two rules to be a water or non water pixel.

Rule 1:

Due to stochastic measurement errors, the influence of tide and wind, the level of one contiguous water area is not equal. However the probability of the existence of a water pixel decreases if the height increases. Thus a filling threshold is used. If the height value of the pixel is higher than the sum of the height of the adjusted plane and the filling threshold the pixel is detected as land. Therefore it is eliminated from the region. If the height value of the pixel is lower than the sum of the height of the adjusted plane and the filling threshold the pixel is detected as water and remains in the region.

Rule 2:

As mentioned in section 2.1 the received intensity of the laser beam is commonly lower if the illuminated area is covered by water. Thus an empirically determined intensity threshold is used to decide whether a water pixel occurs. If the intensity of the pixel is lower than the intensity threshold the pixel is classified as water pixel and remains in the extracted region. If the intensity is higher the pixel is classified as land pixel and is removed from the region.

If not all border points are classified as land pixel it is checked if other local minima overlap the region. In this case the other local minima and the actual extracted water region are melted. Then the iterative process consisting of dilation and applying the rules is done as long as at least one border pixel is classified as water pixel. After accomplishing the first region, all other regions are treated in the same way.

2.2.1 The usage of a trend plane

Due to tide, currents, wind and other natural effects the height within one water region may vary. This can be accounted for by estimating a trend plane from all pixel heights of one region instead of using the mean height value. Thus also tilted water areas such as tidal creeks and rivers can be detected.

2.3 Example

The capability the algorithm was tested with laserscanning data of the south part of the German isle "Sylt" acquired by the company Toposys in 2003. In the left part of figure 2, the area is displayed in a colour infrared image. After deriving all local minima up to an empiric determined height threshold (figure 2, middle), the water area was extracted using the approach above. 98.5% of the existent water area was derived. Only crest of waves could not be detected due to the fact that the height difference between crest and trough is to huge. But in an additional step they can be easily detected and merged with the extracted water area.

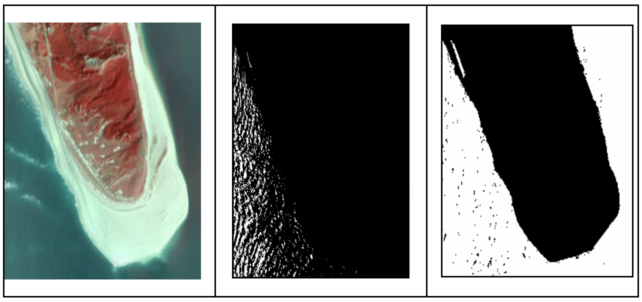

Figure 2: Detection of water areas within coastal area (left: colour infrared orthophoto, middle: local height minima, right: extracted water area)

3. THE PROBLEM OF VEGETATED AREAS

In this part of the project, which is described in the following, the influence of different types of coastal vegetation on the accuracy of digital elevation models (DEM's), derived from laser scanning data, is analyzed. The penetration rate and the reflectance of the laser pulse are changing seriously depending on the kind of vegetation. Therefore thick, felted layers of mulch (i.e. within reed areas) produce important inaccuracies in the calculated elevation model.

The main focus of the project consists in the generation of an exact DEM for the coastal area especially for dunes and the transition zone between land and water. The protection of the coast requires precise information about the elevation of the terrain, thus it is necessary to eliminate or at least to estimate the possible errors in the laser data, caused by the vegetation.
Starting with a comparison of terrestrial control measurements to the data obtained by the Airborne Laser Scanner (ALS) it would become possible to detect problematic areas with regard to the accuracy of the DEM. The work focuses on different types of vegetation, beginning with layers of biomass covering the ground in spring especially during the flight with ALS, produced by felted layers of mulch or bear leaves during winter times. For example dense standings of beach grass and shrubberies in dunes, reed and cane brake in the transition zone between land and water belong to the monitored vegetation types. The characteristic of the specific vegetation varies seriously with the properties of the particular habitat (water supply, nutritional/salt content). Thus a distinction between island and coastal areas is necessary due to the different soils and geological history.
In addition to the vegetation types structure data, like the size and density of vegetation or the leaf area index (LAI), will be collected during the project, in order to classify and combine different kind of vegetation having the same properties and a similar influence to the laser data.
Because this vegetation cover heavily decreases the accuracy of the Laser-DEM, a combined analysis of the terrestrial control measurements and the laser data is performed in the next step for every vegetation unit. Typical features are extracted from the available remote sensing data (ranging from laser heights and intensity information, but also including multispectral data). This is done in order to identify the problematic regions as good as possible in the total data set by computerized classification. For the detected areas the accuracy of the Laser-DEM has to be estimated.

3.1 First Results

The company TopScan conducted a laser flight with a recording of the last pulse and simultaneous multispectral data covering the area of dunes and tidal flats of the island of Juist in spring 2004. As a result irregularly distributed laser points (X-, Y-, Z-coordinates), classified in ground and vegetation points, have been delivered.
Terrestrial control measurements, including the registration of the ground elevation as well as the vegetation height, were accomplished in parallel. For this purpose three test areas with different vegetation have been chosen.
The first region ("Dunes") is covered by various kinds of coastal shrubberies with vegetation heights up to 2.9 m. In contrast the second area ("Grass") is situated in the salt meadows and contains plants up to a height of 0.8 m. The third region ("Reed") is overgrown with reed and can be found in the salt meadows, too. The vegetation height of the last area reaches up to 2.0 m.
For each of the regions "Dunes" and "Reed" two DEM were calculated, using on the one side the classified ground points only, on the other side all laser points of the corresponding area. In the test area "Grass" only one model was derived, because all received laser pulse have been assigned to the category "ground points". The Z-values for the X- and Y-coordinates of the terrestrial control points have then been interpolated from the different Laser-DEMs. Therefore it was possible to calculate the height differences ($H_{Laser} - H_{terr.}$). Table 1 shows the most important results of the test area "Dunes".

Test area	Dunes	
Laser points	ground	all
Number of control points	697	
Mean value of the differences (H_{Laser} - $H_{terr.}$)	0,225 m	0,428 m
Standard deviation (mean value)	0,171 m	0,558 m
Standard deviation (0)	0,283 m	0,703 m
Max. difference (vegetation height)	0,720 m (1,9 m)	2,775 m (2,9 m)
Min. difference (vegetation height)	- 0,577 m (0,0 m)	- 0,077 m (0,0 m)

Table 1: Statistics for the differences H_{Laser} - $H_{terr.}$

The mean height of the Laser-DEM (calculated only with classified ground points) at the control points is 22.5 cm above the height, determined by terrestrial measurements. This difference consists of an offset (10 cm), which was also observed in flat areas without vegetation for this flight session, and the influence of those laser points, which should be classified as vegetation, but were not detected by the filter algorithm. This problem can also be observed at the point of the maximal difference (72 cm) to the corresponding vegetation height of 1.9 m. Although the laser pulse only penetrates the vegetation up to a certain level, the respective point was assigned to the ground.
The inverse effect can be watched at the point of the minimal difference (-58 cm). A small hill without vegetation, which was wrongly filtered from the ground points, is situated at this location. If all laser points of the respective area, including the so called vegetation points, are used to calculate the elevation model, the mean difference in this terrain yields 10 cm according to the already mentioned offset.
The mean value of the differences regarding to the DEM of all laser points amounts to 42.8 cm. For those areas, in which the laser pulse was reflected by the upper layers of the vegetation, maximal differences up to 2.8 m occur comparable to the vegetation height.

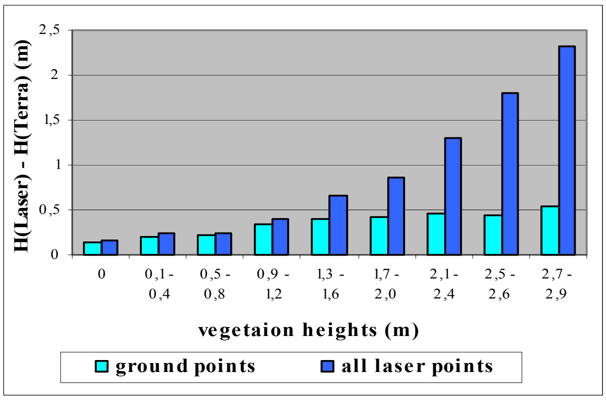

Figure 3: Dependencies between the differences ($H_{Laser} - H_{terr.}$) and vegetation heights

Figure 3 illustrates the dependencies between the height differences ($H_{Laser} - H_{terr.}$) and the vegetation heights. For that purpose the mean values of the height differences of the corresponding points are assigned to the vegetation heights, divided into intervals with an equal number of control points.

At control points without vegetation the mentioned offset (15 cm) is easy to identify again. However this offset is additionally influenced by plants in the immediate vicinity of the control points. The illuminated area of the laser pulse consists of vegetation and ground parts (Figure 4).

Figure 4: Illuminated area of the laser pulse (Katzenbeisser et al., 2004)

The expected dependencies between the vegetation heights and the differences, derived from the control measurements and the DEM, which is calculated with the unfiltered laser points, can be obviously recognised in the diagram of Figure 3. Due to the fact that not all vegetation points were classified correctly, a similar but reduced correlation also exists for the DEM, derived from the ground points only.
With the terrestrial vegetation heights and the determined height differences a possibility exists to estimate the penetration depths of the laser pulse (last pulse measurement), which are visualized by the diagram in Figure 5.

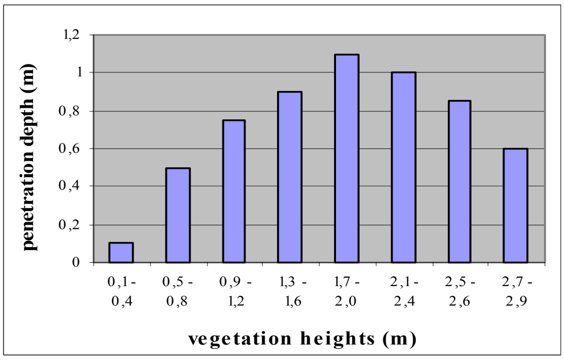

Figure 5: Penetration depth of the laser pulse

The determined penetration depths within the discrete intervals of vegetation heights are also very inhomogeneous (simultaneous to the values of the different intervals in the diagram) and vary altogether from a few centimetres up to 1.8 m. Due to the diverse characteristics of the respective vegetation type (in this case coastal shrubbery) regarding to its structure (density of vegetation, penetration rate, LAI) an estimation of the DEM accuracy requires a distinction of different homogeneous areas within the same kind of vegetation. So it becomes possible to rearrange similar areas of different vegetation types into new classes, which then have to be extracted from the remote sensing data.

4. EXTRACTION OF STRUCTURE LINES FROM LIDAR

To monitor changes of morphological objects in coastal areas in order to secure the anthroposphere, Digital Terrain Models (DTMs) of high accuracy have to be obtained. The implementation of structure lines within the calculation process increases the accuracy of the derived DTMs and even allows data reduction. Moreover the extracted structure lines of different time epochs of the same morphological objects can be compared to detect changes in horizontal and vertical position.

4.1 Structure line extraction by surface reconstruction

The main idea to extract form- and breaklines from the original irregularly distributed point cloud is to reconstruct the surface close to the structure line with one or more suitable a priory known mathematical functions (Brzank 2001). Depending on a à priori given approach of how to calculate the structure lines from the fitted function the structure lines can be derived.
One model to extract 3D Breaklines using two intersecting planes as fitted functions was presented by Kraus and Pfeifer (2001) and Briese et al. (2002), see also Brzank (2001). This approach is capable to obtain breaklines from the irregularly distributed 3D point cloud. However a 2D approximation of the searched breakline is necessary to execute the calculation.
To overcome the need of the 2D approximation Briese (2004) uses 3D Breakline growing. This approach seems to be suitable for Breaklines with only small changes in the direction. However there might be problems in deriving an accurate 2D approximation if huge direction changes occur.
Additionally Briese (2004) implements a robust estimation of the unknown parameters based on robust interpolation technique (Kraus and Pfeiffer 1998). Thus it is possible to model the planes with all originally acquired laser points.

4.2 Developing a suitable model to extract structure lines in coastal area

In coastal areas various kinds of structure lines occur. They can be classified into break- and formlines. If the true surface at the structure line is continuously differentiable, there is a formline. If the true surface is not continuously differentiable a breakline occurs. Figure 6 pictures typical edge profiles, which are common within coastal areas. Typically, always two structure lines appear together.

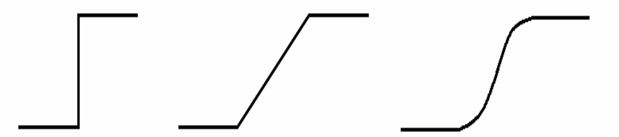

Figure 6: Typical edge profiles in coastal areas – step edge, ramp edge, curved edge (from left to right)

To calculate structure lines within coastal areas several demands have to be defined:

1. The number of estimated structure lines is two.
2. There is one continuous function that is capable to approximate the surface within the two structure lines and their surrounding.
3. The number of parameters to be estimated should be low.
4. The model is capable to determine breaklines as well as form-lines.
5. The calculation of all noted edges (steep, ramp and curved edge) must be possible.

An adapted function which fulfils the demands 1 - 3 is a hyperbolic tangent function (equation 1a). It is capable to approximate all showed edges profiles (figure 10) very accurate.

$$z(u,v) = s\tanh(f(v+p)) + k + tu \quad (1a)$$

$$u = \cos(\alpha)x + \sin(\alpha)y \quad (1b)$$

$$v = -\sin(\alpha)x + \cos(\alpha)y \quad (1c)$$

Actually the number of parameters to model a hyperbolic tangent function is four (**s**,**f**,**p**,**k**). Additionally, two further parameters are needed to enable a slope in direction of the u-axis (**t**) and a rotation parameter (**α**) to rotate the coordinates of the laser points $(x, y, z)^T$ into the function fixed coordinate system $(u, v, z)^T$ (equation 1b and 1c).
In order to fulfil demand 4 and 5 the structure lines have to be calculated from the adjusted hyperbolic tangent function depending on the edge type and edges profile. A super-imposition of the surface function and typical edge profiles clarifies the approach (figure 7).

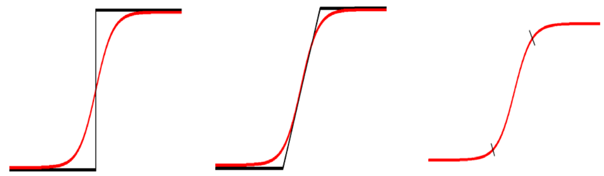

Figure 7: Calculation of structure points depending on edge type - step edge, ramp edge, curved edge (from left to right)

If a step or a ramp edge occurs, a horizontal plane at the lower as well as the higher plateau is calculated. These planes are intersected by a third plane within the line of maximal slope in the direction of the v-axis. If a step edge has to be derived, a vertical plane is used. If a ramp edge has to be estimated, a tilted plane with the maximum slope of the hyperbolic tangent within the v-axis is used. The edge lines are equal to the intersection points of the three planes. If a curved edge occurs the searched form-lines can be calculated by finding the two straight lines with maximum value of curvature.

4.3 Structure line extraction by surface reconstruction with a hyperbolic tangent function

To start the reconstruction of the surface the approximate centre line of the searched structure line pair is needed. It can be derived by using common edge detection in digital imagery like the Canny operator (Sui, 2002). After selecting one centre line all laser points within a buffer are extracted and sorted into patches with a fixed length and an overlapping ratio. For each patch initial values of all six unknown parameters are calculated. Depending on the accuracy of the approximate centre line, the quality of the initial values can be too low to calculate the six unknown parameter successfully. Due to that reason each of the six initial values can be used in an additional equation to stabilize the least-squares adjustment. Then an iterative adjustment calculation process is started, as long as either the unknown parameters converge to a fixed value or a maximum number of iteration is done. Afterwards the calculated unknowns are used as improved start values for a second iterative adjustment process. However no additional observation is used. Finally the six parameters for every patch can be derived. Depending on the a priori known edge type, straight form- or breakline pairs can be calculated for every patch. Then a spline is calculated for both structure lines linking together one automatically selected point of the upper and lower structure line as well as the direction in every patch.

4.4 Example

To visualise the capabilities of our approach a meaningful example is shown. Figure 8 shows the extraction of a formline pair within a tidal area near the German city Bremerhaven. Setting the patch length to 10m with an overlapping rate of 50% - 92 patches had to be solved. One patch could not be calculated successfully. Furthermore 5 patches were eliminated after failing to derive a valid value for parameter **f**.

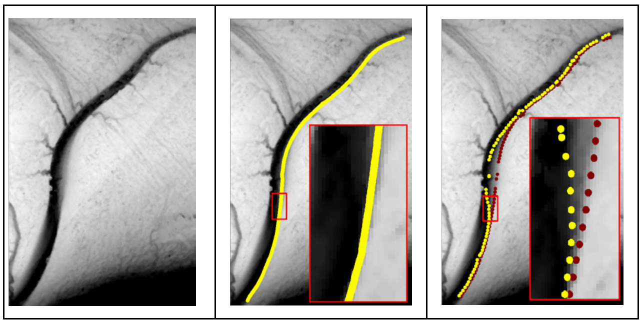

Figure 8: Derivation of one formline pair (left: DTM, middle: extracted centre line, right: valid formline points

5. SUMMARY

An approach has been shown for the extraction of land and water areas within laserscanner data sets. This approach has been successfully tested on a small data set of the TOPOSYS sensor and the very preliminary have to be verified using other data sets. This will be accomplished in future.

The example of the test area "Dunes" in chapter 3 showed obviously, that the accuracy of the laser data should be critically checked. On the one side many vegetation points have been classified incorrectly and remain as interpolation points in the elevation model, on the other side small hills have been wrongly assigned to vegetation. In order to get reliable information for coastal safety, an estimation of the influence of the vegetation on the created DEM is crucial. For this purpose different classes have to be derived from the available data, which not necessarily match the vegetation types similar to a biotope mapping, but rather consider the structure of the vegetation and its influence on the reflection of the laser pulse.

This paper also presents in chapter 4 an algorithm to extract structure lines within coastal areas from Airborne Laserscanner points. The Algorithm consists of two main parts. First a suitable 2D approximation of the structure lines is derived by using edge detectors. Then a model to express the structure lines is created. It implies, that each edge is formed by two structure lines, which have to be derived. The used surface function is hyperbolic tangent. After creating the patches all points within the structure line area are assigned to them. A tricky task is the derivation of exact start values of the unknown. They are estimated from laser points within a patch using an iterative analysis adjustment. Then the main iterative adjustment is being calculated. After checking the results, the structure lines can be derived, depending on the used calculation model.
The example in section 4 shows, that this algorithm is capable to extract structure lines in coastal areas.
However there are several problems within this algorithm that have to be solved in the future.
Thus the calculation of the 2D approximate centre line is not perfect. Line parts obviously belonging together are derived separately from each other. A suitable linking algorithm, which connects line parts has to be found and implemented.
Furthermore the real surface does not match the assumed hyperbolic tangent model. Other suitable functions as well as combination of several functions have to be used in order to describe the surface to the best possible.
Another important problem is to find an intelligent automatic procedure to select the appropriate buffer zone around the structure line, which on the one hand is optimally fitted to the structure of the terrain and on the other hand large enough to give a good estimation of the used functions.

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