Automated extraction of pair wise structure lines using airborne laserscanner data in coastal areas

A. Brzank, P. Lohmann, C. Heipke

Institute of Photogrammetry and GeoInformation
University of Hannover
(brzank, lohmann, heipke)@ipi.uni-hannover.de

KEY WORDS: Laser scanning, LIDAR, structure and breakline detection, surface reconstruction

ABSTRACT:

The coastline of the North Sea is characterized by a large number of different morphological objects like dikes, dunes and tidal creeks. Due to the tidal effects and other natural forces 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 aerial imagery have been used to obtain information about changes in time. In general these surveys include morphological features like structure lines. Important changes of the monitored objects can be detected by comparing identical morphological features of different time epochs. Unfortunately, the terrestrial surveys are very costly and time-consuming.
For this reason airborne laserscanning has been adopted to map changes of morphological objects. The first step of the monitoring task is the extraction of morphological features from the irregularly distributed 3D point cloud. One strategy of the extraction task is to fit suitable 2D functions to the 3D-points. Due to the fact that the choice of the used function represents known a priori information, structure lines can be derived from the estimated parameters of the function. However, a 2D approximation of the searched structure line is generally needed.
This paper presents a new method for the extraction of structure lines from airborne laserscanner data in coastal areas using a hyperbolic tangent function. The method is based on a strategy that pre-defines the number of structure lines to be searched, the shape of the surface, the number of functions to be used and the approach how to calculate the structure lines from the surface function. Additionally, it is shown that the necessary 2D approximation can be estimated by digital edge detectors using a raster representation of the irregular laser points. Two meaningful examples are presented to demonstrate the capability of the algorithm.

1. INTRODUCTION

In general, due to tidal effects the appearance of coastal areas changes very fast. These changes in shape, size and position of objects like dikes, dunes and tidal creeks have to be permanently monitored to protect the safety of people within the coastal area as well as their property. Existing monitoring approaches use terrestrial surveys and aerial imagery to map morphological changes of coastal areas. Usually conspicuous characteristics of the morphological objects like structure lines (formlines as well as breaklines) are captured and compared to those from different time epochs. However, these methods are costly and time consuming. Thus, in general only small parts of the coastal area can be monitored.
In this regard airborne laserscanning opens new possibilities to monitor coastal areas. Due to the fact that several laser points per m^2 can be registered fast, Digital Terrain Models (DTM) of large areas can be derived (e.g. Brügelmann and Bollweg 2002). Because of limited point density, in general, the computation of difference models between two epochs alone is not sufficient. The extraction of features like breaklines is therefore of great importance for coastal engineers.
This paper first summarizes previous algorithmic approaches for 3D structure line extraction before our own approach is presented, which is based on the reconstructing the surface patches from airborne laserscanner points in the form of a hyperbolic tangent function in a non-linear least-squares adjustment. The necessary 2D approximation of the centre line between the two structure lines of an edge (upper and lower ridge) are found by applying edge detection to a gridded version of the point cloud. Then, the two corresponding structure lines can be computed from the parameters of the estimated hyperbolic tangent function.
Two examples demonstrate the capability of this technique. Finally, this paper concludes with a summary and an outlook on further development issues.

2. STATUS OF RESEARCH

The extraction of breaklines is a crucial intermediate step to enable an accurate and morphologically correct computation of DTM’s and to perform proper data reduction in airborne laserscanning (Brügelmann 2000). Various attempts have been made in the past to develop approaches suitable for this task.

2.1 Approaches based of image processing

Weidner and Förstner (1995) propose an algorithm for a parameter free and information conserving surface description by applying a variance component estimation (simultaneously for signal and noise) and using this information for filtering. In doing so, discontinuities in the data are preserved. A similar procedure was proposed by Wild and Krzystek (1996) to automatically derive DTM’s from stereo images.
Many algorithms use digital image processing techniques, based on grids of height data. For example Gomes-Pereira and Wicherson (1999) used the Prewitt edge operator to calculate the first derivate in x- and y-direction. Then, all grid points were classified into ‘slope pixel’ or ‘flat pixel’. Breaklines were

extracted by checking the 8-point neighbourhood assuming that breaklines are situated between slopes and flat areas. Similar approaches using the Laplacian operator (Gomes-Pereira and Wicherson 1999) as well as the Canny operator (Sui 2002) have been published. Brügelmann and Bollweg (2004) created an algorithm which is based on the use of the second derivative kernels of the Gaussian in connection with a hypothesis test. As mentioned, all these approaches have in common that they do not use the original laserscanner points but a raster. This implies a certain decrease of accuracy due to the necessary interpolation process. Furthermore in most cases, the result is a 2D breakline. To obtain 3D lines the z-coordinates are calculated in a separate process.

2.2 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 priori known mathematical functions. This means, a model that includes both, the type and number of searched structure lines, their shape, the surface in the vicinity and a rule how to calculate the structure lines from the estimated function, have to be defined. Depending on the model, a suitable fitting function or a combination of several functions are used. Then, the parameters of the function are estimated, usually in an iterative least-squares adjustment. After the parameters of the function(s) are known, the 3D position of the structure line(s) can be determined.

2.2.1 Breakline extraction using two intersecting planes

One model to extract 3D breaklines was presented by Kraus and Pfeifer (2001) and Briese et al. (2002), see also Brzank (2001). This method estimates the 3D-position of one breakline by fitting two planes (one plane on each side along the breakline) for several interconnected patches. A 2D-approximation of the breakline is required to assign a laser point either to the left or the right plane. The intersection line of the two estimated planes in every patch forms a suitable approximation of the searched breakline.

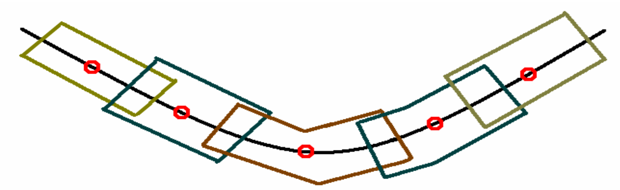

Figure 1: Overlapping patches with derived breakline points and breakline spline

The principle is shown in figure 1. The area near the breakline is divided into overlapping patches with a certain length. In each patch two planes have to be estimated. At first, all points inside the patch are assigned either to the left or right plane depending on their position with respect to the given breakline approximation. Then, a least-squares adjustment is calculated using the observation equations (1a), (1b) and (1c).

3D points $P_{i,l}$, left side:

$$r_{i,l} = \underline{a_l} X_{i,l} + \underline{b_l} Y_{i,l} + \underline{c_l} - Z_{i,l} \qquad (1a)$$

3D points $P_{i,r}$, right side:

$$r_{i,r} = \underline{a_r} X_{i,r} + \underline{b_r} Y_{i,r} + \underline{c_r} - Z_{i,r} \qquad (1b)$$

2D points $P_{i,b}$, approximating the breakline:

$$r_i = \underline{a_l} X_{i,l} + \underline{b_l} Y_{i,l} + \underline{c_l} - \underline{a_r} X_{i,r} - \underline{b_r} Y_{i,r} - \underline{c_r} \qquad (1c)$$

where: $\underline{a_l}, \underline{b_l}, \underline{c_l}$ = parameters of the left plane
$\underline{a_r}, \underline{b_r}, \underline{c_r}$ = parameters of the right plane
i = index of point number
$r_{i,l}, r_{i,r}, r_i$ = residuals of the adjustment

Each 3D-point yields one equation for the least-squares adjustment, as well as each 2D-point approximating the breakline. The unknowns, underlined in the equations, are the six parameters of the two planes. Equation (1c) was introduced as a safeguard against unstable situations. A proper weight must be chosen for this equation to guarantee that the solution does not arbitrarily derivate from the approximation.

After calculating the parameters of both planes, it has to be checked whether the solution is the best fitting plane pair for the laser points. Therefore the intersection line of the two adjusted planes is used to reassign the laser points to the left and right side. If this process of assignment leads to a new classification of at least one laser point, a new least-squares adjustment is calculated. This iterative process of reassignment and adjustment is carried out until no reassignment occurs anymore. The result of this iterative process is the intersection line between both planes. For each intersection line one 3D-point is calculated by intersecting the line with a normal plane at the centre of gravity of all laser points of the patch. These 3D-points represent the searched breakline. A spline function representing the final breakline is the fitted through these 3D-points taking the line direction of every patch into account (see again figure 1).

2.2.2 Improved breakline extraction using two planes

The extraction of breaklines by reconstructing the surface depends on prior information about the 2D-position of the searched breakline. This information is necessary to define the area near the breakline, which is reconstructed by all laser points within this area. Additionally, the breakline approximation is indispensable for assigning the point either to the right or the left plane. Briese (2004a) uses 3D breakline growing to determine this approximation. To start the growing process the approximation (one point and the direction of the breakline) for one starting patch has to be given. Then, the intersection line of the starting patch can be calculated. The breakline growing in both directions is performed using the following rules:

1. Compute the pair of planes for the actual patch.
2. Compute the boundary for the next patch by using the intersection line direction of the actual patch (extrapolation)

The growing procedure is continued until the adjustment is unsuccessful or a certain break off point (e.g. threshold for the intersection angle between both surface pairs) is reached. Futhermore, Briese (2004a) implements a robust estimation of the unknown parameters based on the robust interpolation technique (Kraus and Pfeifer 1998).

A similar approach of breakline growing based on just one initial 2D point next to the breakline was also presented by

(Briese 2004a). In that case the breakline direction is estimated by fitting an adjusted quadric to the laser points near the start point. Then the direction of the breakline can be estimated by an analysis of the principal axis transformation. The approximate breakline direction is given by the eigenvector of the smallest eigenvalue. Subsequently, the start patch can be calculated and the breakline growing can be performed.

2.3 Handling strong curvilinear structure lines

The extraction of an accurate 2D approximation is a crucial step in calculating the breakline. Briese (2004a) tried to overcome this problem by developing a breakline growing process (section 2.2.2). However there is a problem, if strong changes in the direction of the searched structure line occur (Briese, 2004b), see figure 2.

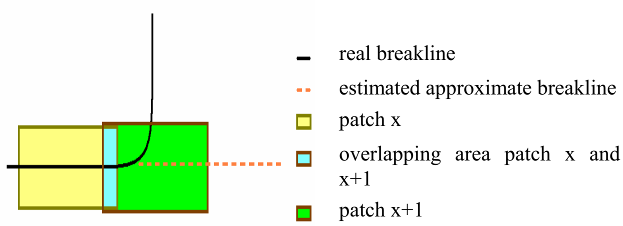

Figure 2: Wrong estimation of the approximate breakline

In this example the real breakline first goes straight but changes its direction rapidly at one place. A suitable solution for patch **x** can be determined. The intersection line of patch **x** is used to compute the boundary of patch **x+1**. Furthermore it is used to assign the patch points either to the left or the right side. It is obvious that in this case the extrapolation of the intersection line of patch **x** leads to a wrong approximate breakline. To avoid this problem the overlapping rate should be very high. Additionally, the length of a patch should be reduced. However, even then a correct solution cannot be guaranteed.

Another way was mentioned by Kraus and Pfeifer (2001). They suggested the use of digital image processing algorithms. Possible methods are described in section 2.1. There are some difficulties in joining detected breakline segments to one line. However, the difficulties in finding an exact solution in case of rapid curvature change are much smaller.

3. A NEW APPROACH FOR THE EXTRACTION OF STRUCTURE LINES

In this section we describe an approach for the extraction of structure lines from irregularly distributed laser points. It builds upon the developments of Briese (2004a), but differs from it in a number of ways.
The algorithm consists of two main parts. First, a suitable 2D approximation of the structure lines is derived by using edge detection applied to a gridded version of the input data. Then, a surface model to express the structure lines is applied. It implies that each morphological object is formed by two structure lines, which have to be derived. The used surface function is the hyperbolic tangent, the parameter of this function are computed in a non-linear least-squares adjustment. A complicated task is the derivation of initial values of the unknown. They are estimated from laser points within each patch in an iterative analysis procedure. After checking the results, the final structure lines can be derived.

3.1 Finding the 2D approximation

In our approach the calculation of the approximate structure line is done by using edge detectors. First, a raster based Digital Terrain Model (DTM) is calculated from the original point cloud. Based on the DTM a suitable edge detector like (Lanser and Eckstein 1991) is used to determine possible edge pixels. To separate between possible edge pixel and non-edge-pixel a non-maxima-suppression is applied. A simple non-maxima-suppression can be performed by suppressing all pixels, if their edge strength is not a maximum in the 8-point-neighbourhood (Steinbecher, 2002). By using the hysteresis-threshold-method, a separation for each pixel between being an edge- or a non-edge-point is possible. Two thresholds (THlow, THhigh) are used. All points whose gradient value exceeds the high threshold value THhigh are fixed as start points for an edge line. Then, a pixel in the 8-point-neigbourhood of a start point is added, if its gradient value is higher than THlow. Thus, a line can only be detected if there is at least one pixel with a gradient value higher than THhigh. Furthermore, the problem of obtaining short lines because of noise is reduced by using the second threshold THlow.
The resulting lines are used as the initial value to perform breakline extraction by fitting surfaces into the point cloud.

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

The choice of a model for structure line extraction includes a decision about the number and the appearance of searched structure lines, the used function(s) and the way to calculate the structure lines from the surface functions.

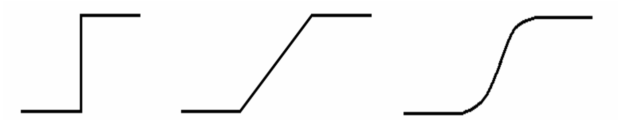

Figure 3: Typical edge profiles in coastal areas – step edge, ramp edge, curved edge (from left to right)

Figure 3 shows typical edge profiles in coastal areas. Typical step edges can be found at the landside of the East Frisian Islands at the transition from the North Sea to the land. These so called fold edges are created by continuous tidal erosion. Ramps and curved edges can be found at dikes, dunes and tidal channels. They all have in common that two structure lines belong together. However there are big differences in the horizontal distance between both lines, the behaviour of slope and curvature as well as between their height differences.

For our task it is crucial to select an appropriate function, which precisely represents the surface. Only a proper selection assures an accurate structure lines extraction. Preferably, the number of parameters of the used function should be low. Although the quality of the surface fit can be assessed by checking the squared sum of the weighted residuals [$\mathbf{v}^T\mathbf{pv}$], the typical blurring effect of a least-squares adjustment occurs if the number of parameters is too high.

Based on the above discussion, we require a suitable model to have the following properties:

1. The number of estimated structure lines is two.
2. There is **one** function that is capable to approximate the surface within the two structure lines and their surrounding.

3. The number of parameters to be estimated is low.
4. Breaklines as well as formlines can be determined.
5. The calculation of all mentioned edge models (step, ramp and curved edge) is possible.

Using one single function to approximate the whole surface patch instead of several combined functions has a number of advantages. No additional information is needed to assign a point to a particular function. Furthermore, the number of estimated parameters remains low resulting in a geometrically more stable solution. Taking into account the low number of laser points between the two structure lines (due to the fact that the two lines are commonly very close to each other), the estimation of a separate function between the structure lines can yield unreliable results or fail altogether.

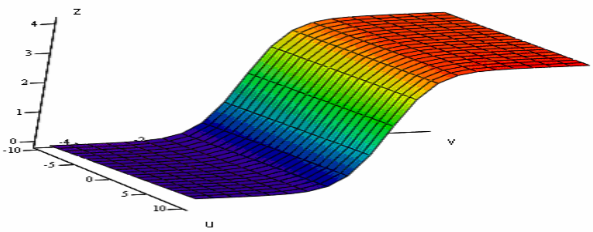

Figure 4: Hyperbolic tangent function

A suitable function that fulfils the first, second and third requirement is a hyperbolic tangent function. The typical appearance of this function is displayed in figure 4. The 2D function is based on a 1D hyperbolic tangent function with four parameters (equation 2).

$$z(v) = s \tanh(f(v + p)) + k \tag{2}$$

Nalwa and Binford (1986) showed that this function is suitable to detect "edgels" (short linear edge segments) within digital images. The parameter **s** is a scale factor. It determines the height difference between the upper and lower plateau. The parameter **f** determines the distance between both lines with maximum curvature: if **f** increases the distance decreases and the tanh-function looks more similar to a step edge; if **f** decreases the distance between both lines increases and the tanh-function has the appearance of a tilted plane. The third parameter **p** is responsible for shifting the function along the v-axis. The parameter **k** shifts the function along the z-axis. An additional parameter **α** is needed to rotate the coordinates of the laser points $(x, y, z)^T$ into the coordinate system $(u, v, z)^T$ (equation 3a and 3b). The sixth parameter **t** is used to introduce a slope of the function in direction of the u-axis. In summary, this leads to a total number of six parameters for the 2D hyperbolic tangent function (equation 3a).

$$z(u,v) = s \tanh(f(v + p)) + k + tu \tag{3a}$$

$$u = \cos(\alpha)x + \sin(\alpha)y \tag{3b}$$

$$v = -\sin(\alpha)x + \cos(\alpha)y \tag{3c}$$

In order to guarantee that requirements 4 and 5 are fulfilled, an approach of extracting the structure lines from the adjusted hyperbolic tangent function has to be developed. Depending on the edge type, the process of calculation has to be adapted. A superimposition of the estimated hyperbolic tangent with the typical edge profiles in coastal areas (figure 5 respectively figure 4) helps to find a suitable solution. .

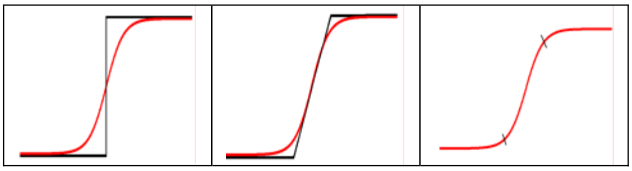

Figure 5: Calculation of structure points depending on edge type - step edge, ramp edge, curved edge (from left to right)

If a step edge has to be derived from the estimated hyperbolic tangent, two horizontal planes at the level of the lower and higher plateau have to be calculated from the parameters of the reconstruction function. These planes are intersected by a vertical plane within the line of maximum slope in direction of the v-axis.
If the model is based on the appearance of ramp edges, again two horizontal planes at the lower and higher plateau have to be derived from the parameters. They are intersected by a plane tilted with the maximum slope in direction of the v-axis.
In both cases the two structure lines are given by the intersection between the vertical / tilted plane with the two horizontal planes.
If there is the a priori information of a curved edge, the structure lines of this patch can be calculated by finding the two straight lines with maximum value of curvature.

Obviously neither the step nor the ramp edge are equal to the hyperbolic tangent function. But taking into account the application area (for instance tidal creeks), the height difference of the lower and higher horizontal ridge is quite low (<2m). Hence the height difference between the step or the ramp edge and the hyperbolic tangent function is commonly within the noise of the height accuracy of airborne laserscanning.

3.3 Different significance of "edge line"

The term edge has a different meaning in digital image processing. An edge in digital image processing consists of one model for an edge (e.g. step edge). The result of an edge detection process is the position of assumed edge points. This is equivalent to the position of the point with the maximum amount of slope.
In the model described in section 3.2, on the other hand, there are two points of maximum curvature for one same edge shape. Thus two positions have to be estimated.
In order to distinguish between both positions, we call the results of edge detection by image processing "centre lines", the results of the complete process are called "structure lines".

3.4 Extraction of structure lines using the hyperbolic tangent function

Having derived the approximate 2D-lines and created a suitable model which includes the manually choice of an assumed edge model based on prior knowledge of the area, the extraction of structure line can be carried out as follows:
First, one centre line is selected. Next, all laser points close to this centre line have to be determined. This is done by creating a buffer around the centre line. Then, a point-in-polygon-test is performed to obtain all laser points inside the buffer. To facilitate an assignment of the laser points into the patches the orientation of each point towards the centre line is necessary. Afterwards, patches with a fixed length and percentage of overlapping of every patch and his neighbouring patches are created. Then, all laser points can be assigned to their belonging patch(es).

A least-squares adjustment to estimate all six unknown parameters for each patch is calculated. Because the used surface function is non-linear, linearization has to be carried out, and initial values of all unknowns are needed. They are calculated by using all laser points within one patch and the approximated centre line.

At first, the origin of the coordinate system $(u, v, z)^T$ for every patch is fixed at the centre of gravity of all laser points within the patch. Then, the rotation angle between the coordinate system $(u, v, z)^T$ and the world coordinate system $(x, y, z)^T$ is determined. Two cases have to be considered. If the patch includes no centre line point (a point where the direction of the centre line changes), the initial value for **α** is the angle between the x- and the centre line direction. If the direction of the centre line changes within the patch an adjusted straight line is calculated by the use of all centre line polygon points within the patch as well as the intersection points of the patch boundary and the centre line. The angle between this line and the x-axis is used as initial value of parameter **α**. Then, the initial value for shift parameter **p** is determined, by calculating the perpendicular distance from the origin of the system towards the centre line and checking whether the centre line is situated left or right of the origin. The initial value for the third parameter **t** is calculated by fitting a plane through all patch points. The tilt of this plane in the direction of the u-axis is used for initial value **t**. To calculate the two initial values of **s** and **k** the influence of factor **t** is eliminated from all laser points within that patch. Afterwards the laser points are divided in left and right side points depending on their relative position towards the centre line. The height values of the points of each side are sorted in relation to their height. The mean value of the highest x%, and the mean value of the lowest x% of the heights are calculated, where x is an empirically determined value (we use 30%). In this way, points one the upper and lower plateau have more influence than the points near the edge. The initial value of **s** can be determined from the difference of the two mean values. The initial value of **k** is equal to half of the sum of the lower and the higher mean. A suitable initial value of **f** can be found by using prior information. The minimum and maximum distance between both structure lines can be transformed into a minimum and maximum value for **f**. Then, a least-squares adjustment for a fixed number of possible values is calculated. The initial value for **f** is determined by finding the least-squares adjustment with the lowest weighted sum of squared residuals $[\mathbf{v}^T\mathbf{pv}]$.

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. That is why each of the six initial values can be used in an additional observation equation to stabilize the adjustment. The a priori standard deviation of every initial value as well as of the height value of each laser point is transferred into weights for the adjustment. In the second iteration process the unknown parameters are again computed. However, no additional observations are used.

After all patches are calculated the estimated parameters are checked, for consistency and plausibility. Invalid solutions are deleted. This is done by using prior information of the investigated structure lines. Feasible height differences between the lower and the upper ridge as well as the horizontal distance between the two calculated structure lines can be transferred into valid intervals for parameter **s** and **f**. Results are only accepted if they fall within this interval.

Afterwards two straight lines are derived from each valid patch by using the assumed edge model. For each straight line one 3D-point is calculated by intersecting each line with a normal plane within the centre of gravity of all laser points of the patch. These 3D-points are finally linked by a spline function with the use of the direction of the straight lines of every patch.

4. EXAMPLES

To demonstrate the capabilities of our approach two examples are shown. Figure 6 displays the most important steps of extracting one breakline pair of a tidal creek near the German island Juist. The dataset was obtained by the company “Topscan” in spring of 2004 with an average point density of 5 per m^2. For the computation of the centre line we generated a DTM with a grid size of 0.5m.

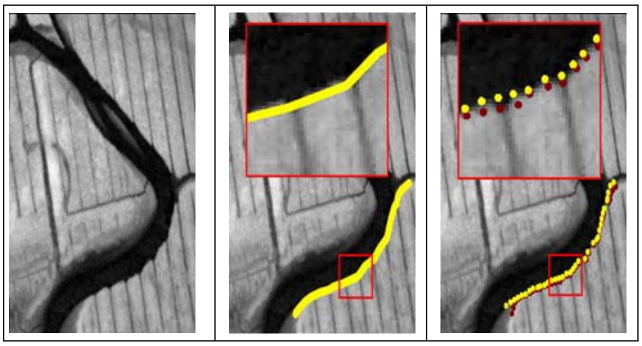

Figure 6: Derivation of one breakline pair (left: DTM, middle: extracted centre line, right: valid breakline points)

At first the centre line of the searched structure line combination was derived by using the edge detector of (Lanser and Eckstein 1991) in combination with non-maxima-suppression and hysteresis threshold.

Afterwards the neighbourhood points were extracted and classified in relation to the centre line. The patch length was set to 5m with a percentage of overlapping of 50%. 38 patches had to be computed.

Following the calculation of initial values for every patch an iterative adjustment was performed to improve the quality of the initial unknown parameters. Finally an iterative adjustment without additional observations was calculated. The results in 36 patches were correct. One patch did not yield a valid result. In another segment the solution of one patch had to be eliminated after checking the validity of parameter **f**. Then, breakline points for the upper and lower line were calculated using the ramp edge model.

The second example (figure 7) shows the extraction of a form line pair within a tidal area near the German city Bremerhaven. In this case, only a 1m grid sized DTM, which was derived from a flight in autumn 2003 by the company “Toposys”, was available. Setting the patch length to 10m with a percentage of overlapping of 50%, 92 patches had to be computed. Only one patch could not be calculated successfully. Furthermore, 5 patches were eliminated after failing to yield a valid value for parameter **f**.

Both solutions of the structure line pair seem to be very accurate. This can be shown by creating a 3D model of all laser points and the obtained structure points. Depending on the tilt angle the distance between the two derived structure lines varies: in steep parts of the area the derived structure lines are very close to each other, in flat areas there is a larger separation. A detailed accuracy assessment of the obtained results was not possible, because reference measurements were not available. Such an assessment is planned for the next flight campaign.

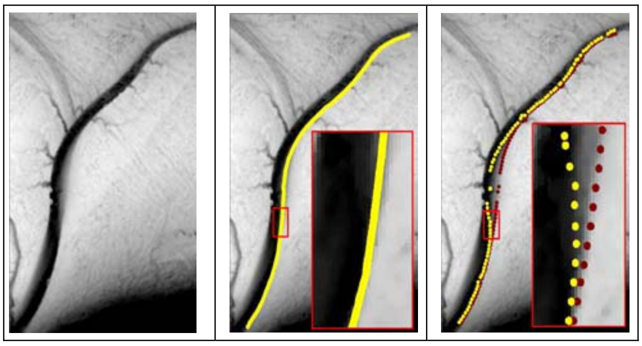

Figure 7: Derivation of one pair of form lines (left: DTM, middle: extracted centre line, right: valid form line points

5. OUTLOOK

This paper presents an algorithm to extract structure lines within coastal areas from airborne laserscanner points. The examples in section 4, which constitute the first obtained results, show, that the algorithm has the potential to yield good results. However, there are several problems that have to be solved in the future:
The calculation of the 2D approximate centre line is not perfect. Obviously, line parts belonging together are derived separately from each other. A suitable linking algorithm that connects line parts has to be implemented. Furthermore the real surface does not always match the assumed hyperbolic tangent model with enough accuracy. Other suitable functions as well as combinations of several functions have to be tested in order to better describe the surface in some areas. Another important problem is to find a reasonable automatic procedure to select the appropriate buffer width 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.

ACKNOWLEDGMENTS

This research has been financed by the Federal Ministry of Education and Research (BMBF) under project no. 03KIS050. We acknowledge the support of our project partners: Department of Rural Area Husum (ALR), Federal Waterways Directorate (WSD) and the Lower Saxony Water Management, Coastal Defence and Nature Conservation Agency Division Norden-Norderney (NLWKN).

REFERENCES

Briese, C. (2004a). Three-Dimensional Modelling of Breaklines from Airborne Laser Scanner Data. In *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXV, B3, Istanbul, Turkey, pp. 1097 – 1102.

Briese, C. (2004b). Breakline Modelling from Airborne Laser Scanner Data. Dissertation, TU Wien. http://www.ipf.tuwien.ac.at/phdtheses/diss_cb_04.pdf, pp. 1 - 67.

Briese, C., Kraus, K. and Pfeifer, N. (2002). Modellierung von dreidimensionalen Geländekanten in Laser-Scanner-Daten. In *Festschrift anlässlich des 65. Geburtstages von Herrn Prof. Dr.-Ing. Habil. Siegfried Meier*, TU Dresden, Institut für Planetare Geodäsie, Germany pp. 47 – 52.

Brügelmann, R. (2000). Automatic breakline detection from airborne laser range data. In *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXIII, B3, Amsterdam, Netherlands, pp. 109 – 115.

Brügelmann, R. and Bollweg, A.E. (2004) Laser altimetry for river management. In *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXV, B2, Istanbul, Turkey, pp. 234 – 239.

Brzank, A. (2001). Automatische Ableitung von Bruchkanten aus Laserscannerdaten, diploma thesis at the Institut of Photogrammetry and Remote Sensing of TU Vienna and the Institute of Photogrammetry and Remote Sensing of TU Dresden (unpublished).

Gomes-Pereira, L. and Wicherson, R. (1999). Suitability of laser data for deriving geographical information – a case study in the context of management of fluvial zones. ISPRS Journal of Photogrammetry and Remote Sensing 54, 105 – 114.

Kraus, K. and Pfeifer, N. (1998). Determination of terrain models in wooded areas with airborne laser scanner data.In *ISPRS Journal of Photogrammetry and Remote Sensing* 53, pp. 193 – 203.

Kraus, K. and Pfeifer, N. (2001). Advanced DTM generation from LIDAR data. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3/W4,* Annapolis, MD, USA, pp. 23 – 30.

Lanser, S. and Eckstein, W. (1991). Eine Modifikation des Deriche-Verfahrens zur Kantendetektion. 15. DAGM Symposium, München; in: *B. Radig (Hrsg.): Mustererkennung*, Informatik-Fachberichte 290, Springer-Verlag, pp. 151 – 158.

Nalwa, V.S. and Binford, T.O. (1986). On Detecting Edges. In IEEE Transactions of Pattern Analysis and Machine Intelligence. Vol. PAMI-8, No.6, November 1986, pp. 699 – 714.

Sui, L. (2002). Processing of laser scanner data and automatic extraction of structure lines. In *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXIV, Xian, P.R. China, pp. 429 – 435.

Steinbecher, R. (2002). Bildverarbeitung in der Praxis. Oldenbourg, 176 – 180.

Weidner, U. and Förstner, W. (1995). "Towards Automatic Building Extraction from High Resolution Digital Elevation Models". In *ISPRS Journal of Photgrammetry and Remote Sensing* 50. pp 38 – 49.

Wild, D. and Krzystek, P. (1996). Automatic breakline detection using an edge preserving filter. In *International Archives of Photogrammetry and Remote Sensing,* Vol. XXXI, 3/W3, Vienna, Austria pp. 946 – 952..