MONITORING AND CHANGE DETECTION OF WADDEN SEA AREAS USING LIDAR DATA

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ABSTRACT:

In coastal areas morphological changes of various kinds are caused by tidal flows, storms, climate change, and human activities. For these reasons a recurrent monitoring becomes necessary in order to detect undesired changes at early stages enabling rapid countermeasures to mitigate or minimize potential harm or hazard. The morphology of the terrain can be represented by highly precise digital terrain models (DTM). Airborne lidar (light detection and ranging) has become a standard method for DTM generation in coastal zones like Wadden Sea areas. In comparison to echo sounding systems, lidar is feasible for data acquisition of large areas. However, only the eulittoral zone can be covered by standard laser because the near-infrared laser pulses are not able to penetrate water which remains, for example, in some tidal channels even during low tide. In the framework of a German research project, we analyse the spatial and temporal variability of Wadden Sea areas in the North Sea. For a systematic monitoring and the detection of morphological changes we compare terrain models of two different epochs in order to determine height differences which can be caused by natural influences or human activities. We focus especially on the analysis of morphological changes near to tidal channels. In order to detect changes we compare the location of edges derived from each DTM based on the gray values' gradients. Our results for a test site in the German Wadden Sea show height differences up to 1 m due to the shifting of tidal channels and relocations of the channels up to 55 m within a period of two years.

1. INTRODUCTION

Since about one decade airborne laserscanning or lidar is operationally in use for monitoring the coasts of German main land and the islands. Initially those efforts aimed at the derivation of geometric information such as the actual coast line, the dimension of dikes and other coastal protection infrastructure, and the detection of sand banks etc. potentially threatening ship traffic. The initial motivation was basically to save human live and to prevent any damage of property. However, in recent years this solely anthropocentric view has been amended by a second aim namely the preservation of nature. This process resulted in a variety of political decisions like EU's Habitats Directive, which in turn require a modified concept of monitoring. The Wadden Sea in the North Sea is a very prominent habitat area whose state enjoys much attention of the public and administration (e.g., inscribed in the UNESCO's World Heritage List). This is one reason why recent laserscanning campaigns were extended to cover the Wadden Sea.

In this context, knowledge of the morphological development of the Wadden Sea and its barrier island system is of great interest. The comprehensive research of the morphodynamics can be implemented by a combination of data analysis, field survey and numerical modelling (Wang et al., 2012). The analysis of lidar data comes along with two main advantages compared to traditional aerial photogrammetry. On the one hand, the active laser technique works independently from illumination from the sun, which allows mapping also during night-time. On the other hand, the elevation model can be directly inferred from the two-way time-of-flight of the pulse reflected at the ground, whereas stereo techniques rely on matching of corresponding points in two or more image. However, the Wadden Sea area looks quite homogeneous in aerial imagery, which often renders matching impossible due to lack of sufficient distinctive features.
In comparison to echo sounding systems, lidar is feasible for the efficient acquisition of large areas. It delivers topographic data with high resolution and accuracy in sub-meter range.

The morphology of the Wadden Sea was investigated in different studies in the past. In this context, the import and export of sediment in the Wadden Sea is significant for the understanding of morphological development. For instance, Ernstsen et al. (2013) determine a drainage channel network from lidar data and derive second-order transport pathways of the sand oblique to the main tidal transport from this. They observe a correlation between the tides and an influence of storm events depending on the wind direction to the transport pathways. A comprehensive analysis of tidal inlet morphodynamics is given by de Swart and Zimmerman (2009). They distinguish between the different units in a tidal inlet system like ebb-tidal delta, channel networks and the intertidal zone of tidal flats concerning the hydrodynamic of tidal currents and wind waves as well as the transport of sediments.

Moreover, there are different publications with the objective of the explanation of tidal channels' development. For instance, Mason et al. (2006) developed an approach for the detection of tidal channel networks in lidar data, including a study site located in the Wadden Sea. In their method, tidal channels are extracted by a multi-scale edge detection composed of edge detectors with varying filter mask and size, first. Then, parallel edges are associated by a transformation based on the distance and the direction of a pixel to the nearest edge. Finally, disconnected fragments in the network are linked by extending the ends to join with nearby channels. The changing of tidal channels is investigated by Brzank et al. (2008). They determine centre lines between the lower and upper structure lines of a tidal channel by digital edge detection. In a second step, the surface between both structure lines is reconstructed based on hyperbolic tangent functions. Then, points of the upper and lower bank are determined. They are used for deriving geometrical parameters such as the channel bed width. Afterwards, 3d shift vectors are calculated for bank line points based on their distance of one epoch to the corresponding bank line of the other epoch.

In this paper, we investigate lidar data of the German Wadden Sea in order to analyse their morphodynamics. For our analysis we benefit from the availability of two lidar data sets of the same area which are acquired with a time difference of only two years. In these data sets we define a test area which includes tidal channels of different size and length. We generate a digital terrain model (DTM) from each point cloud and calculate a differential DTM of both epochs. In this way, regions with deposition and erosion processes can be determined. However, it is not always straightforward to determine the direction of mass displacement. Therefore, in a second analysis, we apply a feature based approach focusing on tidal channels. For this purpose, we extract edges for both epochs by digital edge detectors in order to identify the breaklines and to determine the shift of the tidal channels in a second step.

2. STUDY AREA

The test site comprises the eulittoral part of the German Wadden Sea in the North Sea. It is located in the south of the East Frisian island Norderney and covers an area of 1.0 km x 1.1 km (Fig. 1). Many tidal channels of varying size are located in this area. Some of them extend over the entire test site with a width up to nearly 200 m, whereas others exhibit of a length of some decadic meters and a width in few meter range only. For this area two different flight missions were performed in the framework of coast protection from the public authorities, here the Lower Saxon State Department for Waterway, Coastal and Nature Conservation (NLWKN). Both of them were acquired during low tide in order to ensure a minimal water coverage of the mudflat areas. However, in the tidal channels, especially in the bigger ones, water still remains.

The flight campaigns took place in spring of 2010 and 2012 with different lidar sensors. The technical parameters of both missions are stated in Table 1. The heights of the raw lidar point cloud are interpolated to generate a DTM of 1 m grid size. This leads to 1.1 million points in the whole test site which are analysed in more detail in the following section.

3. CHANGE DETECTION IN THE WADDEN SEA

As the Wadden Sea is a very dynamical system influenced by tide, waves, wind and storms, lots of changes within two years can be expected, especially near to tidal channels. We carry out our investigations based on the difference of two DTMs (Section 3.1) and the implementation of edge detectors (Section 3.2).

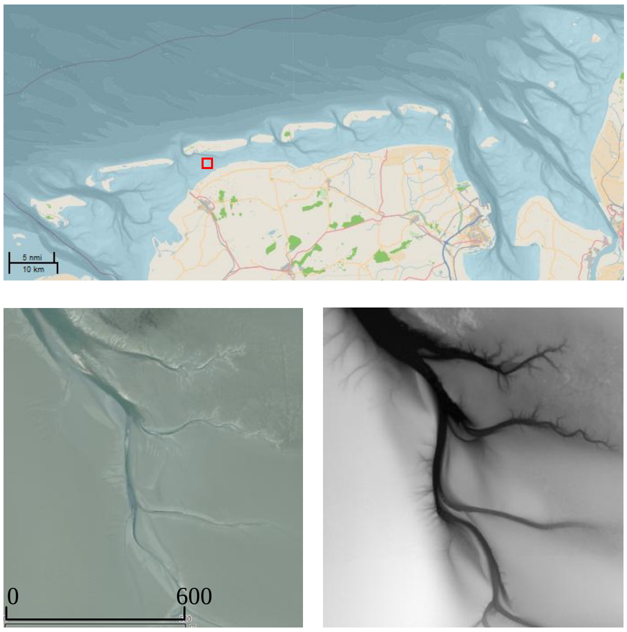


Figure 1. The approximate test site location outlined in red in a general map (top), an orthophoto of the scene (bottom left), and the lidar DTM of 2012 (bottom right)

	data set 1	**data set 2**
date	between 18.03. and 17.06.2010	02.04.2012
sensor	Harrier 56 TopoSys/Trimble	LMS-Q 560
flight altitude	400 m	600 m
wavelength	1550 nm	1550 nm
horizontal accuracy	<±0.25	<±0.4
vertical accuracy	<±0.15	<±0.15
pulse repetition frequency	150 kHz	100 kHz
scan angle	±22.5°	±22.5°
beam divergence	0.5 mrad	0.5 mrad

Table 1. Technical parameters of both flight campaigns.

3.1 Height differences

3.1.1 Method

For the monitoring of the topography the DTM of the first data set from 2010 is subtracted from the DTM of the second data set from 2012. Depositions and erosions refer to positive and negative values in the difference model, respectively. Both data sets have been acquired during low tide and, thus, are comparable for absolute changes in the height. However, the water levels might slightly differ due to differences in the acquisition time. Thus, the comparability within water covered surfaces is limited.

3.1.2 Results

After two years significant changes in the topography can be observed. Fig. 2 shows the differences of the heights between both epochs for the test site and two detailed views. Here, positive values (blue) indicate accumulations and show areas which are higher in 2012 than two years before. Negative values (red) represent erosions, where the heights decreased between both epochs. For most of the grid points the differences are low. 64 % of the points have a difference of only ±0.10 m. The mean of the absolute height differences is 0.11 m with a standard deviation of 0.12 m. However, especially in the tidal channels and at their borders higher differences can be observed. Here, the differences vary up to 1.02 m which can be explained by a shifting of the trenches. Especially the main channel in the middle of the test site from north to south changed his run. For a clearer understanding we divide the test site in four parts. Within these parts it can be observed that in area 1 and 3 the channel shifted from west to east whereas the shifting in area 2 and 4 was opposite. The size of the shifting is determined in Section 3.2. We observe a similar characteristic also for smaller tidal channels, e.g. for the one in *Area a* with a course from west to east (Fig. 2). Here, the meandering changes a few times, the channel shifts from north to south in some parts and opposite in other parts. A further observation is the disappearance of a few small channels, but also the development of new ones, e.g. in *Area b* (Fig. 2). In the difference model channels shown in blue are only contained in the first data set of 2010. Channels depicted in red can be seen only in the data set of 2012.

3.2 Edge detection

3.2.1 Method

Concerning the monitoring of Wadden Sea areas, we are interested in the changes of the tidal channels' courses. However, the analysis of the shifts of the trenches is difficult to evaluate only based on the difference model. Thus, we determine the edges of the channels in a second investigation. For that purpose, we use two methods based on the gradients of the gray values. First, we apply a Sobel operator and, thus, detect edges in x- and y-direction. We empirically determine a threshold for the resulting magnitude of the gradients. All pixels with a magnitude above threshold are retained as edges. In order to thin out the result, we apply a Non-Maximum-Suppression afterwards.

Due to the implementation of a fixed threshold some bank lines with a low slope and, thus, low gradients cannot be detected in this way. In order to enable a more flexible method independent of a fixed threshold and to detect edges more reliable, we apply a second, very simple method. This method is also based on gradients and is outlined in Fig. 3. It is composed of three steps of calculation which are implemented on the rows or columns of the DTM. Tidal channels are characterised by low gray values in the DTM (Fig. 3a). Thus, for the search of vertical channels we calculate the gradients between neighbouring pixels line by line. Then, we determine the pixels with the minimal and the maximal gray values which ordinarily belong to the left and right edges of a channel (Fig. 3b). Here, we assume that there is

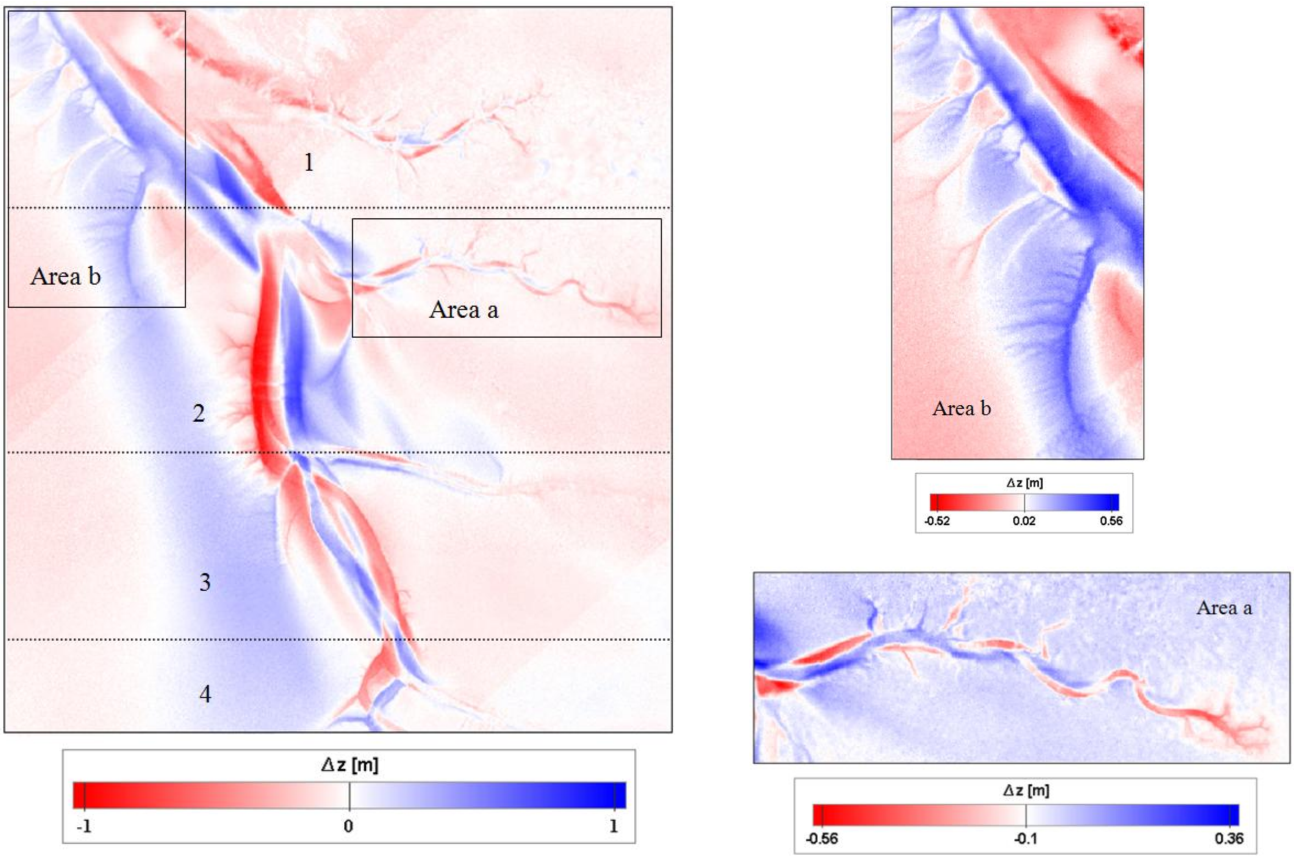
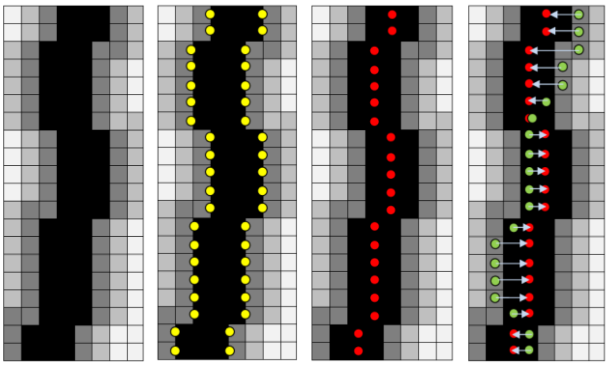


Figure 2. Height differences between the DTMs of 2012 and 2010 for the overall test site and two detailed views. Erosions refer to low values (red), depositions to high values (blue).

only one channel per row. The assumption is justified since the method is applicable also only for local areas.

In order to reduce the number of wrong associations, we implement further criteria for the search of extremes in a line. We assume that the minimal gradient have to be located on the left-hand side of the maximal gradient. Furthermore, the distance between both values cannot be higher than the maximal channel width in the test site which is manually determined before. Moreover, an extreme point has to have at least one adjacent point in a circular neighbourhood with a fixed radius (here $r = 5$m). If the result contradicts to one of the criteria, the point is not saved. That is why gaps might occur for some lines. In the next step, we calculate the mean of the pixel positions for both extremes which corresponds to the skeleton of the channel (Fig. 3c). Afterwards, the positions of the skeletons for each epoch are compared. The differences between the pixels' positions in each row correspond to the shifting vectors of the channel (Fig. 3d). The differences are only calculated if both results have a point in the line and do not contradict to one of the criteria described above. For the determination of the shifting of horizontal channels, the method can be performed based on the search for maximal and minimal gradients column by column.



(a) (b) (c) (d)

Figure 3. Sketch of the method for the channel edge detection: Tidal channels with low gray values (a) are detected by the minimal and maximal gradients per row (b). The mean of the pixel positions corresponds to the skeleton of the channel (c). From the skeletons of two epochs the shifting vectors are calculated (d).

3.2.2 Results

Fig. 4 shows the results for the edge detection based on the Sobel operator for both epochs. It can be seen that most of the tidal channels are detected by this approach. Only some smaller trenches are not found due to gradient magnitudes below threshold. For the second data set from 2012 some rough terrain points in the north of the test site leads to incorrectly edge points. In general, most of the edges are not completely connected and consist of fragments. In some cases channel borders are not detected because some of their points are below threshold. However, the trend of the channels to change their course can be seen from these results.

In order to determine the magnitude of the shift, we apply the second method for the edge detection and derive the skeletons of the channels. Fig. 5 shows the result for a part of the main channel with vertical course. The skeletons are derived from the maximal and minimal gradients in each line. For most lines these pixels could be correctly matched to the edges of the main channel. Some outliers occur when one of the extremes belong to another change in altitude or a second channel in the line. Then, the averaging of both pixel positions, the skeleton, does not match to the middle of the channel which can be observed e.g. in the upper right-hand corner of the first data set from 2010 (Fig. 5). Here, the differences of both epochs lead to wrong displacement values. However, for most lines the skeletons are correctly associated to the main channel and can be compared for both epochs. In Fig. 6 the magnitude of the shift is depicted in a graph. Here, the skeleton of 2010 is defined as reference and the differences to the skeleton of 2012 are calculated. Thus, positive values represent a shifting to east and negative values a moving to west. It can be verified that changes occur in both directions. The maximal shifts attain similar values and rise up to 55.2 m for the shifting to east and 54.8 m for the moving to west.

For *Area a* we apply the method for the determination of the shifting of a horizontal channel. Here, we search the edges in y-direction. Most of the skeleton points are correctly determined (Fig. 7). Only on the eastern end of the channel where the gray

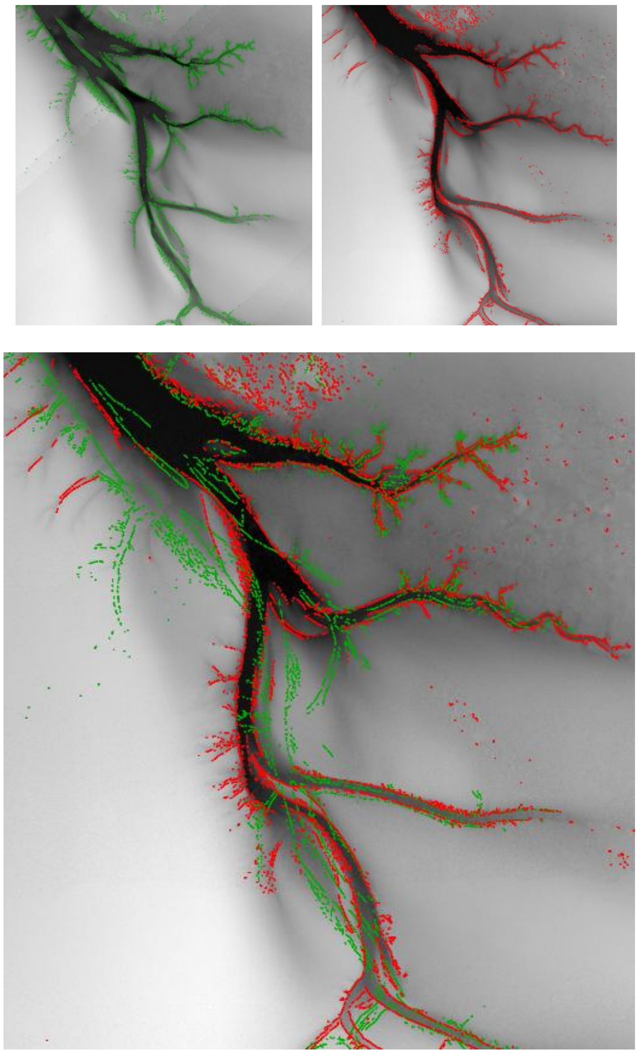


Figure 4. DTM of 2010 (top left) and DTM 2012 (top right, bottom) with channel edges for 2010 (green) and 2012 (red)

values' differences are low due to the fordable transition to mudflat areas wrong extreme points are detected. In Fig. 8 positive differences correspond to the shift of the channel from south to north between both epochs, negative values represent a shifting in the opposite direction. The meandering varies a few times. Here, the maximal shifts are 21.2 m to the north and 14.83 m to the south by an average shifting of 5.6 m.

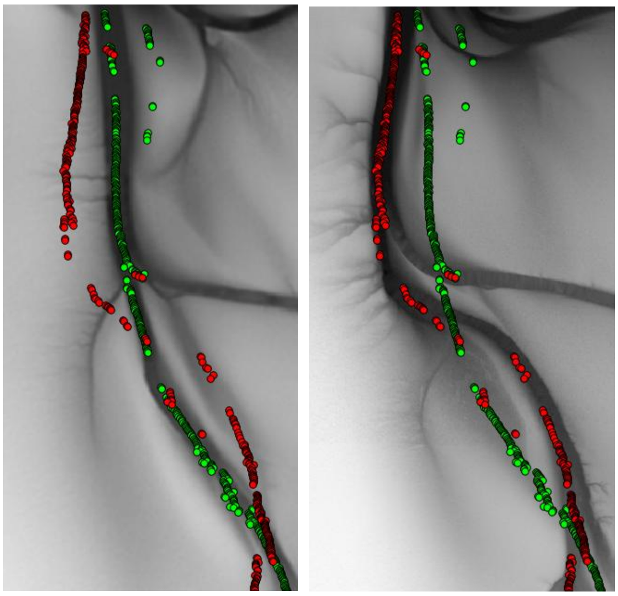


Figure 5. DTM of 2010 (left) and 2012 (right) with the derived skeletons for 2010 (green) and 2012 (red) for the main channel.

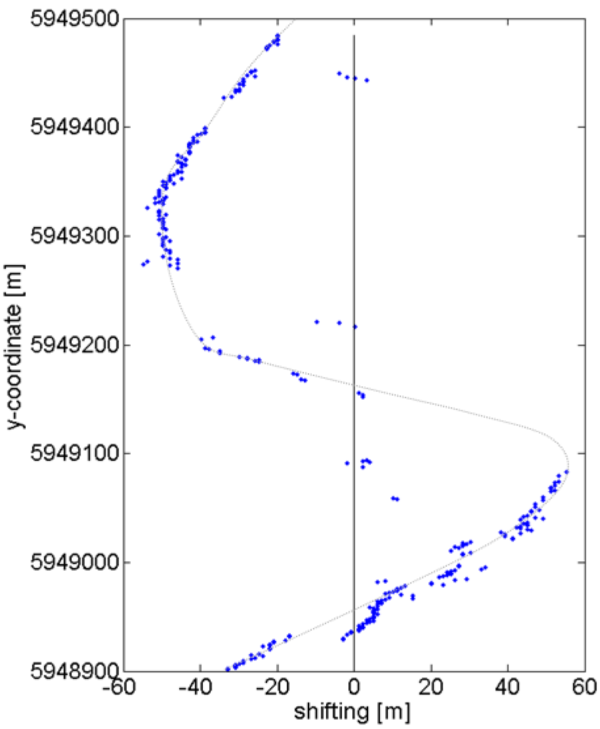


Figure 6. Magnitude of the shifting of the main channel for 2012 in relation to 2010.

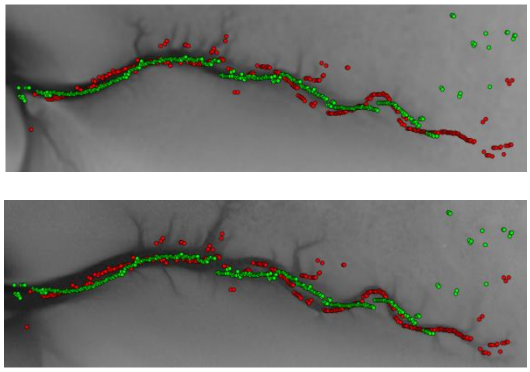


Figure 7. DTM of 2010 (top) and 2012 (bottom) with the derived skeletons for 2010 (green) and 2012 (red) for the channel in *Area a*.

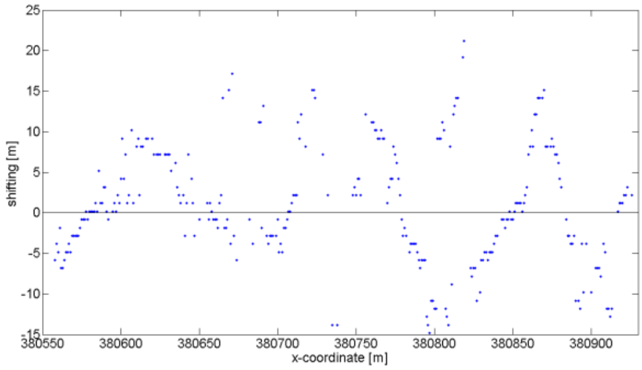


Figure 8. Magnitude of the shifting of the channel in *Area a* for 2012 in relation to 2010.

4. CONCLUSION

In this paper, we proposed a method for the monitoring of Wadden Sea areas based on lidar data. We focused on a test site in the German Wadden Sea which covers several tidal channels of different size and length. In order to determine morphological changes we compared two data sets which are acquired with a time difference of two years. During this period the terrain changed up to 1 m in height which can be derived from the difference of the digital terrain models of both epochs. The differences in the elevation can be primarily explained by the shifting of tidal channels. Also the disappearance of trenches and the development of new ones can be observed. For the calculation of the magnitude of the shifting, we applied standard edge detectors as well as a method which determine maximal and minimal gradients in local areas line by line. In this way, we derived the skeletons of the tidal channels and compared them for both epochs. The distances between both skeletons correspond to the shifting. For our test site we verified a moving up to 55 m for a bigger channel with a width of about 25 m and a shifting up to 21 m for a trench with a width of about 15 m. Here, the shifting occurs not only in one direction of the originally course. Instead the meandering changed a few times and the shifting can be observed in both directions.

We intend to extend our approach on further test sites. Moreover, we plan to combine and automatise our methods for the edge detection. Standard edge detectors could be used in order to detect regions of interest in the digital terrain model. Afterwards, by determining the minimal and maximal gradients in local parts line by line the complete edges can be calculated more reliable.

5. ACKNOWLEDGEMENT

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