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Section: Technologies of Geodesy and Cadastre

Monitoring of coastal processes by using airborne laser scanning data

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Abstract

The three Baltic States and other Baltic Sea countries (Denmark, Finland, Germany, Poland, Russia and Sweden) share over 8,000 km of shorelines. Estonia has a shoreline length of approximately 3800 km, due to many islands, bays, and peninsulas. Coast monitoring with traditional surveying methods would be time consuming and expensive. Remote sensing by means of airborne laser scanning (ALS) could be an alternative to traditional coastal surveying methods. Accordingly, the aim of the study is to determine whether ALS data can be used to quantify volume changes along shorelines.
The case study utilizes ALS data acquired by the Estonian Land Board in 2008–2011. The ALS flights are conducted in different altitudes (yielding a varying point density) and seasons (spring, summer). Study shows also that accuracy of readily available ALS data products may not be suited for the most demanding applications. Certain computational principles and methods need to be applied for remove systematical biases between different ALS campaigns. The methods and algorithms that where developed and tested during this study yield sub-decimetre accuracy for detecting contemporary coastal processes. Thus, ALS data can be used as an alternative to traditional coastal monitoring methods.

Keywords: airborne laser scanning; coastal processes; ALS data enhancements.

1. Introduction

Even though the consequences of coastal processes are known to many, however, there is lack of exact knowledge about their behavior and extent. Since near-shore human activities are constantly growing, there is a need to assess possible risks both caused by natural forces and anthropogenic interventions. A risk source is coastal erosion, which can threaten near-shore housing and infrastructure objects.

Using traditional geodetic surveying methods like levelling, GNSS or tachymetric surveys for prolonged shorelines is very time-consuming and labor-intensive. Therefore the focus of most previous studies has been on limited key areas using mainly three monitoring methods: (*i*) comparing shoreline locations from maps of different time periods, e.g. [1]; (*ii*) repeated geodetic profile-wise measurements for determination of changes in heights, e.g. [2], however these profiles characterize only the near proximity of the profile and not the entire coast; (*iii*) modelling of coastal processes and their possible outcomes, e.g. [3]. The latter gives an estimation of the quantity of the changes, but requires different (often vaguely known) variables to be involved. Therefore a good result for modelling could be considered if the right magnitude order in predictions can be reached [4].

Unfortunately the observations within small test areas may not be suited for the accurate description of coastal processes along the entire coast. Thus suitability of novel remote sensing methods like ALS (Airborne Laser Scanning) for monitoring coastal processes need to be investigated. ALS datasets are already used for different modelling and engineering applications. In particular, one of the well-known scopes of ALS data acquisition is forming Digital Elevation Models (DEM). In many countries nation-wide ALS campaigns have been started. These are flown at altitudes up to a few kilometers, thus resulting in sparse data (~0.1…4 points/m^2). Obviously, repeated ALS measurements over the same area give the possibility to create surface models for different time epochs and therefore enabling detection of inter-epoch volume and mass changes. This study focuses on testing ALS data suitability for monitoring coastal processes. Similar studies with LiDAR data have already been carried out, e.g. along the Baltic Sea shoreline by [5] and also for riverbank erosion assessments by [6]. The former inter-compared results obtained by the transect lines method and that of ALS data. The latter used ALS in conjunction with river gauge data. Neither study attempted to improve the initial ALS data quality.

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This study, however, attempts to enhance the quality of standard ALS data products by developing novel algorithms for minimizing systematic errors between ALS datasets. The case study tackles two sand-beaches at the Tallinn Bay, Estonia.

The outline of the paper is as follows. The Introduction is followed by a review on theoretical principles of ALS. Section 3 explains the basics of coastal processes. Section 4 focuses on the case study and gives an overview of the adopted test areas and used ALS data. Detected problems with the ALS data and their solutions are also described, as are the quality control methods and results. A brief summary concludes the paper.

2. ALS principles

ALS is based on LiDAR (Light Detection and Ranging) technology which uses the time-of-flight of a light pulse to measure the distance (R) from the sensor to the reflecting surface [7].

$$R = c\frac{t_L}{2}, \quad (1)$$

where c is speed of light [m/s] and t_L is travelling time of light pulse [s].

A typical ALS system consists of three main components: (*i*) a laser system with an emitter and receiver, also a scanning mechanism and a control unit; (*ii*) a GNSS receiver for aircraft positioning; (*iii*) an internal measuring unit (IMU) to determine aircraft's attitude.

Point density is dependent on the flying height, pulse and scan rate. Multiple Pulses in Air Technology (MPiA) allows the airborne LIDAR system to fire a second laser pulse prior to receipt of the previous pulse's reflection, therefore the pulse rate at any given flying height can be effectively doubled. In addition, a narrower Field of View (FoV) can be used, resulting in better forest floor penetration in areas covered by vegetation. [7] Modern ALS scanners can also record several reflections per laser pulse, enabling thus the pulse to travel all the way to the ground through various obstacles even in densely forested areas. ALS data of adjacent flight lines are matched together using cross-strips and well identifiable objects like slopes, roofs. The quality of the match is checked in overlapping areas of the flight lines where the planar and height values should match.

There are many different aspects that affect the ALS data accuracy, one of them is the calibration of the laser scanning instrument. In calibration there are some parameters that cannot be measured directly and have to be derived from the ALS data, one of them being the angular misalignment between the laser head and the IMU. These misalignment components (roll, pitch, heading motions) are illustrated in Fig. 1. An incorrect calibration of those parameters will cause position errors of the ALS survey points. [8] For example with roll error elevation differences increase with the scan angle and are dependent on the flight altitude and FoV. Removing roll motion influence from datasets usually requires angular corrections set by special software.

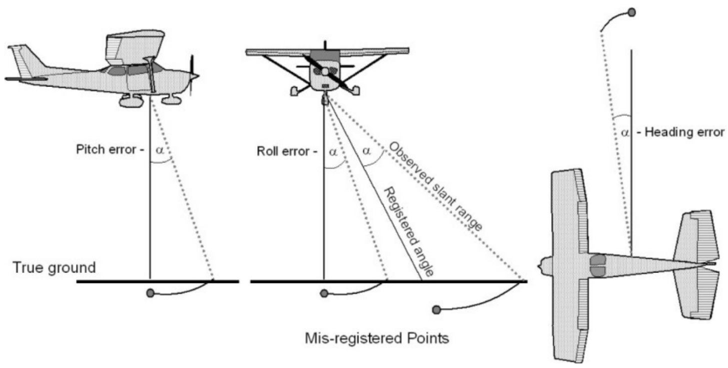

Fig. 1. The errors caused by the misalignment between the laser head and the IMU. The pitch error (left) results in a laser slant range to be recorded as nadir. As the slant range is longer, the entire strip tends to be pushed down. A roll error also causes a slant range to be incorrectly registered. The elevation differences tend to increase with a larger scan angle (centre). The heading error induces a skewing in each scan line (right) [8]

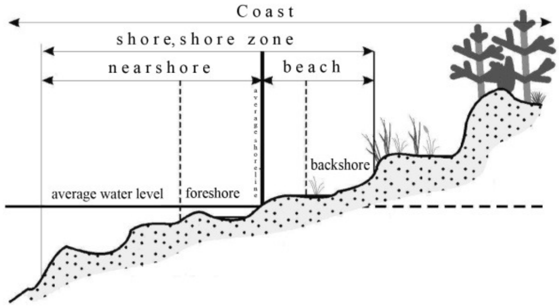

Fig. 2. Coastal subdivision for sand shores. Modified from [9]

Post-processing ALS measured distances and the corresponding scan angles yields a 3D point cloud. These point clouds describe the geometrical properties of the reflecting surface. The accuracy of ALS positions can be reached up to 0.1 m both horizontally and vertically [10]. Further data classification aims at dividing points into classes, which represent different objects e.g. ground surface, buildings, vegetation. Note that the GNSS-derived geodetic (reckoned from reference ellipsoid) heights are usually converted into absolute (sea level related) heights by a national/regional geoid model.

3. Coastal processes

Monitoring of coastal processes requires data from different parts of coast (Fig. 2). Beaches depend on many factors which can dramatically change beach's state from accretive to erosional and *vice versa* [11]. The combined effects of warmer winters, an absence of sea ice, increased cyclonic activity, frequent extreme storms and higher storm surge levels vitalize shore processes and cause abrupt changes in the geological structure and evolution of seashores. For example storms with high sea levels and high waves can cause rapid and extensive changes in coastal areas. These storms may even change the development of existing formations [2]. Ship waves can change the beach processes and under specific conditions are able to completely reshape the beach within a few hours. Wind waves cause accretion with almost all wind directions [11].

Coastal monitoring is necessary to foresee and prevent disasters in the coastal area. Shallow waters of the nearshore are the most complicated in this respect, since hydrographic surveying boats cannot access such shallow waters. Even though ALS pulses cannot penetrate water masses either it will be shown that ALS is as an alternative to traditional coastal monitoring methods (cf. Introduction). The case study focuses on detecting accretion and erosion occurring in the beach sections (cf. Fig. 2) of the shore.

4. Case study

4.1. Test areas and used data

The case study tackles the Kadriorg (length: ~750 m, average width: ~35 m, total area ~28 000 m^2) and Pirita (length: ~2300 m, average width: ~30 m, total area ~95 000 m^2) sand beaches at the Tallinn Bay (Fig. 3), Estonia. These beaches are situated near Port Tallinn, therefore they can be affected by ship waves caused by quite intense traffic of large passenger boats. Since the Baltic Sea is almost entirely lacking tides, then the sea level is dependent more on the regional winds rather than on tidal effects. However, history of floods during unfavorable storm surges show that within these test areas the sea level can rise up to 1.5 m. Previous research has also determined that currents move matter from the northern part of Pirita beach along the shoreline to the south [4].

The ALS surveys were carried out the by the Estonian Land Board (ELB) using the Cessna Grand Caravan 208B aircraft in 2008, 2009 and 2010. Leica laser scanner ALS50 phase II was used. The scanner is equipped with a 200 Hz IMU and a dual frequency L1/L2 GPS receiver. Both GPS and IMU units are used for the determination of coordinates and spatial orientation of the laser returns. The scanning frequency and pulse repetition frequency for the 2400 m flight were set to 31.9 Hz and 93.2 kHz, respectively. The 3800 m flight had a scanning frequency and pulse repetition frequency of 21.2 Hz and 62.7 Hz, respectively. GNSS data with frequency 2 Hz was collected for the aircraft trajectory calculation. The 2008–2009 flights were performed at the 2400 m altitude, whereas the 2010 flights at the altitude of 3800 m. Thus the used ALS data has also a different point density – the 2400 m ALS data have an average point density of 0.45 p/m^2 whereas the 3800 m altitude data have a point density of 0.14 p/m^2.

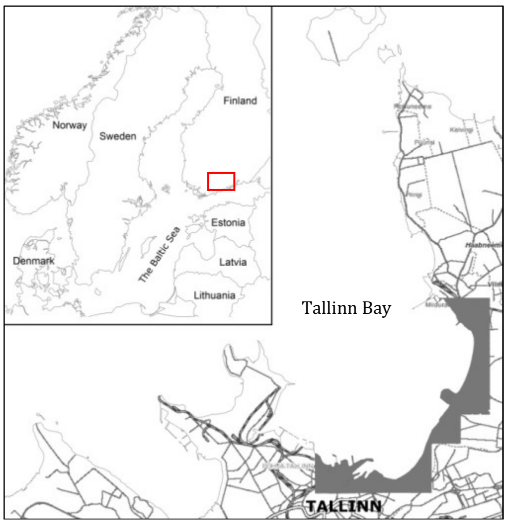

Fig. 3. The location of test area (grey). Inset: location of the test area within the Baltic Sea region (source: ELB and [12])

Accuracy of a similar ALS dataset in the nadir-range was estimated to be 0.06 m in [13]. As the point clouds were already classified by the ELB, then only ground surface points were used for monitoring coastal processes in this study. It should be noted that during the ALS measurements the instantaneous sea level was a few decimeters below the mean sea level. This allowed to acquire ALS data over the dry foreshore parts (cf. Fig. 2) of the beaches as well.

4.2. ALS data processing challenges

ALS point clouds were converted to a raster format DEM, with the pixel size of 1 m. In this way at least theoretically every second raster pixel of the 2400 m elevation flights would have an actual elevation value. For the higher (3800 m) flights the same pixel size was selected to maintain compatibility in raster comparison and analysis. The volume changes in the coastal area were identified in three subsequent steps: (*i*) subtracting one DEM from another indicated areas with ground surface elevation changes; (*ii*) within these areas volume changes were calculated; (*iii*) coastline changes were confirmed by determining the planar location of the zero elevation isoline at different time-epochs.

Comparing time-epoch DEM-s with one another revealed sometimes a systematic pattern where elevation differences were correlated with the scan angle. The differences are close to zero at the nadir of the aircrafts trajectory (cf. Fig. 4a), whereas the farther from nadir the larger the elevation difference.

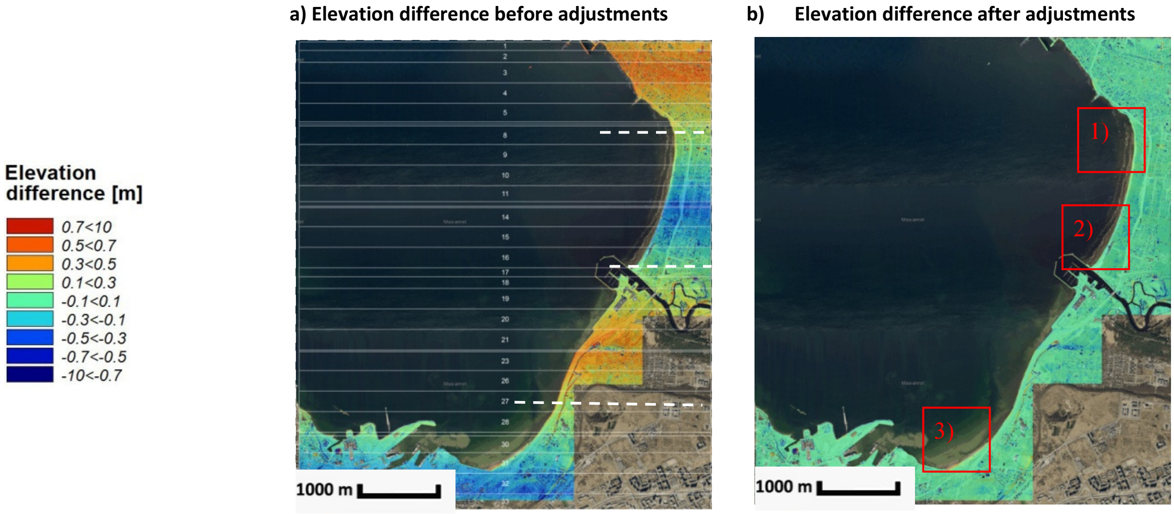

Fig. 4. Initial elevation differences between ground surface models (a) and elevation differences after implementing adjusting algorithms (b). Note that in (a) the ALS data is divided into sections (numbered, denoted by grey solid lines), each section is then reduced to a common height level. Rectangles in (b) enclose beach sections with most significant volume changes after adjustments, white dashed lines in (a) denote aircraft's trajectories. (orthophoto: ELB)

Note how elevation differences change from positive to negative, this is because roll misalignment causes the ALS data within a strip to appear tilted. Up to year 2011 the accuracy of ELB's ALS data was solely depending on the quality of the aircraft trajectory only. This means that standard ALS datasets may be affected by the roll misalignment parameter.

Thus, when using these datasets directly (i.e. without enhancements) the height detection accuracy will be affected by aforementioned systematic biases. However, it was possible to adopt various methods to minimize such biases between the datasets and thus increase the accuracy of ALS heights. Therefore a part of the research focused on developing algorithms for removing such systematic biases between datasets. When a commercial software eliminates these errors by applying angular corrections to point cloud, then this study has a different approach and applies only elevational corrections.

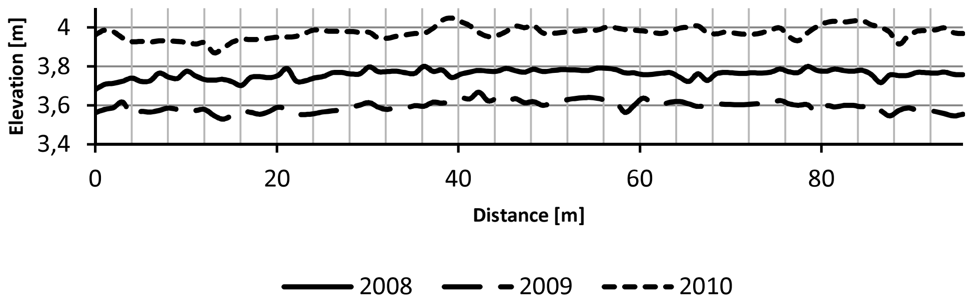

Fig. 5. A sample of elevations originating from different datasets at the same ground profile. Note systematic biases between the different ALS data

A sample of systematic biases between three used ALS datasets is demonstrated on Fig. 5. This particular ground profile is taken over a horizontal surface, which has not changed its physical height during the 2008–2010 ALS measurements. Different ALS data (erratically) do not confirm this, whereas the discrepancies reach several decimetres. Thus, in order to detect volume changes more accurately, all surfaces must be reduced to a common reference level. This makes it possible to identify relative changes with respect to one common level.

Within a profile an average elevation for each ALS data-set can be determined. For example, based on Fig. 5, the 2008 average elevation is 3.76 m, the 2009 average elevation of 3.59 m and the 2010 average elevation is 3.97 m. Thereafter the three ALS data-profiles can be compared with the average height of 3.77 m, yielding individual 1D correction value for each ALS dataset. Thereafter each ALS dataset within the profile-containing section can be uniformly shifted by the detected correction to the common reference (height) level. However, if such calibration profiles appear to be significantly tilted with respect to each other (e.g. Fig. 4a), it would not give a desired result and the contrasted differences would still remain. Therefore an algorithm was developed that suits best for the datasets which are affected by the roll misalignment parameter and where the inter-epoch elevation difference increases with the scan angle. The algorithm works by dividing the dataset into smaller sections (cf. Fig. 4a) and reducing each section into one common level. More specifically, the algorithm divides the ALS datasets into east-west directional sections (similarly to the flight trajectories, therefore the roll error increases in north-south direction). A number of similar ground calibration profiles were manually selected (at least one for each section, cf, Fig. 4a) along the shoreline, to examine and remove systematic biases in ALS heights. Each section was reduced to one common elevation level, e.g. the average elevation of all the years under review. An average width of most sections in north-south direction was 300 m (cf. Fig. 4a), since within this distance the initial elevations do not change significantly. The effectiveness of this method can be evaluated visually in Fig. 4 which shows that after implementing the adjusting algorithms the elevation discrepancies have decreased from a few decimeters to some centimeters. Therefore users can increase the accuracy of ALS datasets and thereby increase also the coastal monitoring accuracy.

4.3. Quality control and accuracy estimation of the ALS datasets

Vertical discrepancies between the surface models were calculated before and after the adjustments to evaluate the efficiency and quality of the developed algorithms. This was proceeded using surfaces like concrete and asphalt roads near the coast, but on the absence of those gravel roads were selected as well. The study showed that asphalt is the best surface to compare and minimize elevation discrepancies between the ALS datasets. Quality assessments are based on the same calibration profiles that were used in the adjustment algorithm. The statistics of detected discrepancies are presented in Table 1.

Table 1. Statistics of the vertical discrepancies between ALS datasets

Parameter	Discrepancies at calibration profiles before adjustment			Discrepancies at calibration profiles after adjustment		
	2009–2008 [m]	2010–2009 [m]	2010–2008 [m]	2009–2008 [m]	2010–2009 [m]	2010–2008 [m]
Minimum difference	–0.27	–0.48	–0.23	–0.03	–0.08	–0.08
Maximum difference	0.31	0.42	0.23	0.03	0.10	0.08
Average difference	0.06	–0.04	0.01	0.00	0.00	0.00
Standard deviation	0.16	0.25	0.14	0.02	0.04	0.04

Note that the average difference after the adjustments is 0.00 m in all cases. Before adjustments the minimum standard deviation between the 2010–2008 datasets was 0.14 m. After adjustments the corresponding standard deviation reached 0.04 m. Using the normal distributions two sigma rule, it can be calculated that with a 95.45% probability the elevation differences between the datasets remain within the –0.08 to +0.08 m range. Thus, height differences exceeding 0.08 m can be considered actual changes in ground elevations.

5. Results

The Pirita beach had remarkable changes in the northern (cf. Fig. 4b region 1) and southern part (cf. Fig. 4b region 2). Comparisons between the 2008–2010 ALS results show an accumulation of material in the northern part of Pirita beach. Most significant changes have occurred five to seven meters from the shoreline, where sand has accumulated up to 0.4 m (cf. Fig. 6). The same has occurred on the southern part on Pirita beach (cf. Fig. 7). In some locations up to 0.4 m of matter has accumulated. Also a 0.2 m thick layer of matter from a strip of beach, 18 meters away from the shoreline has been carried away. The volume calculations for Pirita beach (cf. Table 2) show that the beach has mainly gained matter. Over two years (2008–2010) the total gain is 6034 m^3, whereas the loss is only 399 m^3.

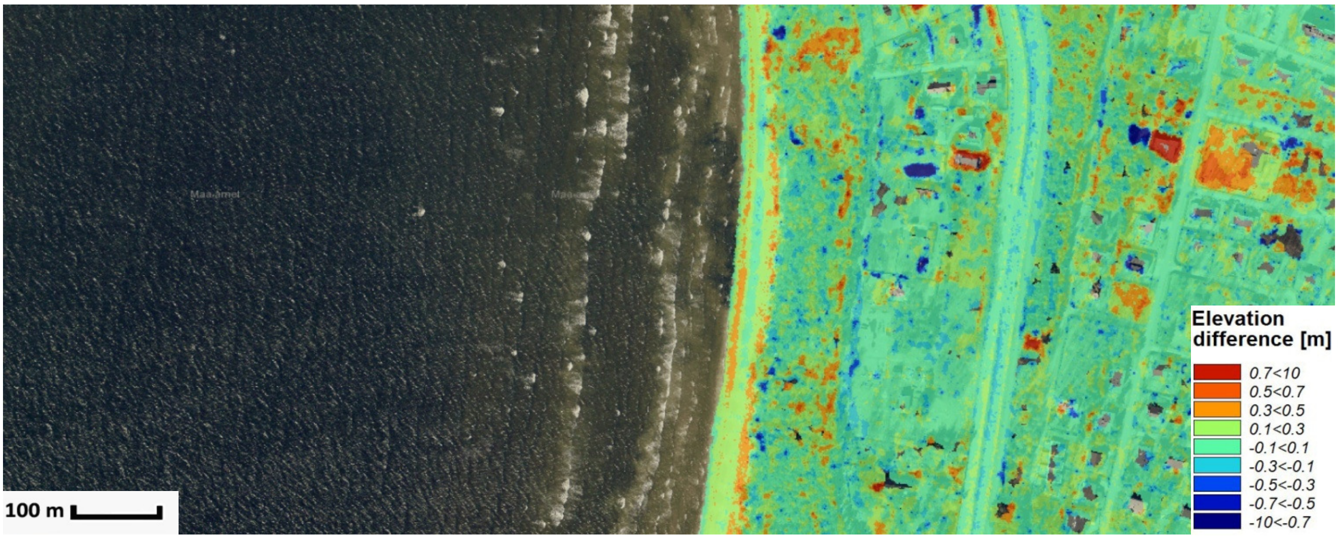

Fig. 6. Ground elevation differences between the 2008 and 2010 ALS data in area 1 (cf. Fig. 4b). Note that the most remarkable changes occur five to seven meters from the shoreline, where sand has accumulated up to 0.4 m. (orthophoto: ELB)

The results for the Kadriorg beach show a gain in matter (cf. Fig. 8). On a large part of the beach the average surface elevation has increased 0.4 m and that up to 20 meters from the shoreline. The maximum ground elevation increase in that area is 0.7 m. The volume change calculations show that Kadriorg beach has gained more matter than lost, cf. Table 2.

Table 2. Volume changes in Pirita (areas 1 and 2) and Kadriorg (area 3) sand beaches.

Period	Pirita beach		Kadriorg beach	
	Gain [m^3]	Loss [m^3]	Gain [m^3]	Loss [m^3]
2009–2008	1938	1009	1828	47
2010–2009	4179	620	1066	77
2010–2008	6034	399	3928	39
Total area [m^2]	94436		27744	

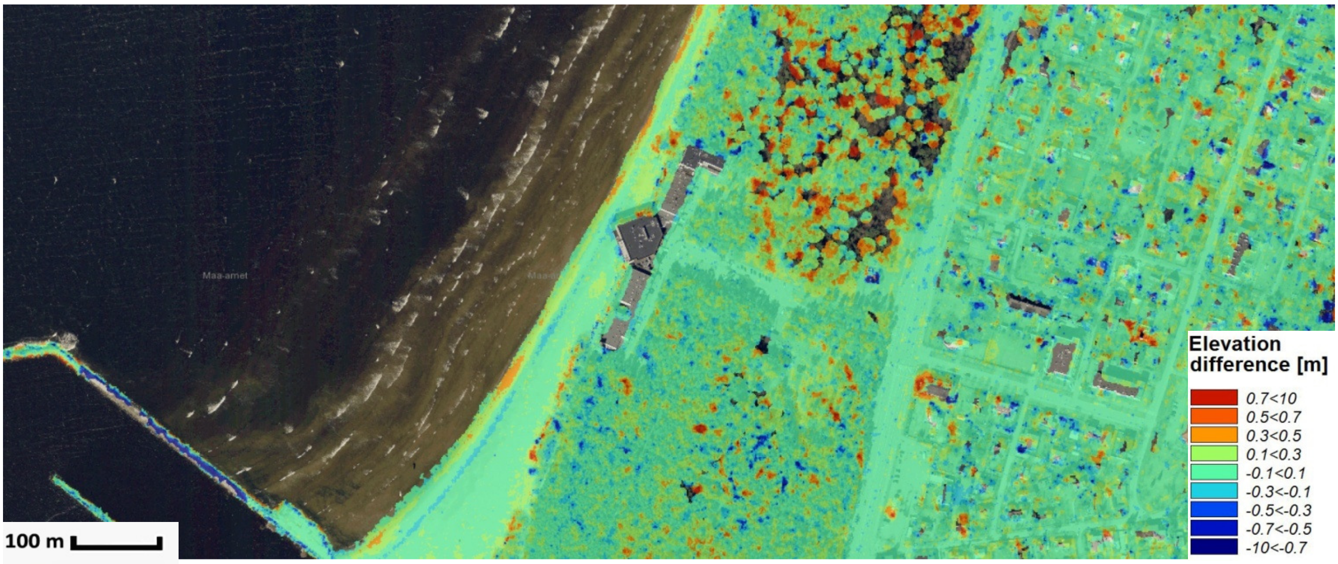

Fig. 7. Elevation differences between the 2008 and 2010 ALS data in area 2 (cf. Fig. 4b). In some locations up to 0.4 m of matter has accumulated. Within a strip 18 meters away from the shoreline a 0.2 m thick layer of matter has been carried away. (orthophoto: ELB)

Summary

This case study showed that airborne laser scanning data is suited for monitoring coastal processes. The main challenge in this study was the elimination of systematical biases between the ALS datasets. The standard ALS data-products need to be enhanced to detect reliably dm range changes in elevations.

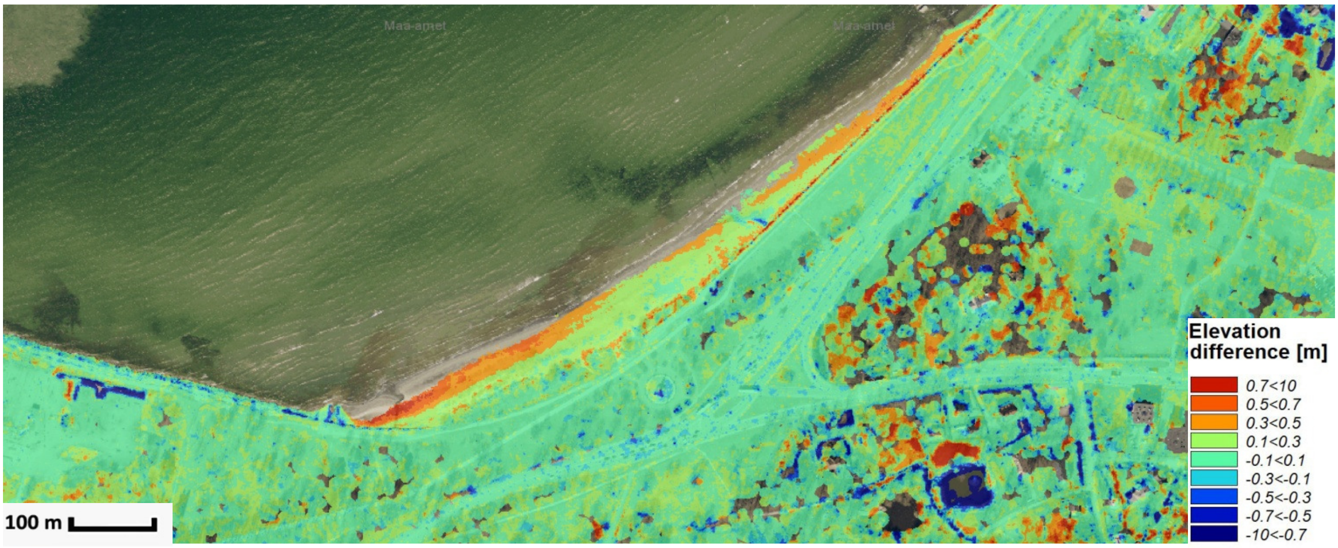

Fig. 8. Elevation differences between the 2008 and 2010 ALS data in area 3 (cf. Fig. 4b). Note that on a large part of the beach the ground elevation has increased for an average of 0.4 m up to 20 meters from the shoreline. (orthophoto: ELB)

Within this study different algorithms were developed that minimize discrepancies between the ALS datasets by reducing the datasets to a common level. The differences can be detected and minimized by using calibration profiles that were selected on a variety of surfaces. Further studies need to be devoted for connecting rigorously the averaged profile heights with the national height system. All in all, this study demonstrates that ALS is a possible alternative to traditional coastal monitoring methods.

Acknowledgements

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