



1 Processing and accuracy of topobathymetric LiDAR

- 2 data in land-water transition zones
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13 Abstract

14 The transition zone between land and water is difficult to map with conventional geophysical systems due to shallow water depth and often harsh environmental 15 16 conditions. The emerging technology of airborne topobathymetric Light Detection And 17 Ranging (LiDAR) is capable of providing both topographic and bathymetric elevation 18 information, resulting in a seamless coverage of the land-water transition zone. 19 However, there is no standard and simple method for processing topobathymetric 20 LiDAR data into a Digital Elevation Model (DEM). In this study, a method is developed for the creation of a DEM based on high-resolution topobathymetric LiDAR 21 22 data from the Knudedyb tidal inlet system in the Danish Wadden Sea. The vertical accuracy of the LiDAR data is determined to ± 8 cm at a 95% confidence level, and the 23 horizontal accuracy is determined as the mean error to ± 10 cm. The LiDAR technique is 24 found capable of detecting features with a size of less than 1 m². The created DEM 25 seamlessly covers the land-water transition zone extending down to approximately 3 m 26 27 water depth which is the maximum penetration depth of the LiDAR system at the given 28 challenging environmental conditions in the Wadden Sea.





1 1 Introduction

2 The coastal zone is under pressure from human exploitation in many and various ways. 3 Many large cities are located near the coast, and they grow gradually with the increase 4 in worldwide population and urbanization. Many industrial activities take place in close 5 vicinity to the coast, e.g. fishery, construction, maintenance dredging for safety of 6 navigation, and mining for raw materials. The coastal zone also provides the setting for 7 many recreational and touristic activities, such as sailing, swimming, hiking, diving and 8 surfing. In addition to human exploitation, climate change also poses a future threat 9 with a predicted rising sea level and increasing storm intensity and frequency, expected 10 to cause erosion and flooding in the coastal zone (Mousavi et al., 2011). All these 11 pressures and different interests underpin the societal need for mapping and monitoring 12 the coastal zone.

13 Traditionally, difficulties of mapping in shallow waters have resulted in an information 14 gap in the transition zone between land and water, and for that reason there has often 15 been a demand for high resolution data in the shallow water zones (Al-Hamdani et al., 16 2008). Topobathymetric Light Detection and Ranging (LiDAR) includes high resolution 17 measurements of both topography and bathymetry, and for that reason it is specifically 18 suited to map the land-water transition zone (Guenther, 1985; Jensen, 2009; Pe'eri and 19 Long, 2011). The technology is based on continuous measurements of the distance 20 between an airplane and the ground/sea bed. The distance (or range) is calculated by 21 half the travel time of a laser beam, going from the airplane to the surface of the earth 22 and back to the airplane. The wavelength of the laser beam is in the green spectrum, 23 usually 532 nm, since this wavelength is found to attenuate the least in the water 24 column, resulting in the largest penetration depth of the laser (Jensen, 2009).

The laser beam may encounter many targets of varying nature on its way from the airplane and back again, and different processes are influencing the laser beam propagation through air and water. First, the laser beam may be reflected by targets in the air, such as birds or dust particles, and these can show up as LiDAR reflection points in the space between the airplane and the surface. When encountering water, the speed of the laser decreases from 3×10^8 ms⁻¹ to 2.25×10^8 ms⁻¹ in 10°C freshwater or $2.24 \times$ 10^8 ms⁻¹ in 10°C saltwater of 30 PSU (Millard and Seaver, 1990). Thereby, the total





- 1 range (R_t) is the mathematical addition of the range in air (R_{air}) and in water (R_{water})
- 2 (Mandlburger et al., 2013):

3
$$R_t = R_{air} + R_{water} = \left(\frac{1}{2} \cdot t_{air} \cdot c_{air}\right) + \left(\frac{1}{2} \cdot t_{water} \cdot c_{water}\right)$$
 (1)

4 where t_{air} , c_{air} , t_{water} , and c_{water} are laser beam travel time (*t*) and speed of light (*c*) in

5 air and water, respectively.

6 The changing speed of the laser beam also affects the direction of the laser beam when
7 penetrating the water surface with an angle different from nadir (Fig. 1) (Guenther,
8 2007;Jensen, 2009). The laser beam will be refracted according to Snell's Law
9 (Mandlburger et al., 2013):

$$10 \quad \frac{\sin \alpha_{\text{air}}}{\sin \alpha_{\text{water}}} = \frac{c_{\text{air}}}{c_{water}} = \frac{n_{water}}{n_{\text{air}}} \tag{2}$$

where a_{air} is the incidence angle of the laser beam relative to the normal vector of the water surface and a_{water} is the refraction angle in water. n_{water} and n_{air} are the refractive indices of water and air, respectively (Mandlburger et al., 2013).

The penetration depth in water is limited by the attenuation of the laser beam. Water molecules, suspended sediment and dissolved material all act on the laser beam by absorption and scattering, resulting in substantial reduction in power as the signal propagates into the water (Guenther, 2007;Mandlburger et al., 2013;Steinbacher et al., 2012). The laser beam also diverges in the water column, resulting in a wider laser beam footprint, which reduces the resolving capability of small-scale morphology the deeper the laser beam penetrates.

21 The returned signal is represented as a distribution of energy over time, also called the 22 'full-waveform' (Alexander, 2010; Chauve et al., 2007; Mallet and Bretar, 2009). The 23 peaks in the full-waveform are detected as individual targets encountered by the 24 propagating laser beam. If the laser hits two targets with a small vertical difference, 25 such as a water surface and sea bed in very shallow water, then the two peaks in the full-waveform may merge together, resulting in the detection of only one target (Fig. 1). 26 27 This results in a detection minimum of successive returns from a single laser pulse, and 28 the vertical distance within this minimum is referred to as the 'dead zone' (Mandlburger 29 et al., 2011;Nayegandhi et al., 2009). The dead zone is a clear limitation to the LiDAR





1 measurements, which is an important parameter to consider in very shallow water, such

2 as in tidal environments.

3 The raw LiDAR measurements are spatially visualized as a point cloud, with each point 4 representing an individual target. The point cloud must be piped through a series of 5 steps before it can take shape as a digital elevation model (DEM). The overall 6 processing steps are known, but there is no standard or universal approach for dealing 7 with the individual steps. In particular, there is no definitive method for detecting a 8 water surface from the topobathymetric LiDAR data. Careful processing of the LiDAR 9 data is important, in order to obtain the best approximation of the real world in the 10 processed DEM. Finally, it is essential to determine the accuracy and precision of the 11 LiDAR data for assessing the capability of the technique to represent the real world 12 surface.

13 The aim of this study is to investigate the potential of topobathymetric LiDAR data to 14 accurately model the real world terrain and surface in land-water transition zones. The 15 aim is achieved by meeting the following objectives:

- 16 1. Develop a processing method for the generation of a digital elevation model in
- 17 land-water transition zones.
- 18 2. Quantify the accuracy and precision of the LiDAR data based on object
- 19 detection.
- 20 3. Evaluate the potential of topobathymetric LiDAR to resolve landforms in land-21 water transition zones.
- 22

23 2 Study area

The Knudedyb tidal inlet system is located between the barrier islands of Fanø and Mandø in the Danish Wadden Sea (Fig. 2A). The tidal inlet system is a natural environment without larger influence from human activity. The tides in the area are semi-diurnal, with a mean tidal range of 1.6 m, and the tidal prism is in the order of $175 \cdot 10^6 \text{ m}^3$ (Pedersen and Bartholdy, 2006). The main channel is approximately 1 km wide and with an average water depth of approx. 15 m (Lefebvre et al., 2013).

30 Three study sites around the tidal inlet system are referred to throughout this work (Fig.

31 2A-D):





1	•	Study site 1, in which a DEM was generated, is an elongated 3.2 km^2 (0.85 $\times4$
2		km) section of the Knudedyb tidal inlet system (Fig. 2B). The section is located
3		perpendicular to the main channel and stretches across both topography and
4		bathymetry.

- Study site 2 is a cement block with a size of 2.50×1.25×0.80 m located on land
 next to the mouth of Ribe Vesterå River (Fig. 2C). The block was used for
 assessing the accuracy and precision of the LiDAR data.
- Study site 3 is a steel frame with a size of 0.92×0.92×0.30 m located in the river
 with the surface just below the water surface (Fig. 2D). The frame was used for
 precision assessment.

Study site 1 extends towards north into an area on Fanø with dispersed cottages (Fig.
2E). The most prominent morphological features within the study site include beach
dunes (Fig. 2F), small mounts (Fig. G), swash bars (Fig. 2H-I) and linear bars (Fig. 2J).

14

15 3 Methods

16 **3.1 Surveys and instruments**

LiDAR data and ortophotos were collected by Airborne Hydro Mapping GmbH (AHM)during two surveys on 19 April 2014 and 30 May 2014.

19 On 19 April 2014, study site 2 and 3 was covered for accuracy and precision assessment of the LiDAR data by object detection of the block and the frame (for location see Fig. 20 21 2). The block was covered by 7 swaths retaining 227 LiDAR points from the block surface. The frame was covered by 4 swaths retaining 46 LiDAR points from the 22 23 surface of the frame. Ground control points (GCPs) were measured for the four corners 24 of the block with accuracy better than 2 cm using a Trimble R8 RTK GPS. 25 Measurements were repeated three times and averaged to minimize errors caused by 26 measurement uncertainties.

- 27 On 30 May 2014, study site 1 was covered by 11 swaths (Fig. 3), which were used for
- 28 generating the DEM. Low tide was -1 m DVR90, measured at Grådyb Barre, approx. 20
- 29 km NW of the study site.





- 1 The weather was similar during the two surveys, with sunny conditions, average wind
- 2 velocities of 7-8 m/s (DMI, 2014a, b) and significant wave heights, measured west of
- 3 Fanø, of approx. 0.5 m coming from NW (Danish Coastal Authority, 2014). Overall,
- 4 both days constituted good conditions for topobathymetric LiDAR surveys.

5 In both surveys, LiDAR data was collected with a RIEGL VQ-820-G topobathymetric 6 airborne laser scanner. The scanner is characterized by emitting green laser pulses with 7 a very high laser pulse repetition rate of up to 520,000 Hz and a narrow laser beam 8 footprint of 40 cm diameter at a flying altitude of 400 m (RIEGL, 2014). The high 9 repetition rate and narrow footprint makes it well suited to capture small-scale 10 landforms (Doneus et al., 2013; Mandlburger et al., 2011; RIEGL, 2014). An arc shaped 11 scan pattern maintains an almost uniform scan angle of 20° (±1°), which is influenced 12 by the roll, pitch and yaw of the airplane. This means that the incidence angle of the 13 laser beam is almost constant at the water surface (Niemeyer and Soergel, 2013). 14 General specifications of the laser scanner are summarized in Table 1 (RIEGL, 15 2014;Steinbacher et al., 2012).

For each returned signal, the collected LiDAR data contained information of x, y and z, as well as a GPS time stamp and values of the amplitude, reflectance, return number, attribute and laser beam deviation (RIEGL, 2012). Primarily the positions and time stamps of the LiDAR points were used in the data processing. The reflectance, which represents the range-normalized amplitude of the received signal, was used to a lesser extent in the filtering process.

22 3.2 From raw topobathymetric LiDAR data to gridded DEM

- A list of essential processing steps was necessary to produce a DEM from rawtopobathymetric LiDAR data. These steps included:
- 25 1. Determination of flight trajectory.
- 26 2. Integration of sensor data (laser scanner data, motion sensor data,
 27 positioning/trajectory data).
- 28 3. Raw point cloud processing.
- 29 4. Boresight calibration: Calculating internal scanner calibration.





- 1 5. Swath alignment based on boresight calibration: The bias between individual
- 2 swaths was minimized.
- 3 6. Filtering: The raw data contained lots of unwanted return signals (noise) located
- 4 both above and below ground. These points needed to be filtered from the point5 cloud.
- 6 7. Water surface detection: A water surface had to be established in order to correct7 for refraction in the following step.
- 8 8. Refraction correction: All the points below the water surface were corrected for9 the refraction of the laser beam.
- 9. Point cloud to DEM: The points were transformed into a surface whichrepresented the real world topography and bathymetry.

Step 1 and 2 were performed prior to the LiDAR survey. The different instruments (LiDAR, IMU and GPS) were integrated spatially by measuring their position relative to each other, when mounted on the airplane, and temporally by calibrating their time stamps.

Step 3-5 were the initial processing steps after the LiDAR survey. A number of reference planes on the ground were measured with RTK GPS, and the swaths covering these planes were adjusted so that they aligned with the planes. The rest of the swaths, which did not cover the reference planes, were aligned with the already adjusted swaths.

Step 6-9 represents the processing of the point cloud into a DEM. The methods involved in these steps are the main focus in this work and they are described in detail in the following sub-sections. Each swath was pulled individually through the processing workflow to account for the continually changing water level in the study area due to tides.

25 3.2.1 Filtering

The raw LiDAR data contained a lot of noise points in the air column originating from the laser being scattered by birds, clouds, dust and other particles, and a lot of noise points were also appearing below the ground/sea bed (Fig. 4A-B). All these noise points had to be filtered before further processing. The filtering process involved both automatic and manual filtering.





1 1. <u>Automatic filtering</u>

The automatic filtering was carried out in HydroVish (AHM) with the tool *Remove flaw echoes*. The filtering tool was controlled by three variable parameters: search radius, distance and density. The search radius parameter specified the radius of a sphere in which the distance and density filters were utilized. The distance parameter rejected a point, if it was too far from any other point within the sphere. The density parameter specified the lower limit of points within the sphere. The automatic filter iterated through all the points in the point cloud.

9 In order to identify the best settings of the three parameters, a sensitivity analysis was 10 performed on three data fragments representing different natural environments in the 11 Knudedyb tidal inlet system: a fragment in the flood channel, one on the tidal flat and a 12 fragment with vegetation. The outcome of the filtering was visually evaluated for 13 different settings to decide the most suitable settings to use for filtering the whole study 14 area. Based on visual inspection of the outcomes, it was impossible to reach a setting 15 which would be optimal for all the different environments. Particularly, the deeper 16 bathymetric parts contained more widely dispersed points, which were easily rejected 17 by the filter. The analyses with different settings also showed that two layers of noise 18 points close to the ground, both above and below, were very difficult, if not impossible, 19 to reject with this automatic filtering method. They were only rejected if the distance threshold was set very low (0.20-0.25 m) or the density threshold was very large, but 20 21 that would result in a large amount of valid points being rejected.

Based on the visual inspection of the filtering sensitivity analysis, the chosen settings
for the automatic filtering were: Search radius = 1 m, distance = 0.75 m and density = 4.

24 2. <u>Manual filtering</u>

The remaining noise points were manually filtered in the software Fledermaus (QPS) based on visual inspection of the point cloud (Fig. 4D). The reflectance of the points helped to distinguish between valid and non-valid points.

The filtered point cloud (with water points) was used in the following step to detect the water surface. Meanwhile, a copy of the data was undergoing additional manual filtering, removing all the water points (Fig. 4E). After this final filtering step, there





- 1 were only points representing topography, bathymetry, vegetation and man-made
- 2 structures left in the dataset.

3 3.2.2 Water surface detection

The water surface detection was based on determining the water surface *elevation* and the water surface *extent*. The water surface elevation was determined based on the water surface points and the extent was determined by extrapolating the water surface until it intersected the surface of the topography. Two assumptions about the water surface were made:

9 1. The water surface was horizontal. This was of course a simplification of the real 10 world. Tidal processes and wind- and wave-setup may cause the water surface to 11 be sloping, and the water is often topped by more or less significant wave action. 12 A linear fit through the water surface LiDAR points along the main channel, showed a changing water level of 0.13 m over a distance of 400 m, 13 corresponding to a 0.325×10^{-3} (0.019 deg.) sloping water surface. A similar fit 14 through the LiDAR points along the flood channel showed a slope of 0.156×10^{-10} 15 ³ (0.009 deg.). The maximum wave heights observed in the main channel were 16 17 20-30 cm. Based on the moderate slope of the water surface and relatively low 18 wave height, it was considered acceptable to assume a flat water surface.

19 2. Study site 1 had water bodies with two different water levels: One represented 20 the water level in the main channel and the other represented the water level in 21 the flood channel. This was also a simplification, as the tidal flat contained small 22 pools of water with potentially different water levels. However, almost all of these pools contained no LiDAR points of the water surface, which means that 23 24 the water depth in the pools must have been within the limitation of the dead 25 zone. Therefore, it was impossible to detect individual water surfaces in the 26 pools.

A series of processing steps were performed to detect the water surface. The first step was to extract a *shallow surface* and a *deep surface* from the filtered point cloud (with water points) in Fledermaus (Fig. 4F). Both surfaces consisted of 0.5×0.5 m cells, and the elevation value in each cell was equal to the highest point within the cell (shallow surface) and the lowest point within the cell (deep surface), respectively. The shallow





1 surface should then display the topography along with the water surface, whereas the

- 2 deep surface should display the topography and the sea bed (as long as the sea bed was
- 3 detected by the laser).

4 The following steps were focused on the shallow surface to determine the elevation of 5 the water surface (Fig. 4G). First, the shallow surface was down-sampled to a surface 6 with a cell size of 2×2 m, and the new cells were populated with the maximum 7 elevation of the input cells. The down-sampling was done for smoothing the water 8 surface, and thereby eliminating most of the outliers. The exact cell size of 2×2 m, as 9 well as populating them with the maximum value, was chosen based on the work by 10 Mandlburger et al. (2013). They compared water surface detection capability between green LiDAR data, collected with the same RIEGL-VQ-820-G laser scanner, and near-11 12 infrared LiDAR data, which was assumed to capture the true water surface. They found 13 that the green LiDAR generally underestimated the water surface level, but that reliable 14 results were achieved by increasing the cell size and only taking the top 95-100% of 15 water points into account. According to their work, it was assumed that placing the 16 water surface on the highest points in 2 m cells provided a good estimate of the true 17 water level. However, based on their results it could be expected that the water surface 18 level in this case would be underestimated in the order of 2-4 cm.

19 The water covered areas in the main channel and the flood channel were manually 20 extracted from the newly resampled raster surface. The mean elevation of the cells was 21 calculated individually in each area, and these values constituted the water surface 22 levels in the main channel and in the flood channel, respectively.

23 Hereafter, the extent of the water surfaces was determined (Fig. 4H). Two horizontal 24 water surfaces was created in the flood channel and the main channel with a cell size of 25 0.5×0.5 m and cell values equal to the determined water surface elevations in each 26 region. The high spatial resolution of 0.5 m cells was chosen to produce a detailed water 27 surface along the edges of the land-water transition. It also made the calculations in the 28 following step straightforward, because the resolution was similar to that of the deep 29 surface. The deep surface cell elevations were subtracted from the water surface 30 elevation and all cells with resulting negative values were discarded from the water surface. Thereby, all the water surface cells which were below the deep surface were 31





- 1 discarded. All the cells above the deep surface were expected to represent the two water
- 2 surfaces. Thereby, two water surfaces were created; one in the main channel and one in
- 3 the flood channel.

4 **3.2.3 Refraction correction**

5 The refraction correction of all the points below the water surfaces was calculated in 6 HydroVish (AHM). The input parameters were the filtered point cloud (without water 7 points), the derived water surfaces and the trajectory data of the airplane. These were all 8 converted to F5 file format to allow import into HydroVish (AHM). The refraction 9 correction was calculated automatically for each point based on the water depth, the 10 incident angle of the laser beam, and the refracted angle according to Snell's Law (Fig. 11 4I).

12 3.2.4 Point cloud to DEM

13 After iterating through the processes of filtering, water surface detection and refraction correction for all the individual swaths, the LiDAR points of all swaths were combined. 14 15 The transformation from point cloud into a DEM was performed with ArcGIS (ESRI) 16 software. The DEM was created as a raster surface with a cell size of 0.5×0.5 m, and 17 each cell was attributed the average elevation of the points within the cell-boundaries. 18 The 0.5 m cell size was chosen to get as high resolution as possible without making any 19 significant interpolation between the measurements. In this way, each cell represented 20 actually measured elevations instead of interpolated values. However, there were still 21 very few gaps of individual cells with no data in the resulting raster in areas with 22 relatively low point density. Despite of the general intention of avoiding interpolation it 23 was chosen to populate these cells with interpolated values to end up with a full DEM coverage (except for the bathymetric parts beyond the maximum laser penetration 24 25 depth). The arguments for interpolation were that 1) the interpolated cells were scattered 26 and represented only 1.7 % of all the cells 2) they were found primarily on the tidal flat 27 where the slope is generally less than 1°, meaning that the elevation difference from one 28 cell to a neighbouring cell is usually less than 1 cm, and 3) the general point density in 29 most of the study area was so high that the loss of information by lowering the DEM 30 resolution would represent a larger sacrifice than interpolating a few scattered cells. The 31 interpolation was performed by assigning the average value of all neighboring cells to





- 1 the empty cells. The final DEM was thereby fully covering the topography, and the
- 2 bathymetry was covered down to a depth equal to the maximum laser penetration depth.

3 3.3 Accuracy and precision of the topobathymetric LiDAR data

The term *accuracy* refers to the difference between a point coordinate (in this case a LiDAR point) compared to its "true" coordinate measured with higher accuracy, e.g. by a total station or a differential GPS; while the term *precision* refers to the difference between successive point coordinates compared to their mean value, i.e. the repeatability of the measurements (Graham, 2012;Jensen, 2009;RIEGL, 2014).

9 Two "best-fit planes" based on the LiDAR points on the block and the frame surfaces 10 were established with the *Curve Fitting tool* in MATLAB (MathWorks). These were 11 used to quantify the precision. Another best-fit plane was established based on the block 12 GPS measurements, and this plane was regarded as the "true" block surface for 13 assessment of the accuracy of the LiDAR measurements. The established planes were 14 described by the polynomial equation:

15
$$z(x, y) = a + bx + cy$$
 (3)

16 where *x*, *y* and *z* are coordinates and a, b and c are constants. Inserting x and y 17 coordinates for the LiDAR surface points in Eq. (3) led to a result of the corresponding 18 elevation (z) as projected on the fitted plane. The difference between the elevation of 19 the LiDAR point and the corresponding elevation on the fitted plane was used as a 20 measure of the vertical accuracy (for the GCP fitted plane) and the vertical precision 21 (for the LiDAR point fitted plane). Statistical measures of the standard deviation (σ), 22 mean absolute error (E_{MA}), and root mean square error (E_{RMS}) were calculated by:

23
$$\sigma = \sqrt{\frac{\Sigma(z_i - z_{\text{plane}})^2}{n-1}}$$
(4)

$$24 \qquad E_{\rm MA} = \frac{\sum |z_{\rm l} - z_{\rm plane}|}{n} \tag{5}$$

25
$$E_{\rm RMS} = \sqrt{\frac{\sum (z_{\rm i} - z_{\rm plane})^2}{n}}$$
(6)

where z_i is the elevation of the measured LiDAR points, z_{plane} is the corresponding elevation on the best-fit plane, and *n* is the number of LiDAR points. The vertical



(7)



- 1 accuracy and precision were determined at a 95% confidence level based on the 2 accuracy standard presented in *Geospatial Position Accuracy Standards Part 3*:
- 3 National Standard for Spatial Data Accuracy (NSSDA) (FGDC, 1998):

4
$$C'_{95\%} = E_{\rm RMS} \cdot 1.96$$

- 5 The horizontal accuracy was determined as the horizontal mean absolute error $(E_{MA,xy})$ 6 based on the horizontal distances between the block corners, measured with RTK GPS, 7 and the best approximation of the block corners derived from the LiDAR points of the 8 block surface. The minimum distance between a block corner and the perimeter of the 9 LiDAR points was regarded as the best approximation. Hereafter, $E_{MA,xy}$ was calculated 10 as the average of the four corners.
- 11

12 4 Results

13 4.1 Refraction correction and dead zone extent

- 14 The vertical adjustment of the LiDAR points due to refraction correction (z_{diff}) is 15 linearly correlated with the water depth (*d*) (Fig. 5). The empirical relationship is given 16 by the equation:
- 17 $z_{\rm diff} = 0.227 * d', R^2 = 0.997$ (8)
- 18 A LiDAR point at 1 m water depth is vertically adjusted by approximately 0.23 m (Fig.
- 5). The variations around the linear trend in Fig. 5 are due to changing incidence anglesof the laser beam that varies with the airplane attitude (roll, pitch and yaw).
- The dead zone is clearly visible in the LiDAR point cloud as a gap with no water pointsat very shallow water depths (Fig. 6).
- The vertical extent of the dead zone is approx. 28 cm, determined by plotting the vertical difference between the shallowest and the deepest LiDAR point within 0.5 m cells – i.e. between the shallow surface and the deep surface (Fig. 7). The difference is manifested by an abrupt change in the dead zone, and the highest rate of change is shown to be at a water depth of approx. 28 cm.





1 4.2 Sub-decimetre accuracy and precision

- 2 The vertical accuracy of the LiDAR data is ±8.1 cm (Table 2 and Fig. 8A). This means
- 3 that there is 95% likelihood for a given LiDAR point measurement to be within ±8.1 cm
- 4 of the actual elevation at that position. The vertical precision of the LiDAR data is
- 5 ± 3.8 cm for the points on the frame, and ± 7.6 cm for the points on the block (Table 2).

6 The horizontal accuracy calculated as the horizontal mean absolute error $(E_{MA,xy})$ is

7 determined to ± 10.4 cm, which is the average of the minimum distances between the

8 four block corners and the edge of the block surface derived by the LiDAR data (Fig.

9 8B).

10 **4.3** Point density and resolution

The average point density is 20 points per m², which equals an average point spacing of
20 cm (Table 3). The point density of the individual swaths varies between 7-13 points
per m².

The point density of the combined swaths varies significantly throughout the area, spanning between 0-216 points per m^2 , although above 50 points per m^2 are rare (Fig. 8A). The highest point density is found in vegetated areas on Fanø, where a single laser pulse potentially returns multiple signals. The density on the tidal flat is generally a little lower. The local point density is, however and not surprisingly, highly related to the number of overlapping swaths, which is evident by comparing the point density (Fig. 9A) with the number of swath overlaps (Fig. 9B).

The large variation of the point density and its spatial relation to swath overlaps is also reflected by the frequency distribution of the point density (Fig. 10). Three peaks are visible in the distribution around 8, 17 and 26 points per m². They fit very well with the expected densities from 1, 2 and 3 overlaps, respectively, when keeping in mind the point density of the individual swaths.

26 4.4 DEM and landforms

The elevations in the studied section of the Knudedyb tidal inlet system range from -4 m DVR90 in the deepest parts of the flood channel and main channel to 21 m DVR90

29 on top of the beach dunes on Fanø (Fig. 11). Beach dunes and cottages of the village





1 Sønderho are clearly visible in the northern part of the study site (Fig. 11A-B). The tidal 2 inlet system is generally flat, with the most varying morphology found in the area of the 3 flood channel (Fig. 11C-D), and in the area close to the main channel (Fig. 11E-F). The 4 flood channel is approximately 200 m wide in the western part and it divides into two 5 channels towards east. The bathymetry of the channel bed is clearly captured by the 6 LiDAR measurements in the eastern part, and also in the western part down to -4 m 7 DVR90, which approximately equal a water depth of 3 m at the survey time. An 8 intertidal creek joins the flood channel from the north (Fig. 11D). From the flood 9 channel towards south, the tidal flat is vaguely upward sloping, until reaching two 10 distinct swash bars, which are rising 0.9 m above the surrounding tidal flat, reaching a 11 maximum elevation of 1.5 m DVR90 (Fig. 11E-F). Further south, the linear bars along 12 the margin of the main channel are clearly captured in the DEM (Fig. 11E).

13

14 **5 Discussion**

15 **5.1** Performance of the water surface detection

16 The method for water surface detection assumes a flat surface, which is a simplification 17 of the real world. The water surface can be inclined, and it can also be topped by waves. 18 An example of wave action directly visible in the LiDAR point cloud is seen in Fig. 12.

The waves lead to a larger degree of uncertainty when determining the water surface level, however, the modelled water surface level in the example is in between the wave crests and troughs. Perhaps more important is the effect of the waves on the water surface angles and thereby the laser beam angles of incidence. It results in different refraction angles than assumed with the horizontal surface. In order to account for this, the water surface should include changing elevations and thereby form a complete surface model, including waves.

The water surface detection method has an advantage by extending the water surface into the dead zone, which makes it possible to correct even the LiDAR points in 0-28 cm water depth for refraction. This is particularly beneficial in a flat area as the Knudedyb tidal inlet system, where the dead zone may cover large areas depending on the tide (Fig. 13).





1 However, there are many small ponds within the study site with a water surface in a 2 different elevation than in the large channels, but no detected water points, since the 3 water depth in the ponds are generally less than the vertical extent of the dead zone, i.e. 4 approx. 28 cm. The presented method is not capable of detecting a water surface in 5 these ponds. This means that the bottom points of the ponds are not corrected for 6 refraction. According to the computed refraction (Fig. 5), omitting refraction correction 7 of a 28 cm deep pond will result in -6 cm elevation error (naturally less error in 8 shallower water). For future investigations it will be an improvement if all the water 9 surfaces are modelled. This could be achieved by implementing NIR LiDAR 10 measurements in the LiDAR survey, since it is reflected by any water surface. It may 11 also be achieved with green LiDAR as the only data source by detecting the returned 12 signals reflecting off the water surface in the dead zone. Potentially, this could be 13 achieved by analysing the waveforms and choosing the first local peak in the returned 14 signal as a valid detected point. Thereby, both the sea bed and the water surface would 15 have a seamless transition between land and water.

16 **5.2** Quality of the topobathymetric LiDAR data

The vertical accuracy of conventional topographic LiDAR has previously been 17 18 determined to ±10-15 cm (Hladik and Alber, 2012; Jensen, 2009; Klemas, 2012; Mallet 19 and Bretar, 2009). Only few previous studies have focused on the accuracy of shallow 20 water topobathymetric LiDAR data (Nayegandhi et al., 2009;Steinbacher et al., 2012). 21 Nayegandhi et al. (2009) determined the vertical E_{RMS} of LiDAR data in 0-2.5 m water 22 depth to ± 10 -14 cm, which is above the ± 4.1 cm $E_{\rm RMS}$ found in this study. Steinbacher 23 et al. (2012) compared topobathymetric LiDAR data from a RIEGL VQ-820-G laser 24 scanner with 70 ground-surveyed river cross sections, serving as reference, and found that the system's error range was $\pm 5-10$ cm, which is comparable to the ± 8.1 cm 25 26 accuracy found in this study. In comparison with these previous findings of LiDAR 27 accuracy, the assessment of the vertical accuracy in this study indicates a good quality 28 of the LiDAR data.

29 Comparing the LiDAR accuracy with previous findings of accuracy derived from 30 multibeam sonar systems indicates similar or slightly better accuracy from the 31 multibeam sonar (Dix et al., 2012;Ernstsen et al., 2006). Dix et al. (2012) determined





1 the vertical accuracy of a multibeam sonar by testing the system on different objects and 2 in different environments, and found the vertical E_{RMS} to be ±4 cm. Furthermore, they 3 tested a LiDAR system on the same objects and found a similar vertical E_{RMS} of ± 4 cm. 4 The vertical E_{RMS} of ±4.1 cm found in this study is very close to both the multibeam 5 accuracy and LiDAR accuracy determined by Dix et al. (2012). Another study by Ernstsen et al. (2006) determined the vertical precision of a multibeam sonar based on 7 6 7 measurements of a ship wreck from a single survey. They found the vertical precision to be ± 2 cm, which is slightly better than the vertical precision of ± 3.8 cm (frame) and 8 9 \pm 7.6 cm (block) found in this study.

10 Determining vertical accuracy and precision are standard practice in studies involving 11 spatial data (FGDC, 1998;Graham, 2012;Jensen, 2009). Accuracy and precision are in 12 many cases provided as single values, such as ± 8.1 cm for the vertical accuracy in this 13 case, and thereafter they represent the accuracy/precision of the whole dataset. 14 However, the values actually only apply to the specific locations, where the assessment 15 is conducted. In reality, the accuracy and precision may vary spatially, which is also the case by the differing precision of ± 3.8 cm at the steel frame and ± 7.6 cm at the cement 16 17 block in this study. Furthermore, spatial variations of the precision throughout the study 18 area are revealed by looking at the vertical difference between overlapping LiDAR 19 measurements (Fig. 14).

There are large differences on Fanø, which is expected due to vegetation causing multiple LiDAR returns from both the vegetation canopy and from the bare ground. In contrast, the differences on the very vaguely sloping, non-vegetated tidal flat do not have a natural explanation. A range of uncertainty factors are causing the observed variations:

<u>Vertical bias between overlapping swaths</u>: Areas covered by more than a single swath,
and hence constituting a higher point density, tend to show more vertical variation in the
LiDAR point measurements. This is evident by comparing number of swath overlaps
(Fig. 9B) and the local point density (Fig. 9A) with the local vertical difference of the
LiDAR points (Fig. 14).

The vertical bias between swaths is varying and it has been observed in the point cloud to be up to 5 cm. In most environments, a bias of 5 cm would be unnoticeable, but





1 because of the large and very flat parts of the Knudedyb tidal inlet system, even a small 2 bias becomes readily evident. The bias between overlapping swaths may explain the 3 lower precision at the block compared to the frame, because the block was covered by 7 4 swaths as opposed to 4 swaths at the frame. It seems counterintuitive that more 5 overlapping swaths, leading to higher point density, eventually result in lower precision 6 of the measurements. In this case, the difference between precision and accuracy should 7 be kept in mind, and that the same relationship between overlapping swaths and 8 accuracy does not necessarily exist.

9 Sloping areas: LiDAR measurements on sloping areas are expected to have lower 10 vertical accuracy than on flat ground, because the laser beam footprint may span across 11 different elevations. The exact position of the detected point can vary within the 12 footprint, and thus it may also vary in elevation. Furthermore, the slope affects the 13 footprint by increasing its area size and changing the shape to more elliptical and less 14 round. The influence of slope is not crucial in the Knudedyb tidal inlet system, since it 15 is generally a very flat area, but it is still an uncertainty factor to keep in mind.

16 Uncertainty with increased water depth: The accuracy and precision are expected to be 17 lower as the laser beam penetrates deeper into the water column. It is first of all due to 18 widening of the laser beam footprint, which means that the elevation of a single LiDAR 19 point is derived from the measurement on a larger area on the sea bed. Secondly, any 20 uncertainty associated to a LiDAR measurement is magnified with increasing water 21 depth, due to the refraction correction. These factors, together with slopes, are causing 22 the LiDAR measurements to be less precise in the main channel and in the flood 23 channel.

Additional factors may increase the uncertainty of the LiDAR datasets. This could for instance be vegetation covering the ground or sea bed, or breaking waves, which makes it impossible for the laser to detect the sea bed. However, these factors do not have a great influence in the studied part of the Knudedyb tidal inlet system, and thus they are not further elaborated. Nevertheless, these factors must be taken into consideration for LiDAR surveys in different areas with lots of vegetation and slopes.





1 5.3 Impact of the findings

2 The study demonstrates the capability of topobathymetric LiDAR to resolve small-scale 3 features, while covering a large-scale tidal inlet system. While bridging between spatial 4 scales, the LiDAR data has further proved to maintain a high accuracy, which means 5 that shallow water zones can be mapped with a high level of detail. The combined 6 characteristics of mapping with high resolution and high accuracy in a traditionally 7 challenging environment provide many potential applications to the society, such as 8 mapping for purposes of spatial planning and management, safety of navigation, or 9 nature conservation.

During a single LiDAR survey, the present state of the environment is captured with high resolution and high accuracy. However, the coastal zone is a highly dynamic environment influenced by complex hydrodynamic processes and feedback mechanisms. Therefore, a continuous monitoring of the coastal zone with high accuracy LiDAR systems will provide an insight to the temporal variation, whether caused by climate variation or inflected by human activities.

16

17 6 Conclusions

18 A new method was developed for processing raw topobathymetric LiDAR data into a 19 digital elevation model with seamless coverage across the land-water transition zone. 20 The point cloud processing is based on simple concepts, which are easily repeatable, 21 and the processing steps are described in detail. The novel method for water surface 22 detection relies on basic principles, which makes it easy to implement for future studies. 23 Specifically, the water surface is extrapolated, so that it also covers the "dead zone", 24 which has been determined to be approx. 0-28 cm in the very shallow water. The 25 method does not model the spatially changing water levels, such as waves and inclined 26 surfaces.

The vertical accuracy of the LiDAR data was determined by object detection of a cement block on land to ± 8.1 cm with a 95% confidence level. The vertical precision was determined at the cement block to ± 7.6 cm, and ± 3.8 cm at a steel frame, placed just below the water surface. The difference between the two sites is an indication of spatial variations throughout the study area, largely influenced by biases between





1 overlapping swaths. The horizontal mean error was determined at the block to ± 10.4

2 cm.

A seamless topobathymetric digital elevation model was created for a 4×0.85 km section in the Knudedyb tidal inlet system. An average point density of 20 points per m² made it possible to create an elevation model of 0.5×0.5 m resolution without significant interpolation. The model extends down to water depths of 3 m, which was the maximum penetration depth of the laser scanning system at the given environmental conditions.

9 Overall this study has demonstrated a high potential for topobathymetric LiDAR to 10 bridge scales, i.e. to resolve small scale landforms at landscape scales, and to bridge 11 environments, i.e. to close the gap between marine and terrestrial environments in the 12 coastal zone or in other shallow-water transition zones like rivers and lakes.

13

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1 References

- Al-Hamdani, Z., Alanen, U., Andersen, J. H., Bekkby, T., Bendtsen, J., Bergström, U., Bučas, M.,
 Carlén, I., Dahl, K., and Daunys, D.: Baltic Sea marine landscapes and habitats-mapping and
 modeling, BALANCE Technical Summary Report, part 2/4, 2008.
- 5 Alexander, C.: Classification of Full-waveform Airborne Laser Scanning Data and
- 6 Extraction of Attributes of Vegetation for Topographic Mapping, PhD Thesis, University of7 Leicester, 2010.
- 8 Chauve, A., Mallet, C., Bretar, F., Durrieu, S., Deseilligny, M. P., and Puech, W.: Processing
 9 Full-Waveform LiDAR data: Modelling raw signals, Internatinal archives of
 10 Photogrammetry, Remote Sensing and Spatial Information Sciences, 2007.
- 11 Dix, M., Abd-Elrahman, A., Dewitt, B., and Nash, L.: Accuracy Evaluation of Terrestrial
- 12 LIDAR and Multibeam Sonar Systems Mounted on a Survey Vessel, Journal of Surveying
- 13
 Engineering, 138, 203-213, 10.1061/(ASCE)SU.1943-5428.0000075, 2012.
- Doneus, M., Doneus, N., Briese, C., Pregesbauer, M., Mandlburger, G., and Verhoeven, G.:
 Airborne laser bathymetry-detecting and recording submerged archaeological sites from
 the air, J Archeol Sci, 40, 2136-2151, 2013.
- 17 Ernstsen, V. B., Noormets, R., Hebbeln, D., Bartholomä, A., and Flemming, B. W.: Precision
- of high-resolution multibeam echo sounding coupled with high-accuracy positioning in a
 shallow water coastal environment, Geo-mar lett, 26, 141-149, 2006.
- 20 Graham, L.: Accuracy. Precision and all That Jazz, LiDAR Magazine, 2, 2012.
- Guenther, G. C.: Airborne laser hydrography: System design and performance factors, DTIC
 Document, 1985.
- Guenther, G. C.: Airborne lidar bathymetry, Digital elevation model technologies and
 applications: The DEM users manual, 2, 253-320, 2007.
- Hladik, C., and Alber, M.: Accuracy assessment and correction of a LIDAR-derived salt
 marsh digital elevation model, Remote Sens Environ, 121, 224-235, 2012.
- Jensen, J. R.: Remote sensing of the environment: An earth resource perspective 2/e,
 Pearson Education India, 2009.
- Klemas, V.: Airborne remote sensing of coastal features and processes: An overview, J
 Coastal Res, 29, 239-255, 2012.
- Lefebvre, A., Ernstsen, V. B., and Winter, C.: Estimation of roughness lengths and flow
 separation over compound bedforms in a natural-tidal inlet, Cont Shelf Res, 61-62, 98-111,
 10.1016/j.csr.2013.04.030, 2013.
- Mallet, C., and Bretar, F.: Full-waveform topographic lidar: State-of-the-art, ISPRS J Photogramm, 64, 1-16, 2009.
- Mandlburger, G., Pfennigbauer, M., Steinbacher, F., and Pfeifer, N.: Airborne Hydrographic
 LiDAR Mapping-Potential of a new technique for capturing shallow water bodies,
 Proceedings of ModSim'11, 2011.
- Mandlburger, G., Pfennigbauer, M., and Pfeifer, N.: Analyzing near water surface
 penetration in laser bathymetry-A case study at the River Pielach, ISPRS Annals of
 Photogrammetry, Remote Sensing and Spatial Information Sciences, 1, 175-180, 2013.
- 42 Millard, R. C., and Seaver, G.: An index of refraction algorithm for seawater over 43 temperature, pressure, salinity, density, and wavelength, Deep Sea Research Part A.





1 Oceanographic Research Papers, 37, 1909-1926, <u>http://dx.doi.org/10.1016/0198-</u> 2 <u>0149(90)90086-B</u>, 1990.

- 3 Mousavi, M., Irish, J., Frey, A., Olivera, F., and Edge, B.: Global warming and hurricanes: the 4 potential impact of hurricane intensification and sea level rise on coastal flooding, Climatic
- 5 Change, 104, 575-597, 10.1007/s10584-009-9790-0, 2011.
- Nayegandhi, A., Brock, J., and Wright, C.: Small-footprint, waveform-resolving lidar
 estimation of submerged and sub-canopy topography in coastal environments, Int J
 Remote Sens, 30, 861-878, 2009.
- 9 Niemeyer, J., and Soergel, U.: Opportunities of Airborne Laser Bathymetry for the 10 Monitoring of the Sea Bed on the Baltic Sea Coast, ISPRS J Photogramm, Remote Sensing
- 11 and Spatial Information Sciences, 1, 179-184, 2013.
- Pe'eri, S., and Long, B.: LIDAR technology applied in coastal studies and management, JCoastal Res, 1-5, 2011.
- Pedersen, J. B. T., and Bartholdy, J.: Budgets for fine-grained sediment in the DanishWadden Sea, Mar Geol, 235, 101-117, 2006.
- 16 RIEGL: LAS extrabytes implementation in RIEGL software Whitepaper, 2012.
- 17 RIEGL: Datasheet RIEGL VQ-820-G, RIEGL Laser Measurement Systems GmbH, 2014.
- 18 Steinbacher, F., Pfennigbauer, M., Aufleger, M., and Ullrich, A.: High resolution airborne
- 19 shallow water mapping, International Archives of the Photogrammetry, Remote Sensing
- 20 and Spatial Information Sciences, Proceedings of the XXII ISPRS Congress, 2012,
- 21





- 1 Table 1: Specifications of the RIEGL VQ-820-G topobathymetric airborne laser scanner
- 2 (RIEGL, 2014).

Flight altitude	~ 400 m above ground				
Swath width	~ 400 m				
Scan pattern	Section of an ellipse – arc shape				
Scan angle	20° ±1°				
Laser wavelength	532 nm				
Pulse width	1 ns				
Laser beam footprint (diameter)	40 cm (at 400 m flight altitude)				
Laser pulse repetition rate	Up to 520,000 Hz				
Max. effective measurement rate	Up to 200,000 meas./sec.				
Laser beam divergence	1 mrad				
Typical water depth penetration	1 Secchi disc depth				
	-				





- 1 Table 2: Vertical accuracy and precision of the LiDAR point measurements, in terms of
- 2 minimum error (E_{\min}) , maximum error (E_{\max}) , standard deviation (σ) , mean absolute
- 3 error (E_{MA}), root mean square error (E_{RMS}) and the 95% confidence level ($Cl_{95\%}$).

Accuracy/ Precision	Object	Best-fit plane	# points	E _{min} (cm)	E _{max} (cm)	σ (cm)	E _{MA} (cm)	E _{RMS} (cm)	<i>Cl</i> _{95%} (cm)
			n						
Accuracy	Cement block	GCPs	227	0.01	12.1	4.1	3.5	4.1	±8.1
Precision	Cement block	Point cloud	227	0.04	12.9	3.9	2.8	3.9	±7.6
Precision	Steel frame	Point cloud	46	0.02	5.5	2.0	1.6	1.9	±3.8





- 1 Table 3: LiDAR point spacing and density for all the 11 individual swaths, which
- 2 covered the study area, and for the combined swaths.

Swath number	1	2	3	4	5	6	7	8	9	10	11	All
Point spacing (m)	0.30	0.30	0.36	0.31	0.36	0.32	0.37	0.29	0.35	0.36	0.28	0.20
Point density (pt./m ²)	10.8	10.8	7.8	10.2	7.5	9.6	7.2	11.7	8.0	7.8	12.7	19.6







1

Figure 1: Conceptual sketch of the laser beam propagation and return signals. The beam refracts upon entering the water body, and it diverges as it propagates through the water column. Return signals are produced both in the air, at the water surface, in the water column and at the sea bed. The LiDAR instrument has limited capability in very shallow water (the "dead zone" in the figure) because the successive peaks from the water surface and the seabed are not individually separated in time and amplitude. Only the largest peak, which is from the sea bed, is detected.







Figure 2: A) Overview of the study area location and the three study sites (22 April
2015 satellite image, Landsat 8). B) Study site 1 in the Knudedyb tidal inlet system (30





- 1 May 2015 Orthophoto, AHM). C) Study site 2 with a cement block on land, used for
- 2 accuracy and precision assessment (19 April 2015 orthophoto, AHM). D) Study site 3
- 3 with a steel frame in Ribe Vesterå River, used for precision assessment (19 April 2015
- 4 orthophoto, AHM). E) Cottages in the dunes on Fanø. F) Beach dunes on Fanø. G)
- 5 Patch of *Spartina Townsendii* (Common Cord Grass). H-I) Swash bars. J) Linear bar.







Figure 3: The 11 swaths covering study site 1, which were used for generating theDEM.







surface (orange). I) Correction for the effect of refraction on all the submerged points. elevation. B) Zoom-in on a cross section of the flood channel with elevations exaggerated ×15 for visualization purpose. C-E) Method for filtering the point cloud. F-H) Method for detecting a water surface (blue) based on the extraction of a shallow surface (red) and a deep Figure 4: Workflow for processing the LiDAR point cloud. A) Point cloud from a single swath with points ranging from -100 m to 300 m









4 transect (see location in Fig. 2C).







- 2 Figure 6: Example of a cross section of the flood channel, with a clearly visible gap in
- 3 the water points in the very shallow water. The vertical dead zone is determined to be
- 4 approx. 28 cm (see text).







Figure 7: Vertical difference between the shallowest and the deepest LiDAR point
within 0.5 m grid cells in the land-water transition zone. The abrupt change is caused
by the dead zone. The vertical extent of the dead zone is determined to approx. 28 cm,
derived by the maximum rate of change of a polynomial fit through the points.







1

Figure 8: Vertical and horizontal distribution of the LiDAR points describing the block surface and the block surface derived from Ground Control Points (GCPs). A) LiDAR points (grey dots) compared to the GCP block surface (black line) for determining the vertical accuracy. The grey line shows the LiDAR block surface as a best-linear-fit through the points. B) Block surface derived from the four GCP corner points and the block surface derived by the perimeter of the LiDAR points.







2 Figure 9: A) Point density (pts./m²) throughout the study site. B) Number of swath

3 overlaps in different sections of the study site.







2 Figure 10: Frequency distribution of the varying LiDAR point density throughout the

3 study area.







1

Figure 11: Topobathymetric DEM across the northern part of the Knudedyb tidal inlet
system with close-up views of different detail level on specific areas. A hill shade is
draped upon the close-ups for improved visual interpretation. A) Northern section with
beach dunes and cottages. B) Cottages. C) Mid-section with the flood channel. D)
Closer view on an intertidal creek. E) Southern section with swash bars, linear bars and
bathymetry of the main channel. F) Swash bar.







2 Figure 12: Examples of observed wave activity in the main channel in the LiDAR data

from a single swath. A) A vertical view of the shallow surface with 0.5 m resolution,
showing waves near the tidal flat. B) A horizontal view along a transect through the

5 point cloud, which clearly captures the waves, together with the determined water

6 surface.







2 Figure 13: Horizontal extent of the dead zone in the studied area at mean low water,

3 mean water level and mean high water.







2 Figure 14: Vertical difference between the highest and the lowest LiDAR point within

3 0.5×0.5 m grid cells.