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Key words: topobathymetry, LiDAR, coastal zone

SUMMARY

Coastal and tidal environments are valuable ecosystems, which, however, are under pressure in many areas around the world due to globalization and/or climate change. Detailed mapping of these environments is required in order to manage the coastal zone in a sustainable way. However, historically these transition zones between land and water are difficult or even impossible to map and investigate in high spatial resolution due to the challenging environmental conditions. The new generation of airborne topobathymetric light detection and ranging (LiDAR) potentially enables full-coverage and high-resolution mapping of these land-water transition zones. We have carried out topobathymetric LiDAR surveys in the Knudedyb tidal inlet system in the Danish Wadden Sea and the Rødsand lagoon connected to Fehmarnbelt. The overall aims are to: (i) derive characteristic properties of the morphology, surface sediment, the vegetation and the water column in land-water transition zones like rivers, lakes, wetlands, estuaries and coasts; (ii) improve the understanding of the dynamics of these properties in shallow water ecosystems, which are under pressure due to changing environmental conditions driven by climate change; and (iii) develop tools for quantifying geological resources, habitat distributions and system-indicators in land-water transition zones, developed in and for a GIS in order to optimize application by end-users. Here, we present the preliminary results of these two surveys which were carried out at two locations with different environmental settings. We demonstrate the potential of using airborne topobathymetric LiDAR for seamless mapping of land-water transition zones in challenging coastal environments, e.g. in an environment with high water column turbidity and continuously varying water levels due to tides as well as in an environment characterized by a very heterogeneous surface sediment composition.

1. INTRODUCTION

Coastal and tidal environments are valuable ecosystems, which are highly impacted by globalization, climate change, and human encroachment in many areas around the world. Detailed mapping of these environments is required in order to manage the coastal zone in an economically sustainable manner, but traditionally used methods are not sufficient to gain full coverage, comprehensive and high-resolution spatial data of these shallow water areas (e.g., Steinbacher et al., 2013; Dobler et al., 2013). This is particularly due to highly variable environmental conditions of the land-water transition zone impeding an efficient monitoring. Furthermore, the results often have a very low spatial resolution, are expensive and time consuming. In contrast, by using a new generation of laser scanning equipment (green

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wavelength 532nm) airborne topobathymetric laser scanning can provide measurements of the land surface and the river bed or seabed within a single measurement process (Fig. 1). The measurements have both a very high accuracy (\pm centimeters) and a very high resolution (about 20-30 points/m²) (Andersen et al., 2016). Contrary to previous methods, which are mostly cross-section/profile based or only consider subareas, the comprehensive spatial information gained by the new LiDAR technique signifies an enormous and game changing advancement in the recording of underwater information. Among other factors the penetration depth of the laser beam crucially depends on the turbidity of the water body. At ideal viewing conditions, the sea/river bed can be detected down to about 10-11 m depth.

Thus, we performed topobathymetric LiDAR surveys in the Knudedyb tidal inlet system, a coastal environment in the Danish Wadden Sea which is part of the Wadden Sea National Park and UNESCO World Heritage, and in the Rødsand lagoon, which is a NATURA2000 site located in close vicinity of the planned Fehmarnbelt fixed link (for locations Figs. 2-3). These two surveys were conducted in order to:

- derive characteristic properties of the morphology, surface sediment, the vegetation and the water column in land-water transition zones like rivers, lakes, wetlands, estuaries and coasts;
- improve the understanding of the dynamics of these properties in shallow water ecosystems, which are under pressure due to changing environmental conditions driven by climate change;
- develop tools for quantifying geological resources, habitat distributions and system-indicators in land-water transition zones, developed in and for a GIS in order to optimize application by end-users.

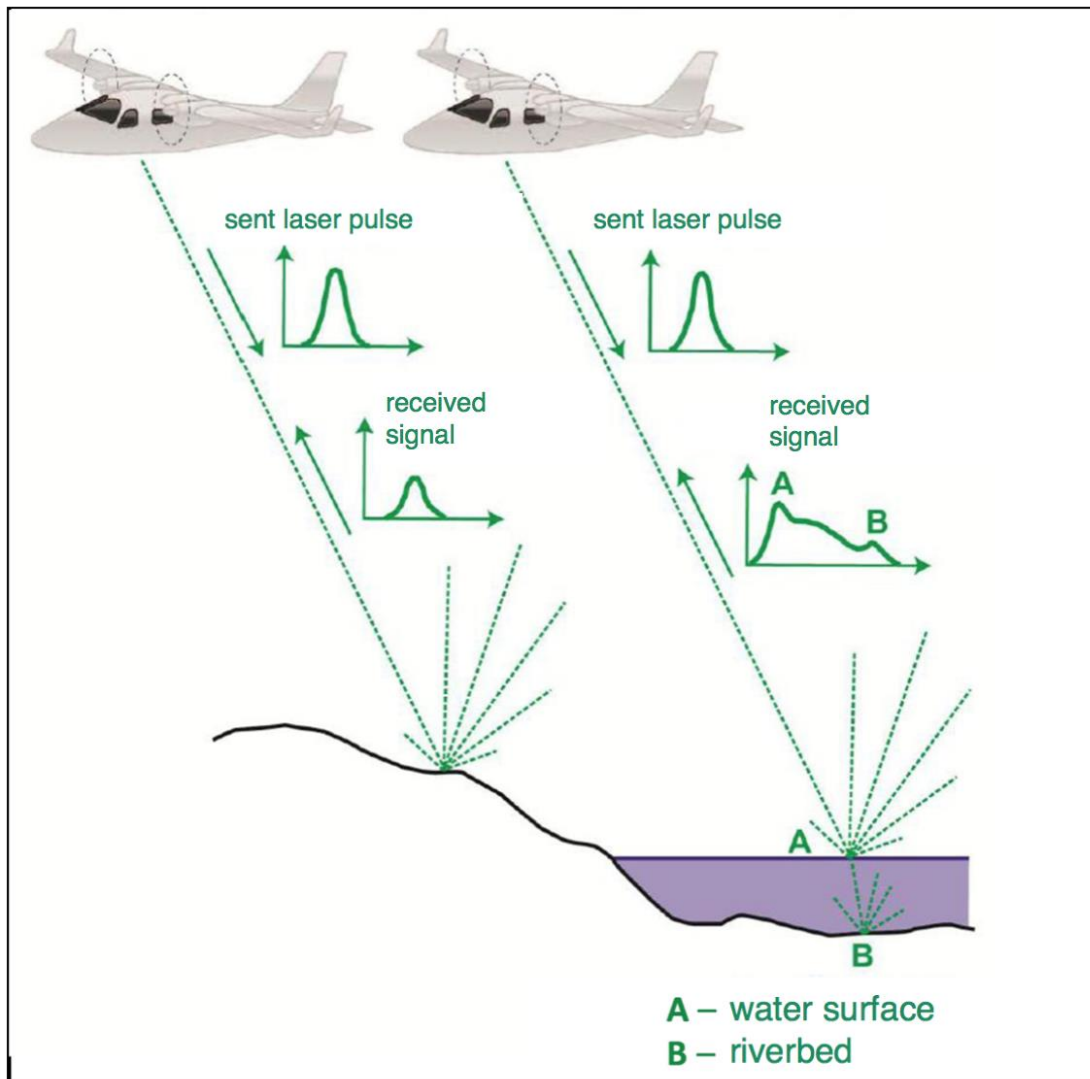


Figure 1: Survey principles of airborne laser scanning on topographic (left) and bathymetric (right) sites.

2. PROJECT SITES AND AIRBORNE SURVEY

The Knudedyb tidal inlet system is located at the west coast of Denmark in the Danish Wadden Sea, and is part of the Wadden Sea National Park and belongs to the UNESCO World Heritage (Fig. 2). The coastal area is strongly influenced by tides with a mean tidal range of 1.6 m (Pedersen and Bartholdy, 2006), and is characterized by a manifold environment in terms of biodiversity, geodiversity, and complexity of coastal processes (sediment transport and morphologic changes). The Knudedyb site was surveyed two times on 19th April 2014 and 30th May 2014 at low tide under clear weather conditions and offshore winds using the VQ820G sensor (RIEGL LMS; Fig. 2). About 118 scan strips were acquired during both surveys: 37 strips in the first run and 81 strips in the second. The strips were adjusted with respect to each other to derive an internally consistent point cloud (internal accuracy of 6-10 cm given as standard deviation). Subsequently, the point cloud was

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georeferenced to terrestrially measured reference planes (accuracy of 4-9 cm given as standard deviation).

The Rødsand lagoon is located at the south coast of Lolland and is connected to the Fehmarnbelt; it is a NATURA2000 site located in close vicinity of the planned Fehmarnbelt fixed link (Fig. 3). The lagoon is approximately 30 x 8.5 km wide. In the offshore area near the lagoon two offshore wind parks are established (Rødsand 1 & 2; www.4coffshore.com/offshorewind, accessed on 7th July 2016). The lagoon is bordered by a broad sand barrier at its southern edge extending from Gedser in the east towards the west, intersected by three inlets. This sand barrier plus several N-S traverses across the Rødsand lagoon were surveyed on 7th September 2015 at clear and relatively calm water conditions as well as clear weather using the VQ880G sensor (RIEGL LMS; Figs. 3-4). In total, 35 scan strips were acquired yielding 70 single strips due to simultaneous forward and backward recording of the VQ880G. The strips were adjusted to each other to gain an internally consistent point cloud similar to the Knudedyb tidal inlet data (internal accuracy of ca. 5cm given as standard deviation).

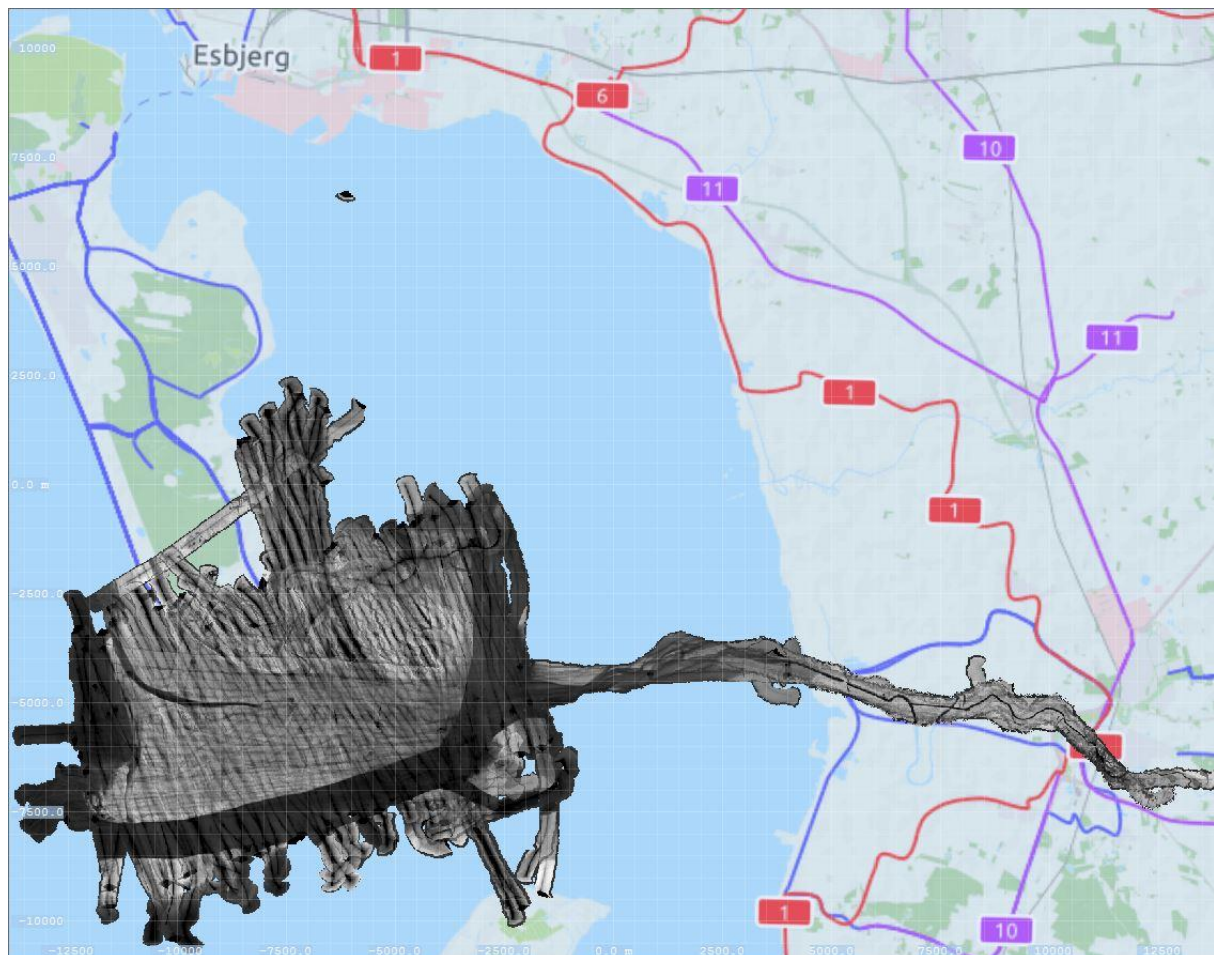


Figure 2: Topobathymetric data for the project site at the Knudedyb tidal inlet system in the Danish Wadden Sea south of Esbjerg, covering a 5 x 10 km area of the central part of the inlet as well as a tidal channel stretching north in the back-barrier environment and the most western part of the river Ribe Å which drain into the Knudedyb tidal basin.

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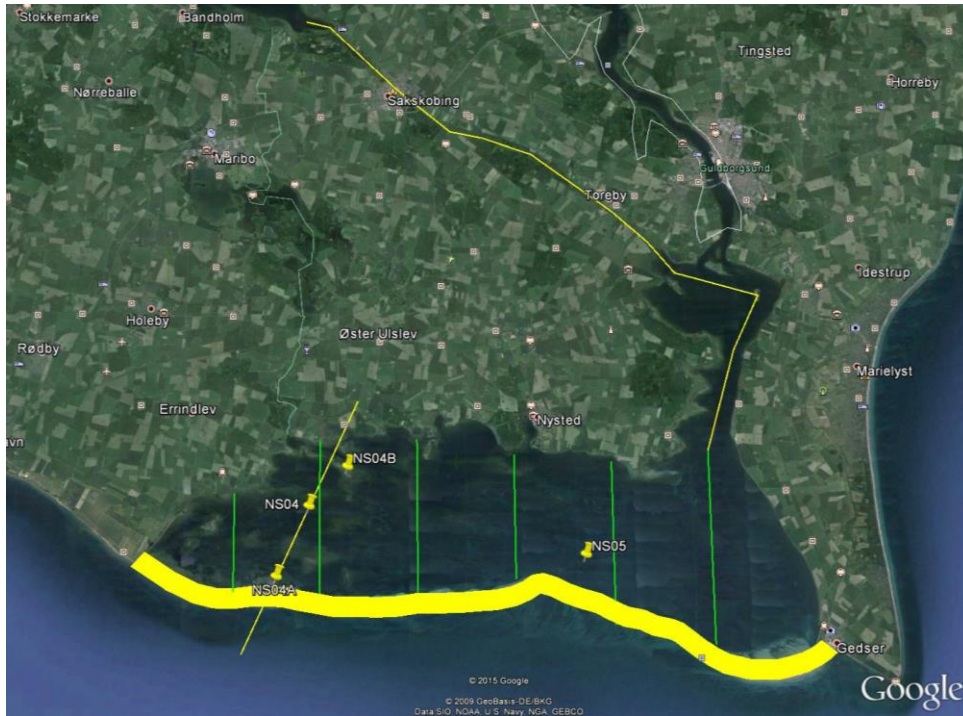


Figure 3: Location map of the project site of Rødsand lagoon in the northern Fehmarnbelt at the south coast of Lolland (taken from GoogleEarth).

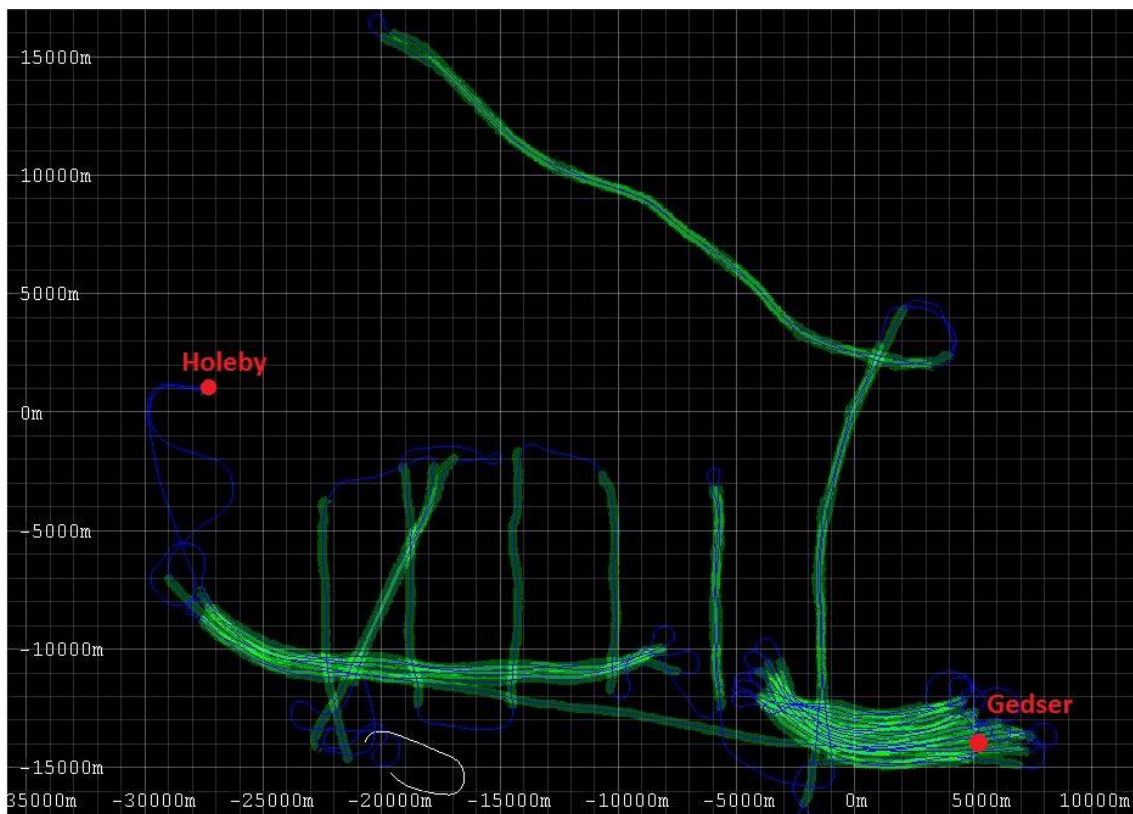


Figure 4: Topobathymetric data coverage for the project site at Rødsand lagoon.

3. POINT CLOUD PROCESSING USING HydroVISH

3.1. Noise filtering

The further point cloud processing of the topobathymetric LIDAR data was done using the HydroVISH software package developed by AHM. Prior to point cloud classification, flaw echos (noise) need to be removed from the raw point cloud (Fig. 5). These echos were recorded because the sensor setting was extremely sensitive in order to capture as many echoes from the water surface as well as achieving a best possible penetration. For each point of the point cloud, the point density within a 0.75 m radius was evaluated and a point was identified as flaw echo, if the number of point neighbours was less than five within the given radius. The cleaned point cloud was subsequently classified.

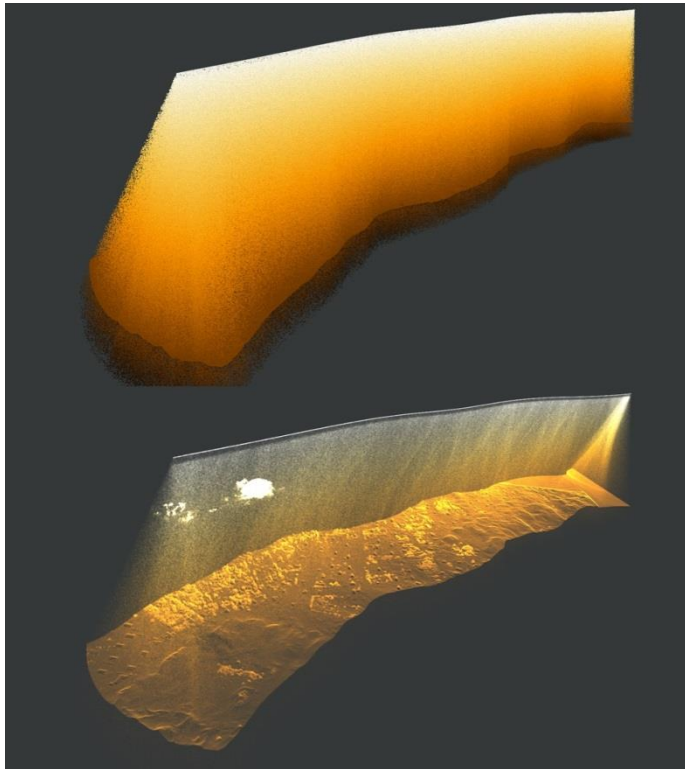


Figure 5: Flaw echos for a scan strip from the Knudedyb tidal inlet system.

3.2. Point cloud classification

First of all, the point cloud was mapped onto a 0.5 x 0.5 m grid using the deepest point per grid cell to classify *terrain* (terrain on land and water ground), and the highest point per grid cell to classify the *rest* (water body, buildings, vegetation). The differentiation among the two follows a height- and slope criterion. By intersecting the two grid data sets, the water land boundary was approximated. After manual correction of the raster classification, all *rest* raster points located within the water-land boundary are classified as water body including water surface, and all *terrain* raster points located within the water-land boundary are classified as

water ground. The results of the raster classification are then transferred to the point cloud and controlled manually.

3.3. Water surface model and refraction

The laser beam is reflected and refracted at the boundary between air and water. The fact that light is about 25% slower in water than in air ($c_{\text{air}} = 299710 \text{ km/s}$, $c_{\text{water}} = 225,000 \text{ km/s}$) requires the application of a refraction- and runtime correction for all measurement points located below the water surface. Therefore, the water surface needs to be modelled based on all classified water-surface points. Those spread over a 20-30 cm thick band around the true water table and only the uppermost points (99% quantile) were considered as valid points to model the actual water surface (Mandlbürger et al. 2013). The water-surface model was defined by element sizes of 1.5 m to 5 m, where the center of each grid cell had the elevation $z = q_{0.99}$. The raster points were triangulated for the final water-surface model, which was then extrapolated towards the water-land boundary.

For applying the refraction correction three data sets are required: the point cloud with time stamp for each measurement point, the trajectory with time stamp for each point of the trajectory and the triangulated water-surface model. First of all, a pair of points with the same time stamp (P from the trajectory, and Q from the point cloud) and the vector between these two points was evaluated to determine the point, where the beam P-Q intersects the water surface S (Fig. 6). Therefore, the beam's entering angle can be determined in order to correct the beam with respect to the refraction angle. Moreover, the beam's length S-Q below water can be calculated in order to apply the runtime correction with respect to the refraction index. Using a refraction index of 1.33 for water and 1.000292 for air, the runtime correction was derived by:

*Beam length under water unrefracted \times (1/refraction index water) =
Beam length under water refracted.*

The angle correction was calculated according the Snell's refraction law:

*Refraction index air \times sin (angle between beam in air & water surface) =
Refraction index water \times sin (angle between water surface & beam in water).*

The difference prior and after application of the refraction and runtime correction is shown in Figure 7 for an exemplary cross-section. Corrected water-ground points (in blue) are located above their original position (in red). Terrain points above the water surface are not affected by this correction.

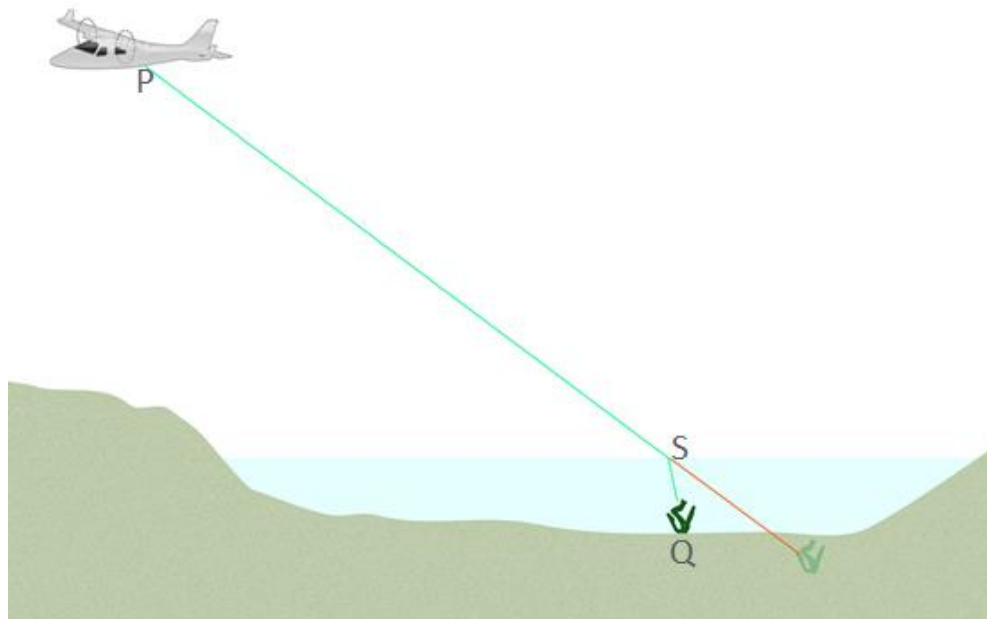


Figure 6: Schematic illustration for refraction calculation (explanations given in the text).

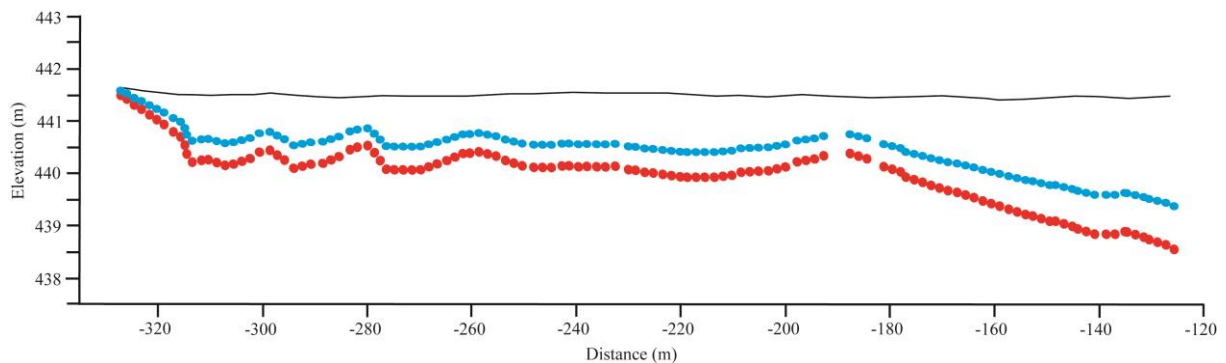


Figure 7: Simplified cross-section to illustrate location of points prior (red) and after (blue) applying the refraction. Water table is marked in black.

3.4. Digital terrain modelling

Finally, in order to generate high resolution digital terrain models (DTMs) for both project sites the classified terrain points were mapped onto a 0.5 x 0.5 m grid using the mean elevation of all terrain points per grid cell (compare with Fig. 8). The DTMs serve as base for detailed mapping purposes as well as morphologic analysis and comparison with terrestrially measured data.

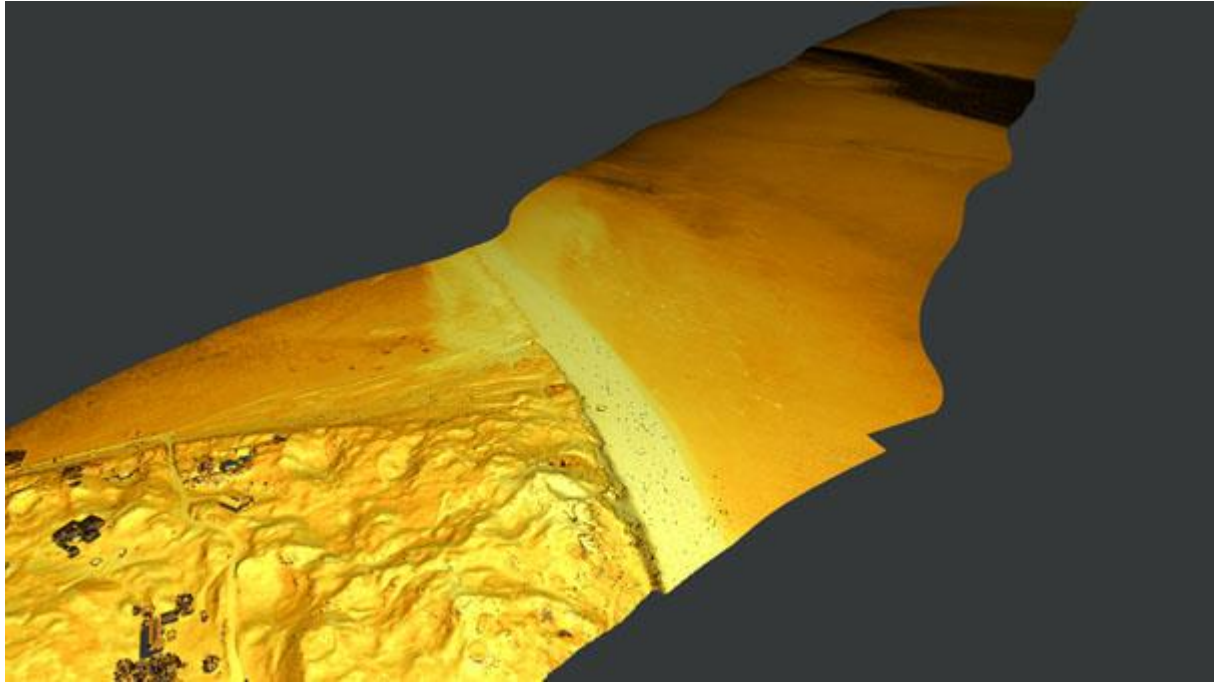


Figure 8: DTM section from the Knudedyb tidal inlet system showing the complex and manifold morphologic patterns.

4. PRELIMINARY RESULTS AND DISCUSSION

Based on object detection Andersen et al. (2016) have demonstrated that the vertical accuracy and precision of the LiDAR data on land was ± 8 cm with a 95% confidence level; while the vertical precision below the water surface was ± 4 cm. Andersen et al. (2016) determined the horizontal mean error to ± 10 cm. Hence, the overall vertical and horizontal precision is within sub-decimetre scale. The same objects, a cement block (250 x 125 x 80 cm) located on land as well as a steel frame (92 x 92 x 30) positioned in a shallow water area (Fig. 9), were also used to assess the feature-scale detection. The two objects, which were clearly visible in the point cloud, were modelled based on different approaches (triangulation vs. grid) and subsequently detailed morphological analysis (slope etc.; Fig. 10) were conducted. The results indicate that such sharp-edged, sharp-cornered, and steep-angled features are smoothed, e.g. underestimation of slope angles (Fig. 10). This smoothing is mostly due to the footprint size of the topobathymetric LiDAR system (about 40 cm). Nevertheless, decimetre-scale features are well detected by airborne LiDAR topobathymetry. Hence, the preliminary results demonstrate that airborne topobathymetric LiDAR is a valuable tool to bridge land and water environments as well as to bridge morphological scales, thereby closing the gaps between terrestrial and marine surveys and between the mapping of individual morphological features and complete landscapes.

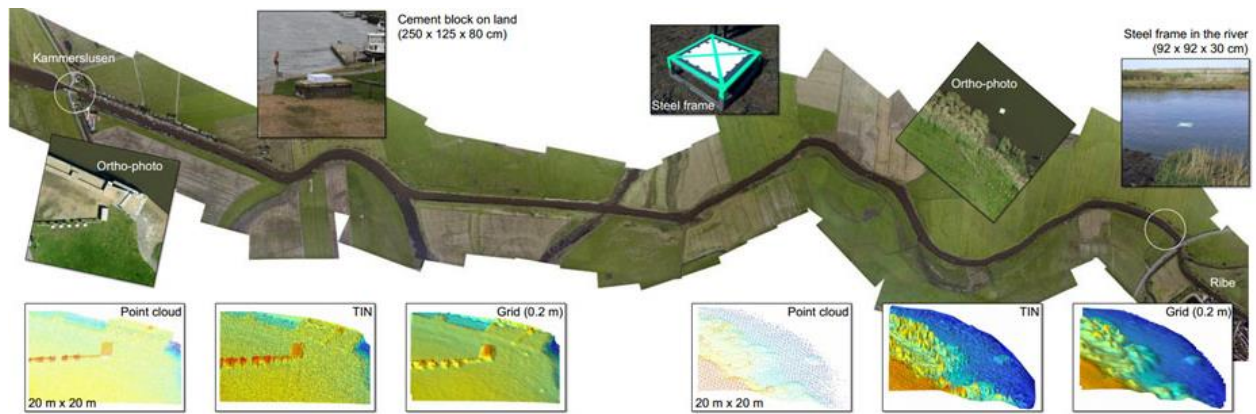


Figure 9: Small-scale objects at Knudedyb project site. Both objects are visible in the point cloud and are modelled based on triangulation and rasterization.

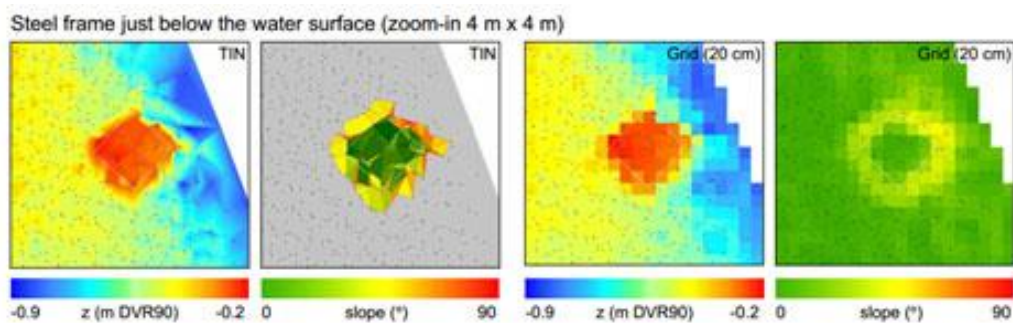


Figure 10: Elevation and slope distribution of the steel frame given for both the triangulated and gridded model.

5. CONCLUSIONS

The results of our study underpin that topobathymetric surveying is a highly efficient and valuable tool for monitoring complex coastal areas. In tidal influenced areas with extremely variable water surface conditions, the seabed can be well detected at low tide down to depths of about 3-4 m (Knudedyb site), whereas in calm and clear water conditions within the Rødsand lagoon the seabed was detected down to depths of 6-7 m. Moreover, small scale under water features (dm- to m-scale) can be readily identified in the data allowing detailed and area-based analysis of sediment transport and morphologic changes and to evaluate specific habitat characteristics and distribution.

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