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Storm Surge Barrier Kalveboderne – Feasibility Study

Bathymetric and topographic survey



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Storm Surge Barrier Kalveboderne – Feasibility Study

Bathymetric and topographic survey report report

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Appendix 1
Bathymetric and topographic overview chart

Appendix 2
Orthophoto overview chart

1. Introduction

In 2025, a preliminary study for storm surge protection around Copenhagen (*Forundersøgelse af stormflodssikring omkring København*) was conducted, ref. [1]. In connection with this, a need was identified to establish a storm surge barrier at Kalveboderne south of Copenhagen to protect against flooding from eastern and southern directions. The preliminary study did not conduct detailed investigations into possible structural solutions for the storm surge gate and associated side facilities (collectively referred to as the storm surge barrier) or examine possible environmental impacts, as the framework for the preliminary study was an initial investigation into protecting Copenhagen against storm surge.

To explore possible technical solutions and their potential impacts on the environment, Sund & Bælt has initiated the preparation of a more detailed preliminary study of the storm surge barrier at Kalveboderne. This is being further investigated by Rambøll+Jacobs in the present project "Storm Surge Barrier Kalveboderne – Feasibility Study."

The overall purpose of the preliminary study is to develop one or more feasible concept designs that will form the basis for subsequent design and environmental impact assessment of the storm surge barrier at Kalveboderne. As part of the feasibility study, the following is expected assessed in more detail (the list is not exhaustive):

1. Identification of the dimensional factors, both structural and environmental, significant for the selection and design of the storm surge barrier, with the aim of pointing to relevant gate solutions and solutions for the overall storm surge barrier.

2. Collection of data and basic information, including additional investigations, to provide a detailed basis that will also form the foundation for the further development of the project.

3. Hydraulic modelling of waves, current conditions, etc., for current and future climate-affected conditions.

4. Assessment of the reservoir capacity of Kalveboderne and Copenhagen Harbor and derivation of a closure protocol for the gate.

5. Preparation of construction estimates (CAPEX) and operation and maintenance costs (OPEX) as well as investigation of sustainability potentials and conducting LCA calculations.

6. Description of rejected solutions at a level such that they can be included as documentation in a later environmental impact assessment and in a possible deviation case under the Habitat and/or Water Framework Directive.

The concept designs developed in the feasibility study are described to a level of detail and with clarity of reasoning that ensures that the project owners understand and can communicate about the project to relevant stakeholders and the broader public.

The overall project area included in the feasibility study can be seen in Figure 1-1.



Figure 1-1: Overview map of the project area with location specifications.

1.1 Introduction of the present report

As part of the feasibility study a campaign was initiated to support hydraulic modelling. The campaign consisted of vessel-based multibeam, and aircraft based green laser (LiDAR). The aim of the investigations was to achieve high-resolution bathymetric and topographic data within the provided area of investigation shown in Figure 1-2.

This report describes the survey activities consisting of vessel-based multibeam and aircraft based green laser. The aim of the survey was to acquire full coverage and high-resolution bathymetric and topographic data within the provided area of investigation.

The survey vessel-based multibeam was acquired by Ramboll Surveyor owned and operated by Ramboll, and the Cessna T303 aircraft operated by ALM (Airbourne LiDAR Mapping A/S) which was subcontracted by Ramboll. Ramboll have prepared the data which will be used later as part of the hydraulic modelling also performed by Ramboll in the feasibility study.

Furthermore, this report will go through the bathymetric and topographic results and describe the data deliverables.

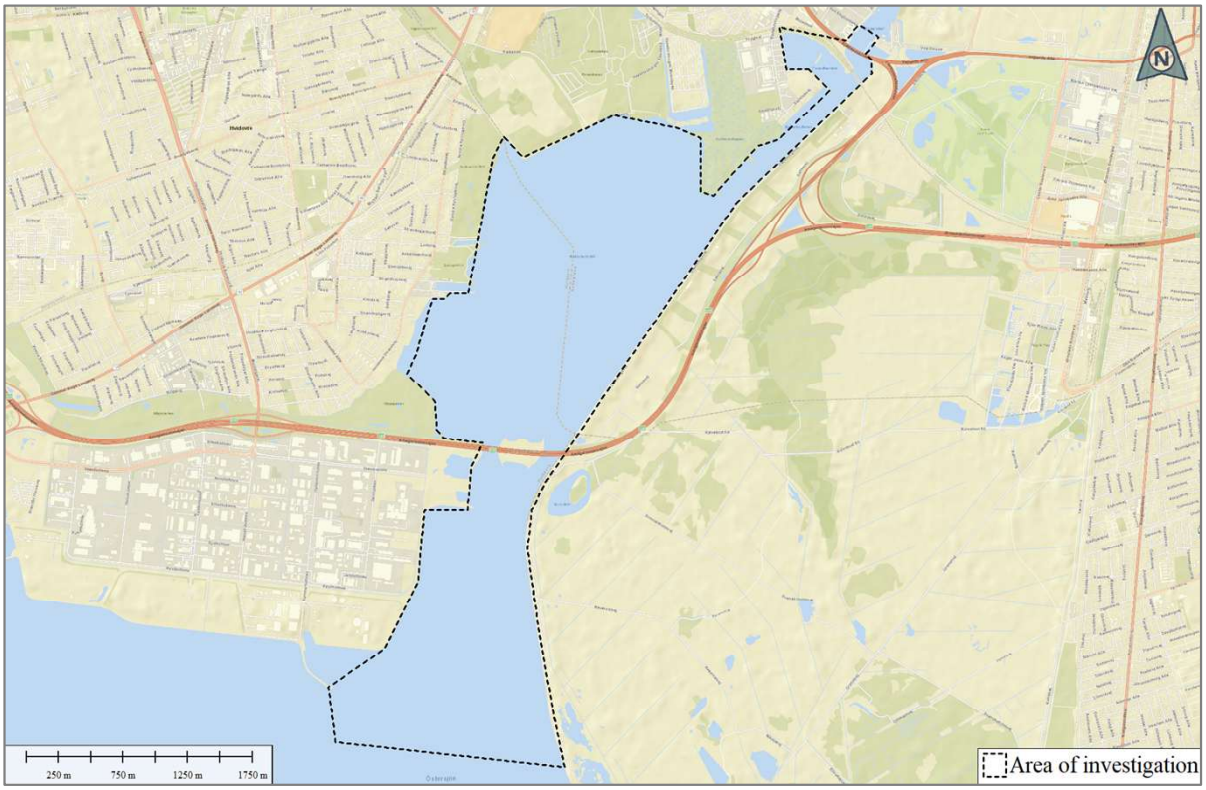


Figure 1-2: Overview of the area of investigation for the bathymetric and topographic survey.

1.2 Definitions

A list of abbreviations can be found in Table 1-1.

Table 1-1: List of abbreviations and definitions.

Abbreviation	Explanation
ALM	Airbourne LiDAR Mapping A/S
Approx.	Approximately
DGNSS	Differential Global Navigation Satellite System
DKTM3	Dansk Transverse Mercator 3
DTM	Digital Terrain Model
DVR90	Dansk Vertikal Reference 1990
EPSG	European Petroleum Survey Group
ETRS89	European Terrestrial Reference System 1989
GCP	Ground Control Point
GPS	Global Positioning System
GSD	Ground Sampling Distance
h	Hour
IHO	International Hydrographic Organization
IMCA	International Marine Contractors Association
IMU	Inertial measurement unit
INS	Inertial Navigation System
kHz	Kilo Hertz
km	Kilometre
km2	Square kilometres
LiDAR	Light Detection and Ranging
m	meter
m3	Cubic meter
MBES	Multibeam Echosounder
mm	milimeter
mrad	milliradian
NA	Not applicable
nm	nanometer
POB	Persons onboard
RTK	Real-Time Kinematic
SBET	Smoothed Best Estimate of Trajectory
SVP	Sound Velocity Profile
tan	Tangens
TPE	Total Propagated Error
UTM	Universal Transverse Mercator

2. Dansk Resume

Som led i forundersøgelsen af stormflodssikringen omkring København i 2025 blev der identificeret et behov for at etablere en stormflodsbarriere ved Kalveboderne syd for København for at beskytte mod oversvømmelser fra østlige og sydlige retninger.

For at undersøge mulige tekniske løsninger og deres potentielle miljøpåvirkninger har Sund & Bælt igangsat udarbejdelsen af en mere detaljeret forundersøgelse af stormflodsbarrieren ved Kalveboderne.

Som en del af denne undersøgelse blev der igangsat en bathymetrisk og topografisk opmålingskampagne for at understøtte projekteringsfasen og den hydrauliske modellering. Formålet med denne kampagne var at indsamle højopløselige bathymetriske og topografiske data inden for et veldefineret undersøgelsesområde.

Til dataindsamlingen benyttede Ramboll sit eget fartøj, Ramboll Surveyor, samt ALM, som var underleverandør til at udføre de luftbårne LiDAR-målinger med grøn laserscanner. Først blev de luftbårne LiDAR-data indsamlet for hele området, hvorefter dataene blev vurderet for at identificere huller og om dataene var af tilstrækkelig kvalitet. Da disse områder var identificeret, blev skibsbaserede multibeam-undersøgelser planlagt. Den luftbårne LiDAR-opmåling tog 1 dag, mens den skibsbaserede multibeam-opmåling tog ca. 2 dage.

Området er i høj grad påvirket af store mængder søgræs, som kan og vil påvirke opmåling af havbundens faktiske position, eftersom søgræs forstyrrer både multibeam- og LiDAR-data til en vis grad. Der blev foretaget flere justeringer af opmålingsindstillingerne under dataindsamlingen, og forskellige processer blev anvendt på dataene under efterbehandlingen for at tage højde for søgræs. Store mængder søgræs blev fjernet fra dataene for at opnå den mest pålidelige bestemmelse af havbundens position. Det skal dog bemærkes, at det ikke var muligt at fjerne al søgræs fra dataene på grund af den omfattende og tætte vækst. Der blev dog gjort alt for at reducere dens tilstedeværelse uden at skabe huller i dataene.

De indsamlede data er af god kvalitet med en relativt høj punkttæthed pr. kvadratmeter, hvilket gør det muligt at producere grids med 1 m opløsning. Undersøgelsesområdet har en samlet størrelse på 6.979 km^2, hvor den bathymetriske og topografiske opmåling udgør 6.690 km^2, hvilket svarer til ca. 96 % af undersøgelsesområdet, som dermed er dækket.

De bathymetriske data viser vanddybder fra 0 m til -8.7 m i forhold til DVR90.

Nord for Kalvebodbroen ligger vanddybderne generelt mellem -0.5 m og -2.0 m. De største vanddybder nord for Kalvebodbroen mod Amagerbroen ses i den største østlige rende, hvor vanddybden i gennemsnit er -4.2 m, samt i de vest-øst-orienterede render, hvor vanddybden i gennemsnit er ca. -4.0 m.

Syd for Kalvebodbroen øges vanddybden svagt mod syd fra ca. -2.0 m til -5.7 m. De største vanddybder observeres i sejlrenden til Avedøreværket, hvor vanddybden når ca. -8.7 m.

Ud over de bathymetriske og topografiske data blev der også leveret et højopløseligt ortofoto med en cellestørrelse på 5 cm. Ortofotoet blev optaget af flyet, Cessna T303, sammen med LiDAR-dataene og dækker hele området.

3. Survey setup

This section describes the survey vessel, platform for LiDAR operations, equipment and executed activities.

3.1 Survey platforms

Survey platform specifications are shown in Table 3-1.

Ramboll Surveyor was used for the bathymetric survey. *Ramboll Surveyor* is a purpose built nearshore and landfall survey platform designed in close cooperation between Ramboll and Alucat. The vessel is IMCA certified and carries a CE/C category work boat approval.

Besides the geophysical equipment the vessel is installed with an Oxe marine 300HP Diesel engine, this engine uses 30-40% less fuel than a similar gasoline engine. The Oxe marine uses biodiesel, WHO100, which reduces the CO2 footprint by 92% compared to gasoline. The cabin is installed with a Helmsman monitor for survey navigation, 4 survey monitors, an autopilot system for precise survey line keeping, garmin echo-sounder with dual-transmitter (one vertical-looking and one looking ahead for obstacle detection in shallow environments). The vessel is also equipped with a crane, winch and a bow ramp.

The Cessna T303 is a twin-engine light aircraft, which is 9.27 m in length and 11.9 m span-width. The aircraft performed the green-laser and orthophoto survey. The survey speed was approx. 230 km/h in an altitude of approx. 300 m. It includes a front hatch to make loading easier, and to take full advantage of the passenger area for cargo or equipment such as LiDAR, scanners, or camera.

Table 3-1: Overview of equipment platforms, Ramboll Surveyor and Cessna T303.

	Ramboll Surveyor	**Cessna T303 Crusader**
		
Length	8.20 m	9.27 m
Width	2.45 m	11.9 m (span-width)
Draft	0.45 m	NA
POB	2	2
Duration	12h (max)	12h (max)
Equipment	MBES	LiDAR (Green)

3.2 Equipment

To map the bathymetry on the site the survey vessel was equipped with an multibeam echosounder and the aircraft was mobilised with a green laser scanner (LiDAR). To get the best possible data other sensors was installed on both platforms which includes equipment such as motion sensors to account for movement and attitude of the survey platform and GNSS receivers for accurate surface positioning. The equipment list can be found in Table 3-2.

Table 3-2: List of equipment installed on the vessel and aircraft.

Item	Description	Type / Model	Survey Platform
1	Surface Positioning	Trimble SPS855 receiver with RTK-correction	Vessel
2	MBES	Norbit iWBMSh with built-in Applanix OceanMaster INS.	Vessel
3	IMU	Applanix OceanMaster INS	Vessel
4	SVP	AML Minos	Vessel
5	Surface Positioning	Applanix POSAV 150	Airplane
6	IMU	Applanix PosPac AV510	Airplane
7	LiDAR	Riegl VQ840g	Airplane
8	Camera	Hasselblad A6c 100	Airplane

The following two subsections describe the main sensors used to achieve the detailed bathymetric- and topographic data.

3.2.1 Multibeam Echosounder (MBES)

The bathymetric data were acquired using a Norbit iWBMSh mounted on a pole on the port side of the vessel. The MBES system was operating with 1024 beams and with a swath between 90-120° depending on water depth. The operating frequency was 200-400 kHz. This system offers state of the art vertical and spatial resolution in the water depth encountered in the working area. Table below shows the main parameters for the Norbit MBES sensor.

Table 3-3: MBES – Norbit iWBMSh specifications.

Specifications	Operating range
Frequencies	200 kHz to 700 kHz (400 kHz Nominal)
Sampling rate	Up to 60 Hz
Swath Coverage	5-210° (shallow water IHO Special Order >155°)
Number of beams	256-1024
Heading Accuracy	0.02° (RTK)
Pitch/Roll Accuracy	0.01°
Heave Accuracy	2cm (trueheave)
Beam distribution	Equi-distant mode

Sound velocity profiles (SVP casts) were taken every six hours during the multibeam survey to correct the sonar beams and improve depth accuracy and seabed positioning. The system also includes a sound velocity sensor (SVS) that is installed on the multibeam head which continuously monitor the variations near the multibeam sensor.

Data coverage and grid cell sounding hit count was monitored online during the survey. The multibeam data were recorded using NaviPac acquisition software, which displayed the recorded DTM online for efficient quality control.

3.2.2 Green laser (LiDAR)

The LiDAR survey was acquired using the Riegl VQ840g green laser scanner (532 nm) combined with a Hasselblad A6c 100 camera mounted on the Cessna airplane. The *RIEGL* VQ-840-G is a fully integrated compact airborne laser scanner for combined bathymetric and topographic surveying with a pulse repetition of 50-200 kHz and a laser beam divergence of up to 6 mrad. The system is offered with an optionally integrated and factory-calibrated IMU/GNSS system with a sampling rate up to 200 kHz.

The scanner carries out laser range measurements for high resolution surveying of underwater topography with a narrow, visible green laser beam, emitted from a pulsed laser source.

Table 3-4: Green laser – Riegl VQ840g specifications.

Specifications	Operating range
Laser Pulse Repetition Rate	50 to 200 kHz
Laser Wavelength	532 nm (green)
Laser Beam Divergence	1 to 6 mrad (selectable)
Precision [1)]	15 m

[1)] *Precision, also called reproducibility or repeatability, is the degree to which further measurements show the same result*

3.2.3 Software

Table 3-5 shows the various software packages used for acquisition, processing and data preparation.

Table 3-5: Used software for data acquisition, post-processing and preparation.

Sensor	Software
Survey Software	
Navigation/MBES	NaviPac & NaviScan
LiDAR	Applanix MMS
Processing Software	
MBES	NaviEdit, NaviModel, PosPac
LiDAR	Riegl RiPorcess
Data Preparation Software	
GlobalMapper ArcGIS	

3.3 Projektion information

The coordinate reference system used is shown in Table 3-6 and Table 3-7.

Table 3-6: Coordinate reference system.

Ellipsoid	
Horizontal datum	DKTM3 / ETRS89
Spheroid	GRS1980
Semi-major axis	6378137.00
Semi-minor axis	6356752.31
Flattening factor of the earth	1/f = 298.257222101
Projection parameters	
Projection	Universal Transverse Mercator
UTM zone	UTM 33N
Latitude origin	0°
Longitude origin	10°
Scale factor	0.99998
False northing	-5.000.000 m
False easting	400.000 m
EPSG	4094

Table 3-7: Vertical datum.

Vertical datums	
Vertical datum	DVR90

3.4 Survey summary

First, the LiDAR survey was acquired in the entire area to identify areas where gaps or less confident data was observed. Second, all gaps and unreliable data was identified, hereafter, a planning of vessel-based multibeam was prepared and then performed to ensure full data coverage within the area of investigation.

Table 3-8: Dates and duration of the aircraft survey and vessel-based survey.

Task	**Start date**	**End date**	**Duration [days]**
LiDAR Acquisition	17-05-2026	17-05-2026	1
Multibeam Acquisition	17-06-2026	18-06-2026	2

3.5 Survey split

The survey was split between LiDAR from aircraft and vessel-based multibeam. The LiDAR was acquired on the entire site while the multibeam was planned based on the LiDAR coverage and quality. Figure 3-1 shows the MBES area polygons inside the area of investigation, while areas outside the MBES polygons are all covered by LiDAR data with acceptable coverage and quality.

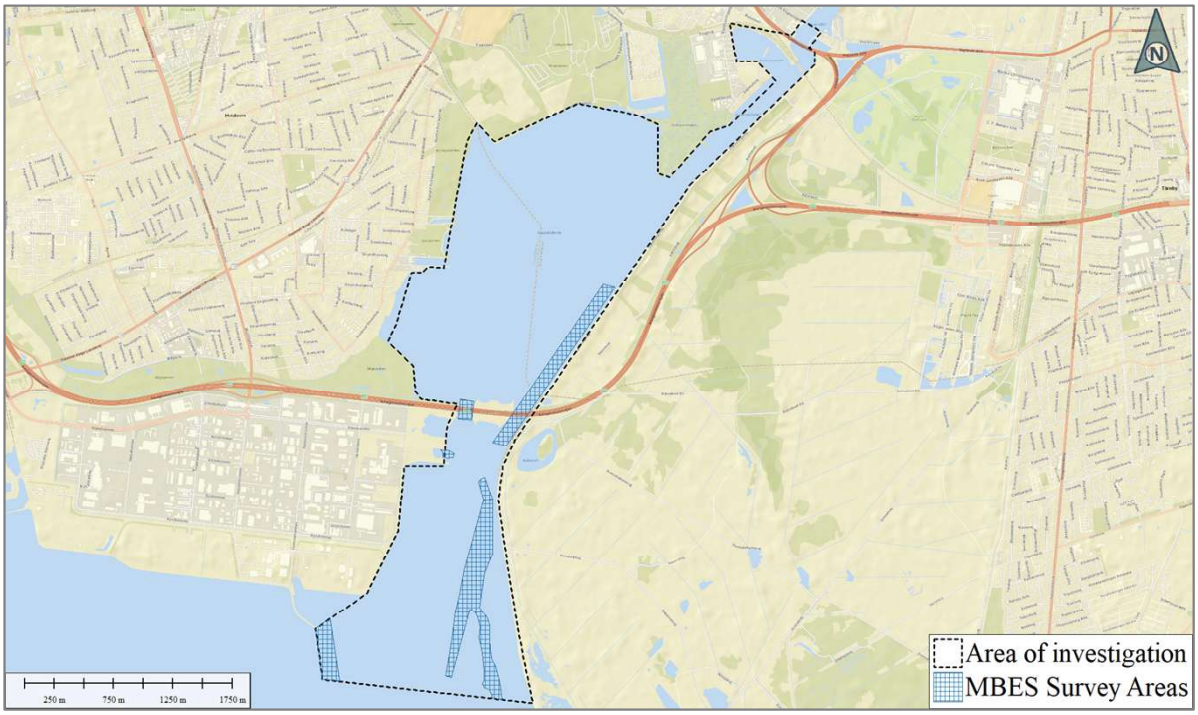


Figure 3-1: Shows the multibeam polygons where vessel-based multibeam was acquired while the rest of the site was acquired by LiDAR.

3.6 Data uncertainties

The following sub-sections describe the data uncertainties and accuracy of the vessel-based multibeam and the aircraft-based LiDAR data.

3.6.1 Multibeam echosounder uncertainties

The accuracy depends on the combined uncertainties of all elements in the process. E.g. the accuracy of the bathymetry is affected by the combined uncertainties of the following processes:

I. height of reference position of vessel by GNSS
II. roll and pitch of vessel by motion sensor
III. vector from reference point to multibeam transponder
IV. mounting angles of multibeam transponder
V. timing accuracy in the combination of position, angles and data stream from transponder

Uncertainties can be estimated a-priori by calculating Total Propagated Error, TPE. The contributions from the separate processes are combined based on an assumption of uncorrelated and normal distributed errors. A-posterior estimates are derived for the DGNSS positioning and the bathymetry.

Besides the instrumental uncertainty results are affected by the natural variability of the seabed; few surfaces in nature are smooth. The representation of this natural variability must be added to the instrumental uncertainty. In the following all references to error, uncertainty or accuracy are by the value of two times the standard deviation. Error contributions from various sensors and processes are shown in Table 3-9.

Table 3-9: Error contributions from separate sensors and processes for MBES.

System	Vertical error	Horizontal error	Source
GPS Positioning	0.02 m	0.02 m	Estimate
Gyro heading		0.02° → r[1)] × *tan*(0.02°)	Specifications
Motion sensor	0.01°→ r × *tan*(0.01°)	0.01°→ r × *tan*(0.01°)	Specifications
Echosounder transducer	0.01 m		Estimate
Pole movement	0.02 m	0.03 m	Estimate

By combination of the above separate error contributions the total propagated error, TPE, can be estimated for the resulting data products: The bathymetry, the sonar-gram etc. Calculated Total Propagated Error is presented in Table 3-10. The calculation assumes each error source independent and normally distributed. Thus, the variance of the sum of the error distributions equals the sum of the variances: $\sigma_{\sum i^2} = \sum \sigma_i^2$.

Table 3-10: Calculated TPE for the bathymetry.

Data type	Vertical TPE [m]	Horizontal TPE [m]
Bathymetry	0.06	0.08

In addition to the theoretical calculation of the obtainable accuracy, it is important to observe the fact that any acoustic ranging to the seabed has a certain acoustic 'footprint' on the seabed and the result of the measurement depends in a complicated way of the average within this footprint. For this reason, there is a lower limit to the accuracy of acoustic ranging. This is estimated to be comparable to the short-scale roughness of the seabed. Also, some areas were heavily affected by seaweed which in some cases couldn't be filtered without creating gaps in the data in these areas the vertical TPE will increase as the seabed is an average of the actual seabed and the top of the seaweed which are not filtered out.

3.6.2 LiDAR uncertainties

For airborne green-laser bathymetry in 0–3 m depth, the final vertical and horizontal uncertainty is not controlled by one single sensor specification, but by the combined effect of trajectory quality (GNSS/IMU), sensor calibration, aircraft dynamics, and especially water-surface/refraction and bottom-detection conditions.

In this depth interval, the final point accuracy is controlled not only by the geometric quality of the airborne laser scanning system, but also by the physical interaction of the green laser with the water surface and water column. The uncertainty assessment therefore considers sensor performance, aircraft dynamics, environmental conditions, and data-processing assumptions.

To verify the equipment performance four onshore ground control points (GCP) was measured using a GNSS-receiver with RTK-corrections. The XY (horizontal) and Z (vertical) position from the GCP's was compared with the acquired LiDAR data to verify the onshore positioning accuracy of the equipment installed on the aircraft. The comparison shows an accuracy of:

- Horizontal: 0.04 m
- Vertical: 0.02 m

Table 3-11: Error contributions from separate sensors and processes for LiDAR.

System	Vertical error	Horizontal error	Source
Combined equipment performance	0.02 m	0.04 m	Estimate
Precision	0.015 m	0.015 m	Specification
Environmental conditions	0.03 m	0.03 m	Estimate

Environmental conditions in above table includes factors such as; water surface, water column, bottom type, detectability, light and weather. The survey was planned under most favourable weather conditions and with calm sea with limited waves and sediment suspension. Also, the skies and light were optimal for LiDAR survey. Therefore, these factors are considered to have minor impact on the accuracy of the data.

By combination of the above separate error contributions the total propagated error, TPE, can be estimated for the resulting data products. The calculation assumes each error source independent and normally distributed. Thus, the variance of the sum of the error distributions equals the sum of the variances: $\sigma_{\sum i^2} = \sum \sigma_i^2$.

Table 3-12: Calculated TPE for the LiDAR.

Data type	Vertical TPE [m]	Horizontal TPE [m]
Bathymetry	0.04	0.05

4. Description of data processing

The following sub-sections describe the various post-processing steps for multibeam- and LiDAR data. These sections also describe different considerations that were made regarding the seaweed and how to accommodate for the areas strongly affected by large volumes of dense seaweed. It should be noted that it was not possible to remove all seaweed from the data due to the extensive and dense growth. However, every effort was made to reduce its presence without creating gaps in the data.

4.1 Multibeam processing

PosPac was used to process the data from the Applanix POS MV GNSS. This provides highly accurate position and orientation. Here the PP-RTX method is used which is a multi-frequency GNSS positioning technology that combines the high accuracy of reference stations based differential GNSS with the highly productive wide-area coverage of global satellite corrections. Once the navigation was processed the data were exported as SBET files relative to DKTM3/ETRS89 datum. SBET contains all corrections for altitude, motion and navigation ready to be applied to the bathymetry data.

The multibeam bathymetric data were recorded using the software, NaviPac, and were collected over several parallel run-lines. The multibeam echosounder data acquired was in general of high quality with very low noise. Processing of the raw multibeam echosounder data were performed using the software NaviEdit and NaviModel. The processing steps in NaviEdit comprise the application of sound velocity profiles and tidal data to reduce data to DVR90. Sound velocity profiles were measured regularly during the survey, and a linear temporal interpolation was made between each sound velocity profile. The data underwent a preliminary cleaning to remove significant outliers and then a filter was applied to remove erroneous points.

Finally, data were merged in NaviModel and from here the point cloud soundings in XYZ format and the binned data with 1.0 m grid cell size in XYZ format were exported. The exported XYZ files were loaded into GlobalMapper where GeoTiffs were generated with sufficient shading to highlight contacts and seabed variations.

The following software packages from EIVA were utilized to process the bathymetric datasets:

- NaviEdit – Project file manager and editing of overall survey parameters.
- NaviModel – 3D modelling for visualization and data deliverable generation.

Figure 4-1 shows the processing sequences for the acquired bathymetric data.

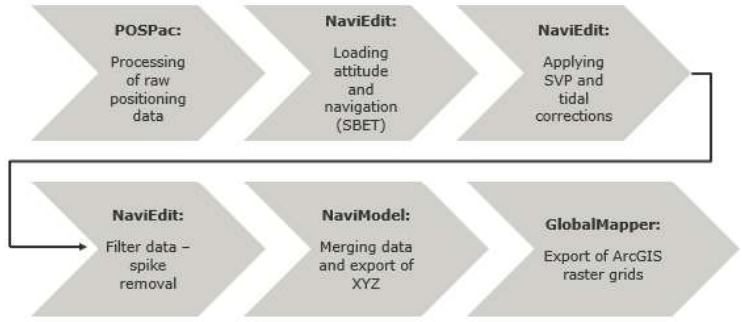


Figure 4-1: Workflow for MBES processing.

4.1.1 Multibeam – seaweed

Multibeam echosounders can be strongly influenced by seaweed because the acoustic pulse is reflected not only by the seabed, but also by vegetation growing above it. Dense or tall seaweed creates many small scatterers in the water column, which can weaken, spread, or partly block the signal before it reaches the true bottom. As a result, the system may detect the top of the seaweed instead of the seabed, especially in shallow areas with thick vegetation.

In the data, seaweed often appears as a "fuzzy" or diffuse layer above the seabed. Bathymetric data may show artificially shallower depths, rougher terrain, or unstable bottom picks. In water column displays, seaweed can appear as suspended or vertically extended echoes. Overall, seaweed can reduce bottom-detection quality and increase uncertainty in both depth and seabed interpretation.

For survey areas affected by seaweed, MBES acquisition parameters were tried optimized to improve true seabed detection by applying the lowest practical frequency, short pulse lengths, high stable ping rates, reduced vessel speed, and, where necessary, reduced swath width.

To accommodate for the seaweed during the operations different parameters were tested to reduce the effects. The main parameters which may help, and which was tested includes:

- Frequency: use the lowest practical frequency available on the system. Lower frequencies are generally less dominated by the seaweed canopy and are more likely to detect the bottom beneath vegetation. Trade-off: lower resolution and a larger footprint.
- Pulse length: use the shortest practical pulse. Short pulses improve range separation, so the system is less likely to merge the seaweed canopy and seabed into one broad return.
- Ping rate: use a high but stable ping rate. Ping rate does not remove seaweed echoes directly, but more pings give better along-track sampling and increase the chance of getting clean bottom detections through gaps in the vegetation.

Additionally, the following was tested during operations:

- Reduce swath width in dense seaweed areas, as outer beams are often more affected.
- Maintain good line overlap to support validation and cleaning – this was also considered when planning the campaign.

It was observed that change of parameters did not have any impact on the seaweed effects in areas with very dense seaweed. For these areas the seaweed was tried to be removed during the post-processing. Under the post-processing the following steps were applied:

- Filtering of seaweed in areas where it could be separated from the actual seabed
- Removal of noisy outer beams
- Manual clipping in areas with dense seaweed

For some isolated areas it was not possible to remove the seaweed completely without creating data gaps. Figure 4-1 and Figure 4-2 shows some examples of how the seaweed are affecting the true seabed and some areas where it wasn't possible to remove the seaweed without creating gaps – fortunately, most of these areas was also covered by the LiDAR data.

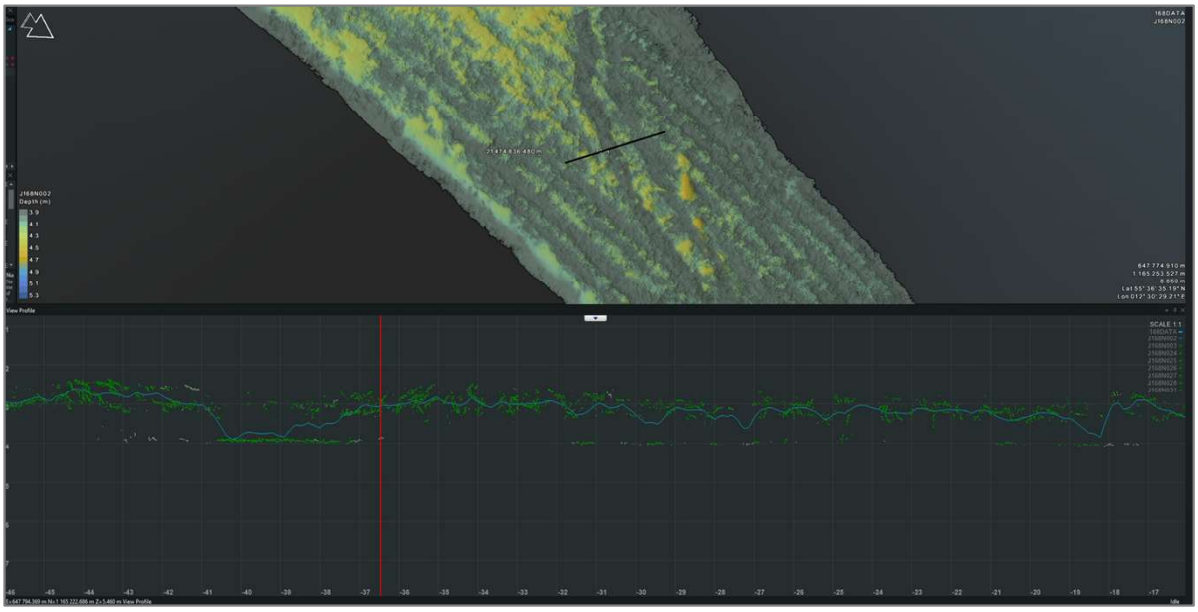


Figure 4-2 Example of how the seaweed affects the multibeam data. In this area the seaweed is very dense. Upper panel: gridded data, Lower panel: profile of the data. The profile shows "fuzzy" return from the seaweed and the "flatter" seabed return beneath. It can also be seen in some areas how the seaweed completely absorbs the signal.

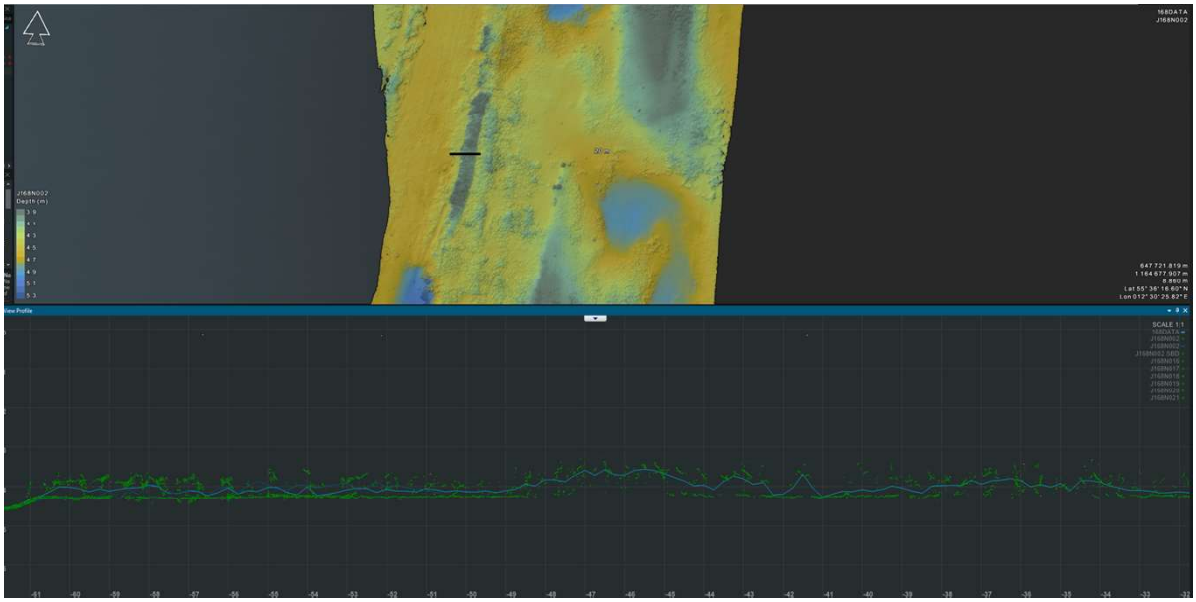


Figure 4-3 Example of how the seaweed affects the multibeam data. In this area the seaweed is less dense, and the seabed can be identified. Upper panel: gridded data, Lower panel: profile of the data. The profile shows "fuzzy" return from the seaweed and the "flatter" seabed return beneath. It can also be seen in some areas how the seaweed completely absorbs the signal.

4.2 LiDAR processing

All GPS/INS data were processed in Applanix MMS suite and correlated with base stations from the national net. The parameters were checked to ensure precise positioning and orientation. If the trajectory data was of good quality, the data were exported as a trajectory data POS file which was used to process the lidar and camera data.

The lidar data was correlated with the positioning and orientation data using the Riegl program, RiProcess. Here, the point cloud data was getting filtered and georeferenced for every line acquired. All lines were analysed and corrected for misalignments in RiPrecision.

The ground control points from are used as reference points to ensure no torsion of the point cloud data. The control points were used in RiPrecision to twist the data and correct for any potential offsets. Figure 4-4 shows the processing steps for lidar and camera data.

No correction has been made on the point cloud along the X,Y and Z axis, as the accuracy is well within parameters. Overlap beyond +/- 30 degrees have been cut away.

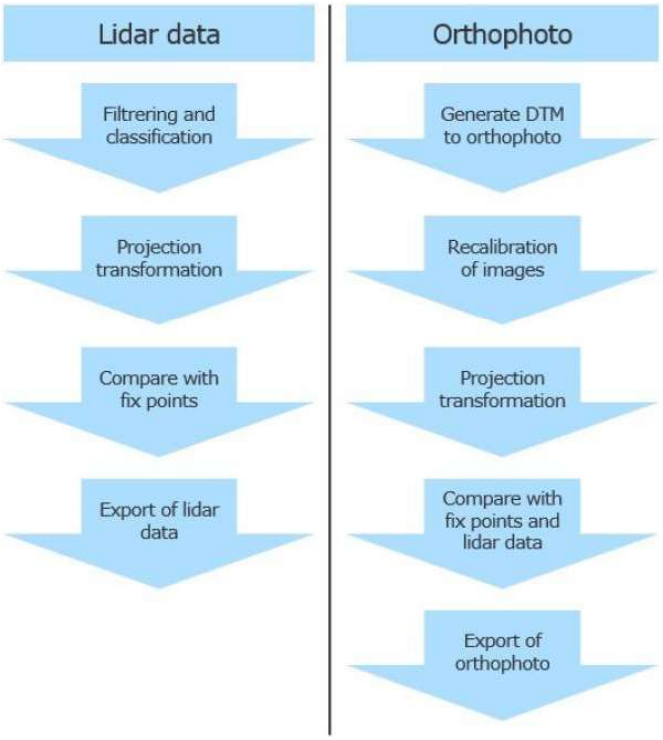


Figure 4-4: Shows the processing workflow for lidar data and orthophoto.

For quality control the following were checked:

- Accuracy of the point cloud and the GSD of the images (orthophoto) have been crosschecked.
- Hit count for point cloud
- Coverage across the survey corridor
- Image orientation file crosschecked with images
- Images have undergone sampling to determine correct quality

4.2.1 LiDAR – Seaweed

The green laser is an optical sensor, so it depends on a clear line of sight through the water and through or between the vegetation. Dense seaweed can absorb and scatter the laser energy and often produce returns from the top of the seaweed with reduced penetration to the seabed below.

The only way to separate seaweed returns from true seabed in green-laser bathymetry should be based on a combination of waveform or return-order analysis, lower-envelope seabed extraction, and neighbour-based surface consistency filtering. Seabed points are selected from the deepest

valid submerged returns and refined using progressive terrain or morphological filters to retain the lowest coherent surface. Seaweed points are identified by their shallower elevation, higher local vertical scatter, reduced continuity, and lower confidence relative to the inferred bed. Overlap between adjacent flight lines should be used to confirm the persistence of the interpreted seabed surface. Where no consistent lower return is present, the area was classified as vegetation or no reliable bottom detection rather than forcing a seabed solution.

Above filters and point classification reduced the seaweed effects from the green laser data and gave the most reliable seabed return as possible.

5. Data results

This section gives a short presentation of the general results from the green laser and multibeam survey.

5.1 Bathymetry

Overall, the data and coverage were good with a very high density above 30 pings/m^2 on average. All vertical information is provided as elevations relative to DVR90.

The bathymetry data from the investigation area shows that the water depths range from 0 m to -8.7 m relative to DVR90. An overview of the bathymetric data can be seen in Figure 5-1. More detailed bathymetric overviews can be found in Appendix 1 and 2.

North from *Kalvebodbroen* (Kalveboderne) the water depths are in general ranging between -0.5 m to -2.0 m. The greatest water depth north from *Kalvebodbroen* towards *Amagerbroen* are seen in the largest eastern channel where the water depth in average is -4.2 m, and in the west-east orientated channels where the water depth in average is approx. -4.0 m.

South from *Kalvebodbroen* the water depth increases slightly towards south going from approx. -2.0 m to -5.7 m. The greatest water depths are observed in the channel to *Avedøreværket* where the water depth reach approx. -8.3 m.

The AOI have a total size of 6.979 km^2 where the bathymetric and topographic survey represent 6.690 km^2, which is approx. 96 % of the AOI which is covered. The acquired bathymetry and topography represent. Table 5-1 shows water depth intervals and the percentage of the 6.979 km^2 survey area that they represent.

Table 5-1: Shows water depth divided in intervals, how large each interval is and what it represents of the total AOI.

Water depth interval [m]	Size of interval [km^2]	Percentage of the total area [%]
< 0.5	0.542	7.8
0.5 – 1.0	0.625	9.0
1.0 – 2.0	2.777	39.8
2.0 – 3.0	1.156	16.5
3.0 – 4.0	0.807	11.6
4.0 – 5.0	0.602	8.6
5.0 – 6.0	0.139	2.0
6.0 – 7.0	0.016	0.2
7.0 – 9.0	0.025	0.4
0.0 – 9.0	6.690	95.8

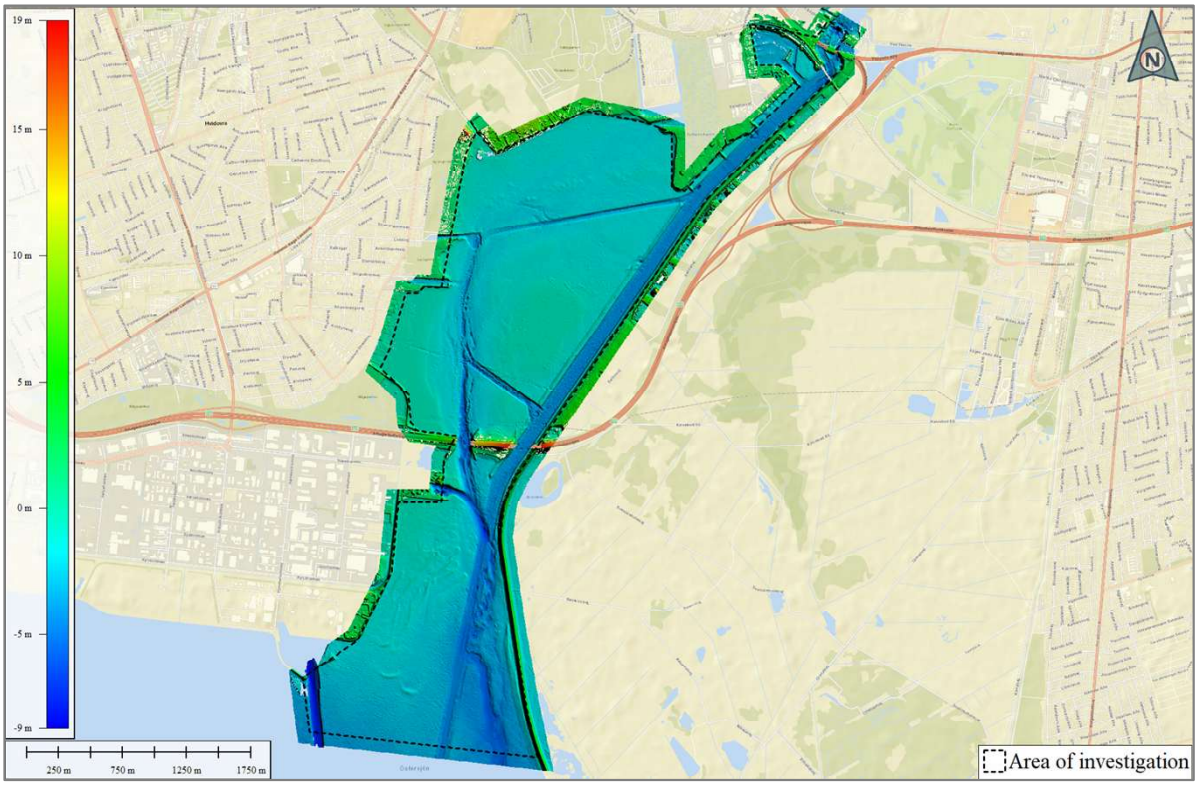


Figure 5-1: Bathymetry of the investigated area at Kalveboderne.

Figure 5-2 shows an overview of west-east seabed profiles drawn across the site with various intervals. Where Figure 5-3 and Figure 5-4 shows the seabed profiles from A to F.

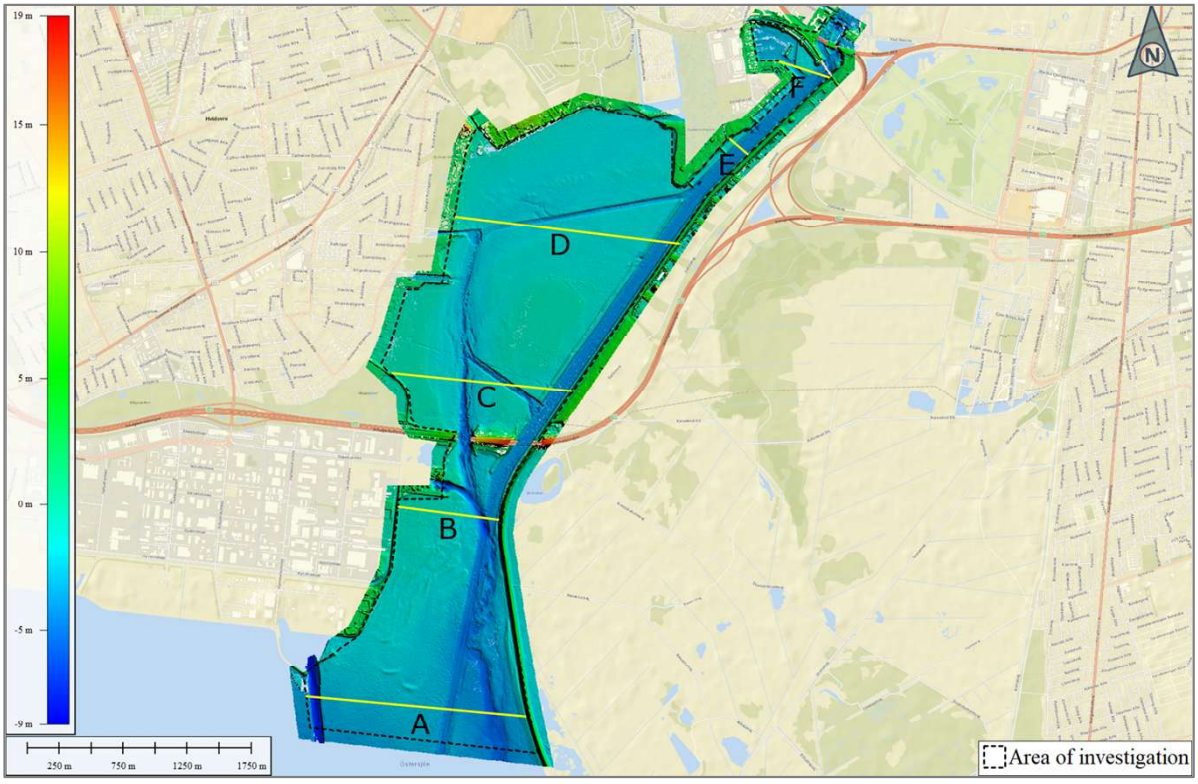


Figure 5-2: Overview of seabed profile locations.

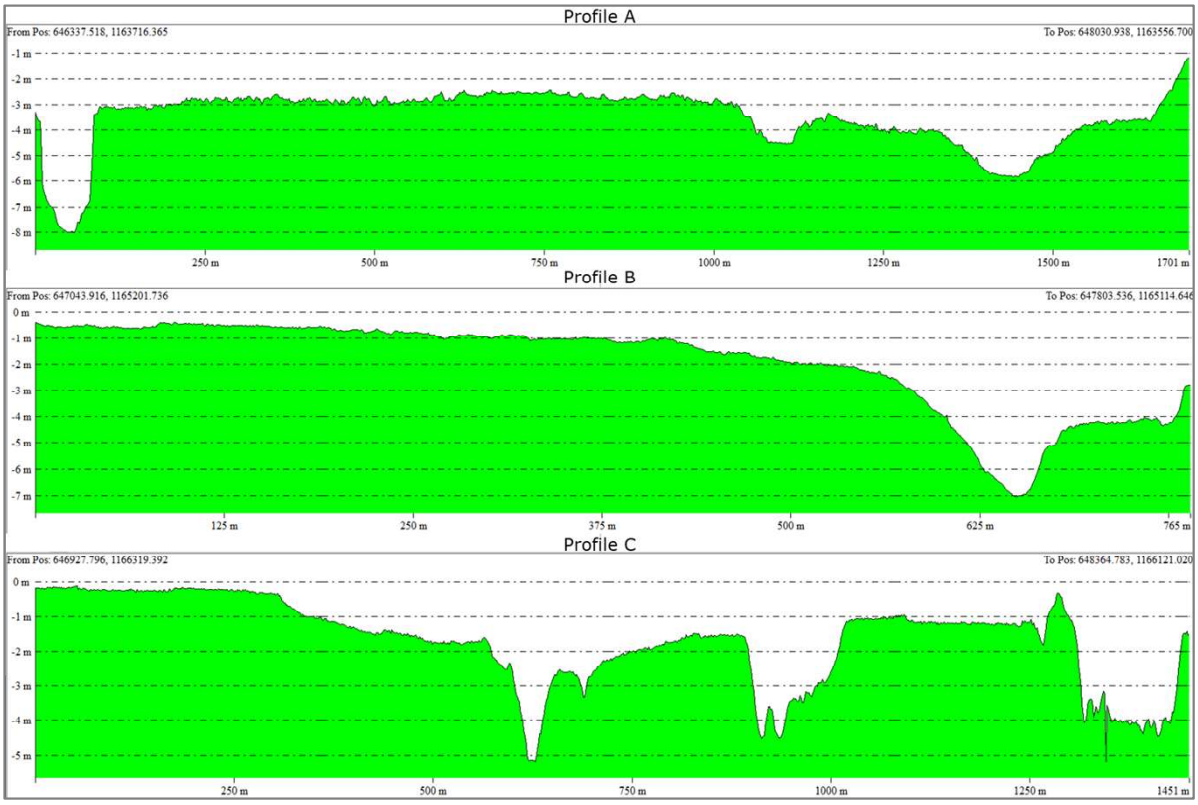


Figure 5-3: Shows the seabed profiles A, B and C. The profiles go from west (left) towards east (right).

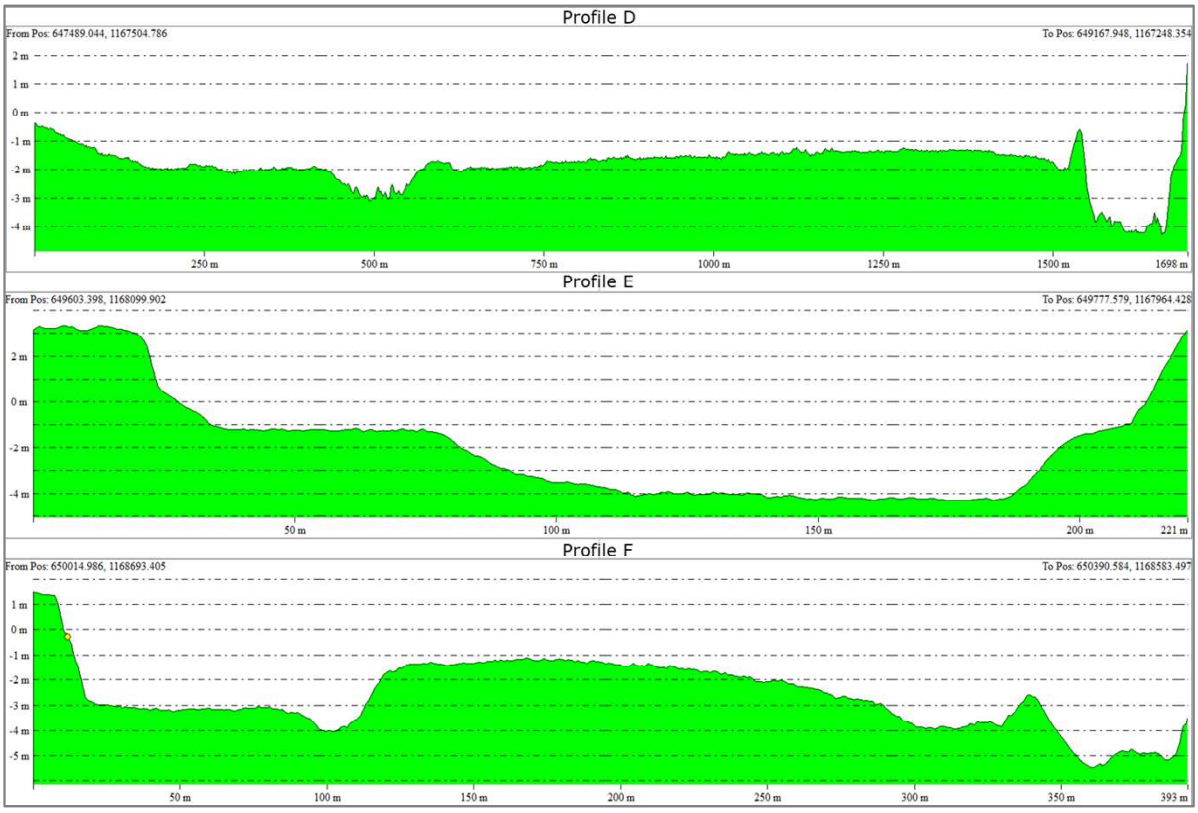


Figure 5-4: Shows the seabed profiles D, E and F. The profiles go from west (left) towards east (right).

From the bathymetric data a slope map has been produced, see Figure 5-5. The seabed is generally flat with the steepest slopes towards shore and along the channel structures. The steepest slopes are located along the channels with slopes up to ~80°. The slopes in the area are however mainly between 0-10 degrees.

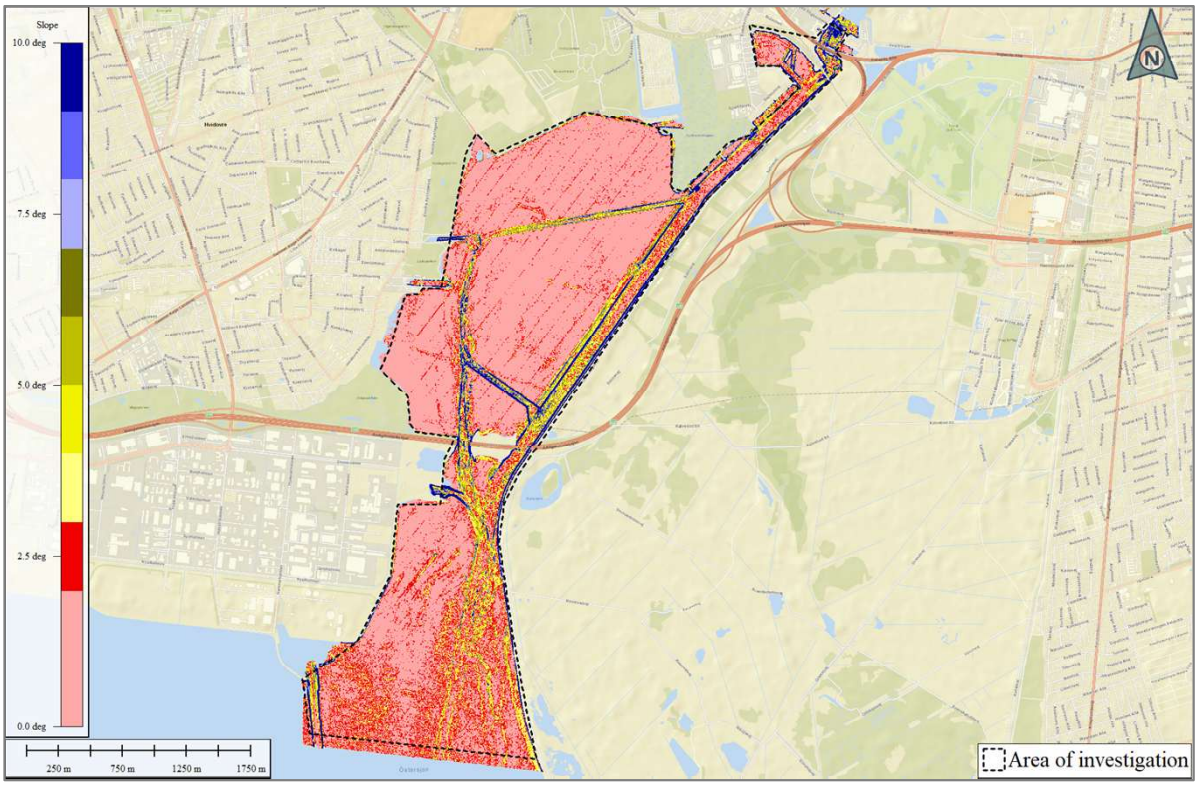


Figure 5-5: Seabed slopes. Note that seabed slopes above 10 degrees has the same colour.

Sound velocity profiles were acquired to process the multibeam data properly. The SVP casts give information of the water column conditions at the given time the cast was performed. Figure 5-6 shows information from a cast showing temperature, salinity, the sound velocity, density and conductivity through the water column.

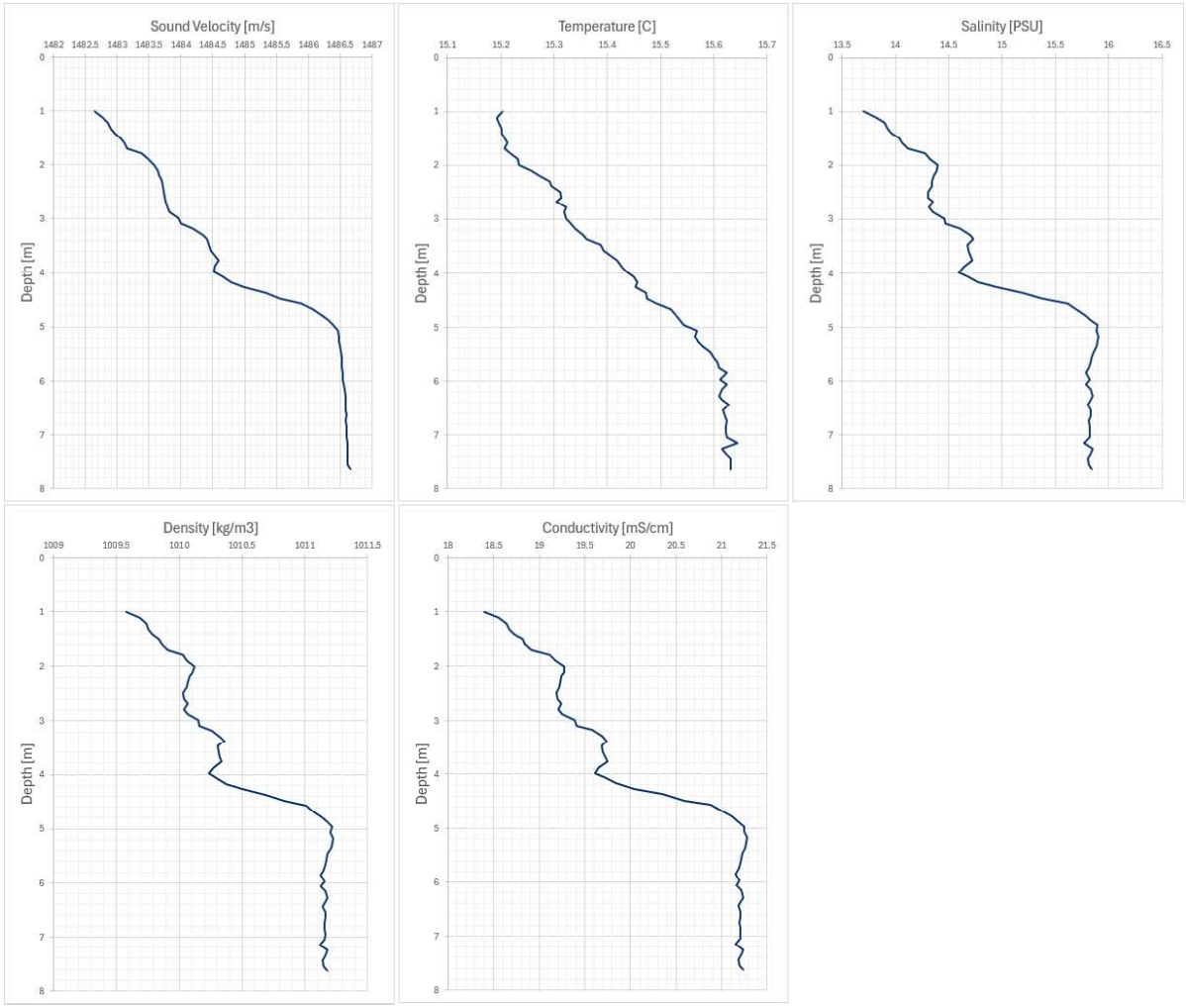


Figure 5-6: Example of one of in total six SVP casts that were performed during the multibeam survey.

As part of the airborne LiDAR survey an orthophoto has been acquired and produced for the project. The orthophoto is delivered as a high-resolution image in 5 cm cell size. The orthophoto can also be used to get an overview of the extent of the large amount of dense seaweed on the site. Figure 5-7 shows the provided orthophoto where Figure 5-8 shows a zoom to illustrate the resolution of the image.

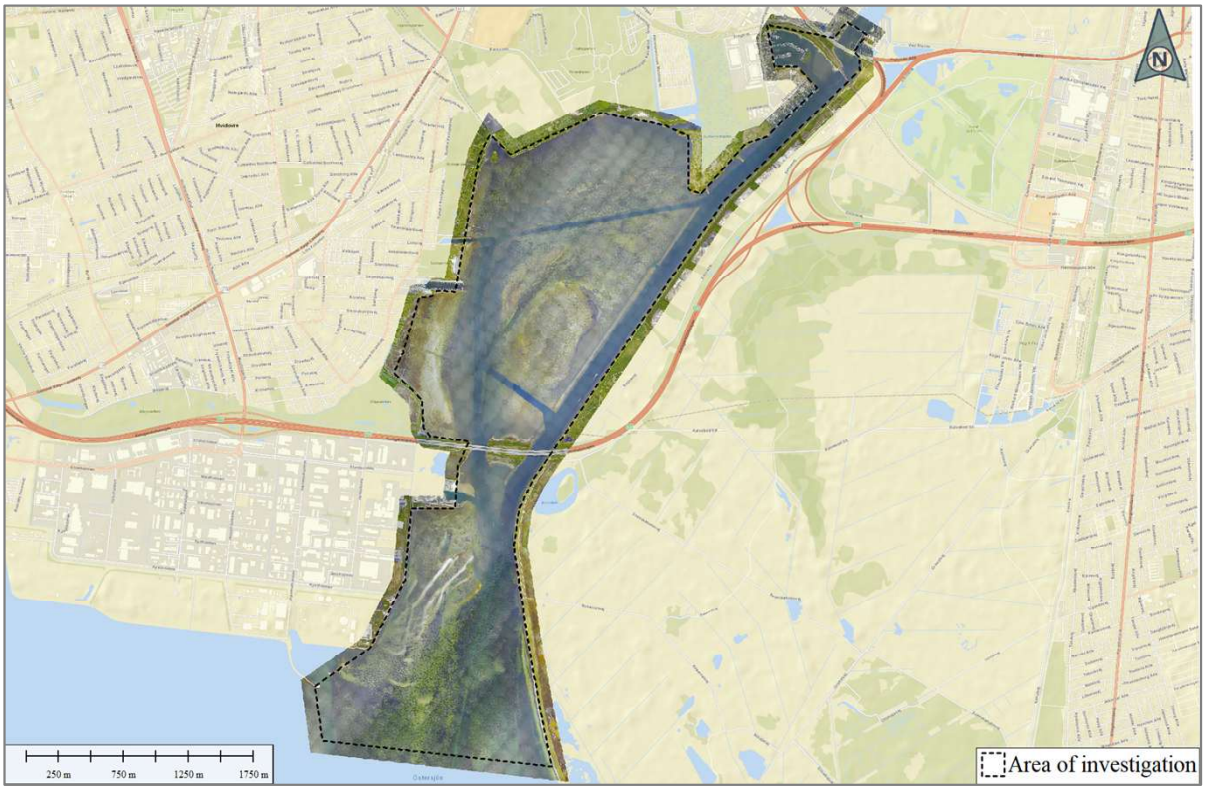


Figure 5-7: Shows the provided high-resolution orthophoto:



Figure 5-8: Zoom of the provided orthophoto near the Kalvebodbroen crossing:

6. Deliverables

Table 6-1 shows the provided deliverables, format and resolution.

Folder	Deliverable	Format	Bin size
00_AOI	Polygon of the area of investigation	Shape file (.shp)	NA
01_Orthophoto	High-resolution orthophoto	Image format (.ecw)	5.0 cm
02_Bathymetry	Only includes bathymetry from the green laser and multibeam survey	Text file (.xyz), elevation grid (.tiff) and design format (.dgn)	1.0 m
03_Topography_Bathymetry	Combined bathymetry and topography grid	Text file (.xyz), elevation grid (.tiff) and design format (.dgn)	1.0 m
04_Contours	Bathymetric contours in 0.5 m intervals	Shape file (.shp)	NA

7. References

[1] Forundersøgelse af stormflodssikring omkring København – Sammenfattende rapport; Transportministeriet; April 2025

Appendix 1

Bathymetric and topographic overview chart

Area of Investigation

mDVR90

19 m
15 m
10 m
5 m
0 m
-5 m
-9 m

N

GEODETIC DATUM

Projected Coordinate System: ETRS 1989 / DKTM3
EPSG Code: 4095
Vertical datum: DVR90

SCALE 1:25,000 (at A3)

0 0,5 1 Kilometers

RAMBØLL

Sund & Bælt

IO8 Phase 1
Bathymetry and Topography Surveys

Map showing bathymetry and topography

Rev.	Description	Drawn	Chkd.	Appr.	Date
0	Release version	ESVJ	JROU	RUBJ	28/08/2026

Survey Platform Ramboll Surveyor & Cessna T303	**Survey Date** May-June, 2026
Project Ref. Name: IO8 Phase 1	**Project no.** 1100063940
Client Sund & Bælt	**Drawing no.** 001

Appendix 2
Orthophoto overview chart



GEODETIC DATUM

Projected Coordinate System: ETRS 1989 / DKTM3
EPSG Code: 4095
Vertical datum: DVR90

SCALE 1:25,000 (at A3)

0 0,5 1 Kilometers

RAMBØLL

Sund ≋ Bælt

IO8 Phase 1
Bathymetry and Topography Surveys

Map showing orthophoto from May 2026

Rev.	Description	Drawn	Chkd.	Appr.	Date
0	Release version	ESVJ	JROU	RUBJ	28/08/2026

Survey Platform Cessna T303	**Survey Date** May, 2026
Project Ref. Name: IO8 Phase 1	**Project no.** 1100063940
Client Sund & Bælt	**Drawing no.** 002