Enhancing the positional accuracy of merged regional Acoustic Corer data sets: A case study from an Offshore Wind Farm in the Baltic Sea

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***Abstract*—In offshore wind farm (OWF) construction, mitigating the risk of sub-seabed geohazards and investigating the foundation conditions for fixed bottom wind turbine generator (WTG) and offshore substation (OSS) platform locations is of paramount concern. In October 2023, Kraken Robotics carried out a sub-bottom survey using one of our cutting-edge imaging systems, the Acoustic Corer (AC), for an OWF development project in the Baltic Sea. The aim was to assess the conditions of the potential foundation legs for two OSS platforms, each with four legs. This involved interpreting and mapping cobbles and boulders below the seabed. The AC is equipped with low- and high-frequency chirp projectors and a parametric source on each boom that enables data collections spanning from 1.5 kHz to 12.5 kHz (Guigné et al., 2010; Guigné et al., 2012; Guigné & Blondel, 2017). This configuration operates from a stationary landed survey platform. The AC produces a 14 m diameter volumetric dataset, known as an "acoustic core", down to 60 m below the seabed, depending on soil conditions. For this project, the main objective was to assess the shallow soil conditions for the survey area down to 15 m below the seabed while identifying acoustic responses that are suggestive of the presence of cobbles and boulders 0.2 m in length and width or greater. Kraken Robotics proposed to the client the utilization of the AC triple core application (Abbott et al., 2023). This technique had previously been employed at a proposed wind turbine generator (WTG) site in the Baltic Sea for a similar investigation into the soil conditions of the location, including the interpretation of geohazards, obstructions and stratigraphy. In the triple-core application, three acoustic cores are acquired separately, however they are positioned to partially overlap to provide increased data coverage over the location of interest. Subsequently, all three acoustic cores are merged into a single unified volumetric dataset and corrected laterally and vertically based on a common anomaly detected by each acoustic core, with the support of an ultra-short baseline acoustic positioning system (USBL). This approach integrates all volumetric datasets into a common framework, enabling a more coherent summation of anomalies within that volume. However, shallow water USBL positioning for the OWF survey typically resulted in an uncertainty of ±50 cm due to the shallow water in the survey area. Kraken Robotics devised a new approach to reduce positional uncertainty. A beacon was placed onto the seabed at each triple acoustic core location where all three acoustic cores could capture it. The beacon remained in the same position on the seabed until all three AC data sets were acquired. Subsequently, the beacon response captured by all three acoustic cores is vertically and laterally shifted to the exact location of the beacon during the pre-migration data conditioning. This adjustment, applied to the entire dataset, provided higher confidence towards merging three regional acoustic cores and the lateral and vertical correction of acoustic cores. This was followed by the standard seismic processing steps and three-dimensional (3-D) pre-stack Kirchhoff time migration using Kraken Robotics proprietary signal processing software, ZoomSpace. After processing and interpreting each triple-core, Kraken Robotics successfully reported 1057 anomalies suggestive of cobbles or boulders equal to or greater than 0.2 m in length and width at the two OSS platform legs. Additionally, the AC results were compared and correlated with stratigraphic interpretations obtained from previous geotechnical and geophysical surveys, showcasing that the acoustic cores represented the sediment stratigraphy of the survey area.**

Keywords—positional accuracy, SAS, seismic processing, high resolution, data merging, offshore wind farm.

I. Introduction

A client contracted Kraken Robotics to conduct an Acoustic Corer™ (AC) survey at an offshore wind farm (OWF). The purpose of the AC survey was to visualise and interpret sub-seabed cobbles and boulders at the two proposed offshore substation (OSS) platform leg footings. The sub-seabed cobble and boulder interpretation was used to plan for the safe emplacement of the OSS platform leg footing foundations. To increase the coverage of the AC data across the survey area, a triple core (three AC scans partially overlapping each other) at each leg of the two OSS platforms was suggested to the client, which had been previously applied to another OWF site in Baltic Sea (Abbott et al., 2023).

The project aimed to acquire 24 acoustic cores (AC) at two proposed OSS platform leg footing locations within the OWF. The foundation design for the proposed OSS platforms leg footing locations was understood to be either suction bucket or pin pile foundations. The AC data were used to investigate the foundation conditions and interpret and map sub-seabed cobbles and boulders equal to or greater than 0.2 m in length and width that were used to assist the foundation design.

Even though the positional accuracy of any trace relative to the centre of AC is within millimetres error, when merging multiple AC data with a landed position provided by an Ultra-short baseline (USBL) positioning system, which populates the X-Y coordinates of the source (SrcX and SrcY) and receiver (RecX and RecY) positions, the accuracy of the landed position for the AC cores are crucial to prevent destructive overlapped acoustic responses. However, the accuracy of the USBL positioning system in shallow water can deteriorate, resulting in positioning errors (Tong et al., 2019). To overcome this issue and enhance the positional accuracy of the collected dataset, a beacon was located on the seabed where each AC scan captured its acoustic response during the data acquisition so that each response corresponding to the beacon could be shifted laterally to the real location of the beacon along with the rest of the data.

II. METHODOLOGY

A. *Acoustic Corer™ Technology*

AC provides acoustic data collection using high-frequency (HF) and low-frequency (LF) chirps and a parametric source ranging from 1.5 kHz to 15 kHz. It produces a 14 m diameter volumetric acoustic cube (e.g., LF SAS, HF SAS and Innomar SAS) while penetrating down to 60 m below the seabed, depending on the soil condition of the survey area. AC is a stationary seabed deployed unit with a sonar head mounted to each arm or 'boom', rotating 180 degrees to produce a complete 3-D volumetric acoustic core (Fig. 1). The sonar head is also referred to as the 'acoustic package', and each arm comprises three collocated acoustic sensors: HF chirp (4.5kHz to 12.5kHz), LF chirp (1.5 kHz to 6.5 kHz), and Parametric source ($f_{primary}$ = 85 kHz to 115 kHz and $f_{secondary}$= 4 kHz to 15 kHz) running multi-aspect acoustic imaging to map sub-seabed stratigraphy, shallow gas, and buried infrastructure and mitigate risk from geohazards (e.g., boulders and cobbles).

B. *Data Acquisition*

In the AC surveys, two types of data are collected: JYG-Cross multifold data and Synthetic Aperture Sonar (SAS) data. JYG-Cross is a technique that collects two orthogonal seismic lines with high precision and folds the data to image stratigraphic layers within the seabed (Guigné and Blondel, 2017). Additionally, a velocity model is built by using a sem-

Fig. 1. Acoustic Corer with a tripod leg deployed on seabed.

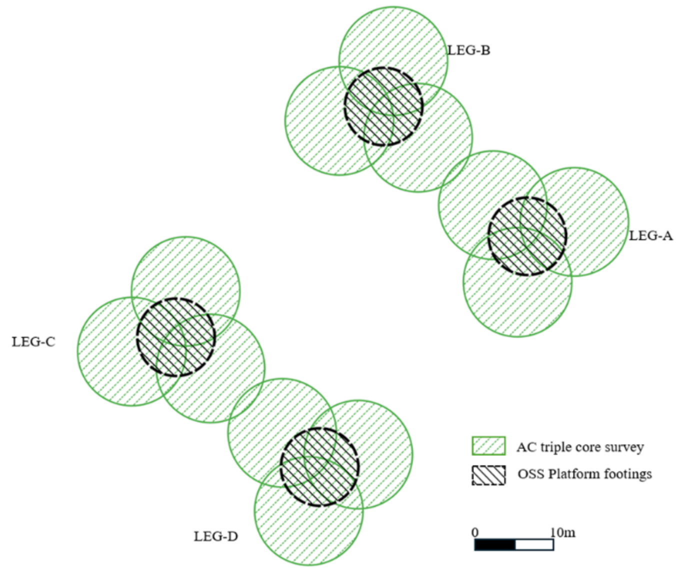

Fig. 2. The survey layout showing the location of OSS platform footings (dashed black line) and AC triple core acquisition at each footing (solid green line).

blance analysis of the JYG-Cross data, which is used to migrate SAS datasets. The AC triple core surveys (Fig. 2) were conducted across two OSS platform footings, each with four footings. At each footing, four acoustic cores, HF SAS, LF SAS, Innomar SAS and JYG-Cross data, were acquired separately, however they were positioned to partially overlap each with other to extend the data coverage for the potential foundation legs of the platform. Eight AC triple core surveys were acquired throughout the campaign, which included a total of twenty-four individual AC locations. By applying the AC triple core survey approach, the 3-D volumetric SAS dataset were integrated into a common framework. This enables a more precise anomaly interpretation by increasing coherency within that volume.

All raw data acquired offshore were subject to the Kraken Robotics continuous QA/QC checks to ensure consistent data quality. The QA/QC reports were generated offshore following each AC scan showing the required coordinates versus the landed AC position. The data coverage statistical plots for JYG-Cross and SAS scans were also presented to confirm all predetermined positions had been achieved. A sample shot-gather for the JYG-Cross scan and a sample echogram of the SAS scan were provided in these reports. All acquired data were transmitted via StarLink to the Kraken Robotics reporting office.

C. *Positional Accuracy*

AC surveys offer high-resolution and precise SAS acoustic data acquisition. The positional accuracy of each recorded trace for the AC surveys plays a crucial role. The relative positioning of the AC data are referenced to the centre of the AC. The absolute position of the AC is a function of the vessel positioning system and the position of the USBL beacon, which is mounted on top of the AC. The positioning of the AC was verified during the AC acceptance test, along with the confirmation of the data heading and the USBL spin test.

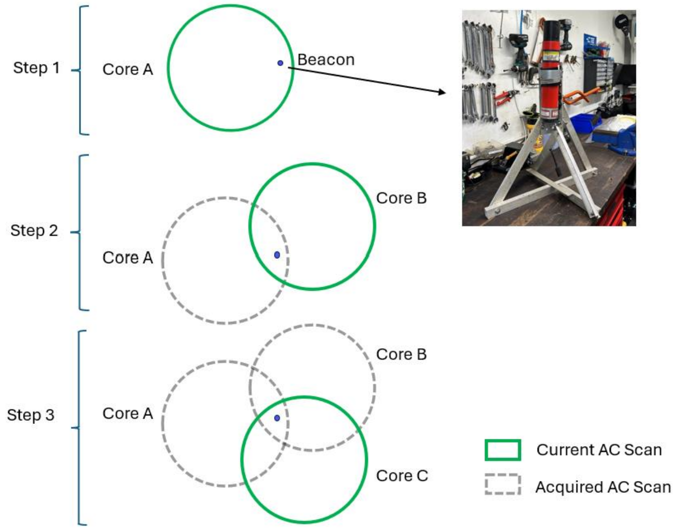

Fig. 3. The steps of AC triple core applications in the survey with the image of beacon used (at the top right).

The X-Y-Z position was determined at each site by averaging 60 points collected from the USBL beacon. The heading of the AC subsea scanning system is provided by a Tiny Optical Gyro System (TOGS), which has an accuracy of ±0.3˚. This equates to a positional uncertainty of the acoustic packages of ±16 mm at the mid-point of the AC scan, which increases to ±31 mm at the scan perimeter. The precision of the sonar package linear motor positioning system along the AC booms is ±10 mm. However, it is important to understand that the position of any traces recorded corresponding to the scan location is confirmed many hundreds of times during the AC survey. Therefore, the final position of any trace relative to the centre of the AC is known within millimetre accuracy. The overall positional error of any traces within the AC data scan radius is essentially the error associated with the landed AC position provided by the USBL system.

During the campaign, the USBL positioning error measured was ±50 cm due to the high slant angle caused by the shallow water (~20 m to 30 m) within the survey areas. Therefore, merging three AC scans acquired at each platform leg with a positional error of ±50 cm for each core could smear the data during imaging, produce multiple false anomalies and cause the change in size of anomalies unless each AC data is properly positioned. Accurately merging three individual AC data volumes into a single triple core for each platform leg location and providing a confident interpretation of anomalies requires lateral and vertical positioning corrections. Laterally aligning each AC location before merging required a known reference location to which each AC location could be translated. The reference used was a beacon placed onto the seabed before the start of the first scan at each of the OSS platform leg locations, which remained in place until data acquisition of all three cores was completed (Fig. 3). Once the processing and imaging of each core were completed, the post-processed data was brought into a visualization software for identification and analysis of the beacon location within the datasets (Fig. 4). The observed average beacon position provided (i.e., true beacon position; black circle in the top image of Fig. 4) was plotted and against

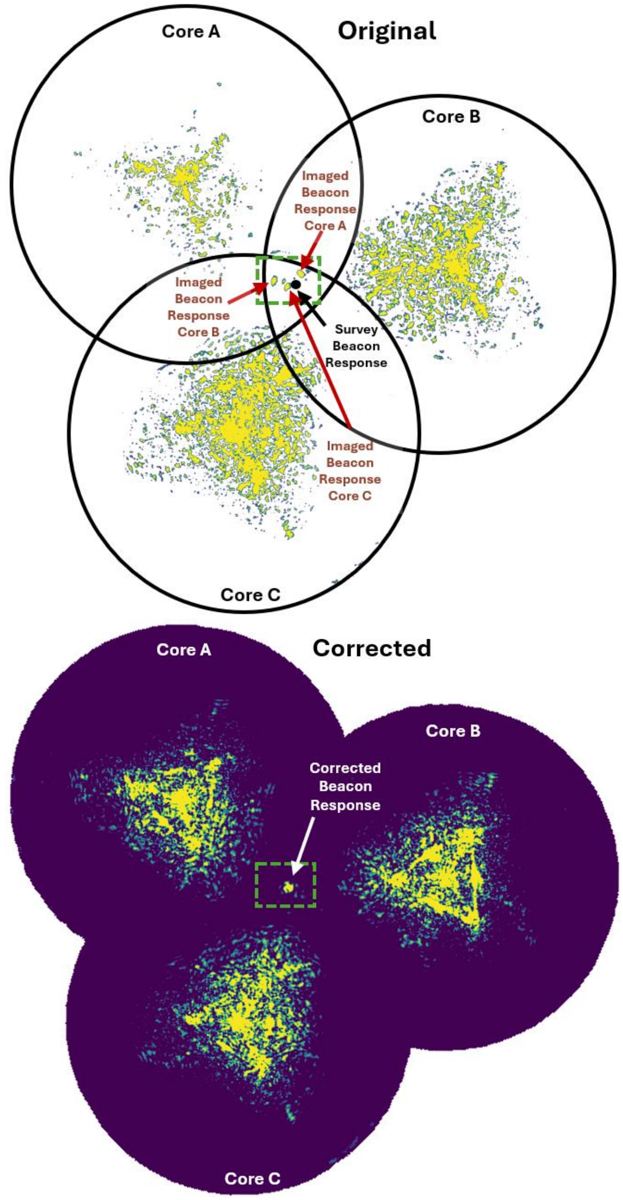

Fig. 4. Example of the triple core lateral alignment procedure before (top) and after (bottom).

compared the beacon position as it appeared in the acoustic core (i.e., the imaged beacon position). The difference, Δx and Δy, between the Eastings and Northings of the true and imaged beacon positions relative to each core was calculated. Subsequently, each AC landed position was translated to the true beacon position by the calculated offset amounts, Δx and Δy. The lateral offset corrections were applied to each core, which was then merged and migrated. The accuracy of the lateral offset corrections was evaluated in the resulting aligned triple core by verifying that the corrected beacon appeared within the data set as a singular beacon response at the true beacon position.

Upon completion of the lateral alignment of the triple core, the merged data set was evaluated for variations in topography between the three site locations. Topographic static corrections were performed by defining a flat datum and shifting the traces in time, Δt, toward that datum using the TOGS pitch and roll readings. For each triple core site, one of the three cores was arbitrarily selected as the processing datum, shifting the remaining two cores relative to the chosen datum, as required.

D. Data Processing

Data processing techniques were executed onshore at the Kraken Robotics reporting office after the field campaign. For pre-processing (Fig. 5), the data underwent a series of steps, with particular emphasis on pulse compression and pass-band filtering. The raw data were subjected to match filter pulse compression, a process designed to optimize the signal-to-noise ratio (SNR) of the received signal. This approach is especially effective in augmenting the quality of raw seismic data. Subsequently, a pass-band filter was applied to eliminate frequencies outside the AC's bandwidth, thereby categorizing them as noise. Pre-stack Kirchhoff time migration was used to transform the acoustic data into a more refined representation of the Earth's subsurface. Its primary objective is to facilitate a comprehensive understanding of subsurface features, such as cobbles and boulders, by generating high-resolution images. A series of post-processing steps were applied to prepare the data for interpretation. After completing the workflow in Fig. 5, all three AC unmerged datasets were loaded into a visualisation software individually to detect the acoustic responses corresponding to the beacon on the seabed. The selection criteria of the beacon responses were to choose the center (bullseye) of each response within three AC datasets for the beacon at which depth they are observed first. By using a customized workflow (Fig. 6) within ZoomSpace, the location of acoustic responses was then shifted laterally, if necessary, to the measured location of the beacon as a reference point, which was provided by the USBL system. All three AC datasets were also statically corrected (if required).

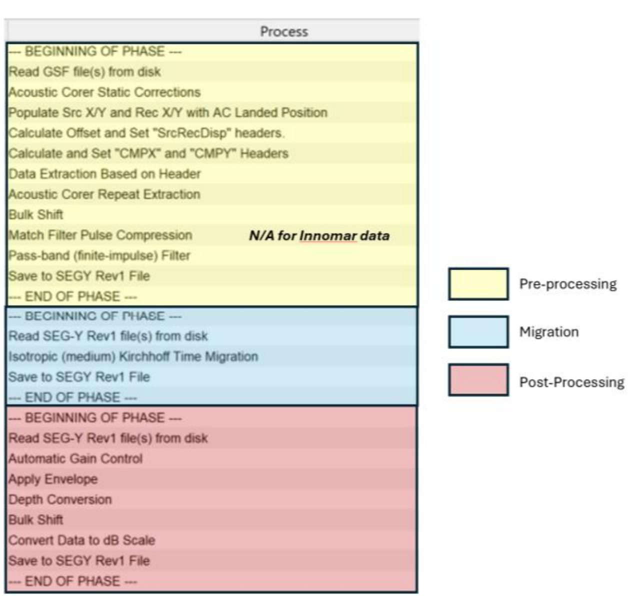

Fig. 5. The processing workflow used in our in-house software, ZoomSpace, for Innomar, HF, and LF AC data.

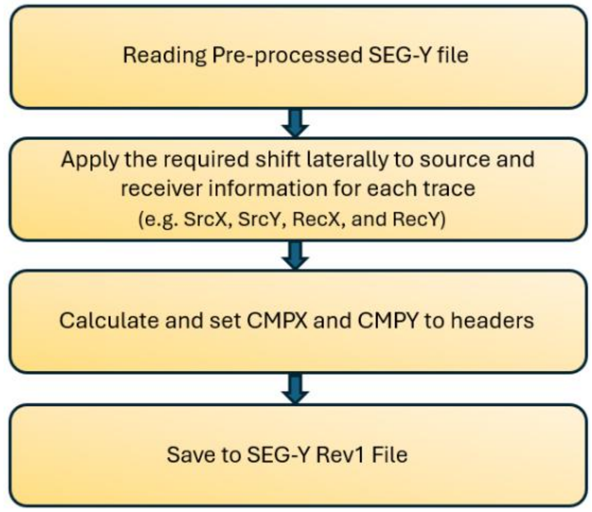

Fig. 6. The workflow for aligning AC data to the reference beacon location.

In Fig. 6, a customized workflow is shown where the pre-processed SEG-Y is used as input during the first step. Then, the X-coordinate of Source (SrcX), Y-coordinate of Source (SrcY), X-coordinate of Receiver (RecX), and Y-coordinate of Receiver (RecY) were updated. Since we have new X-Y coordinates for the source and receiver locations, new Common Mid-Points (CMPX and CPMY) positions were re-calculated. Once this step was applied to all three AC datasets, they were merged for pre-stack Kirchhoff time migration, followed by post-processing for the migrated data.

III. Results and Interpretation

Across the eight triple cores covering the location of two OSS Platform footing legs, 1057 acoustic anomalies suggestive of cobbles or boulders equal to or greater than 0.2 m in length

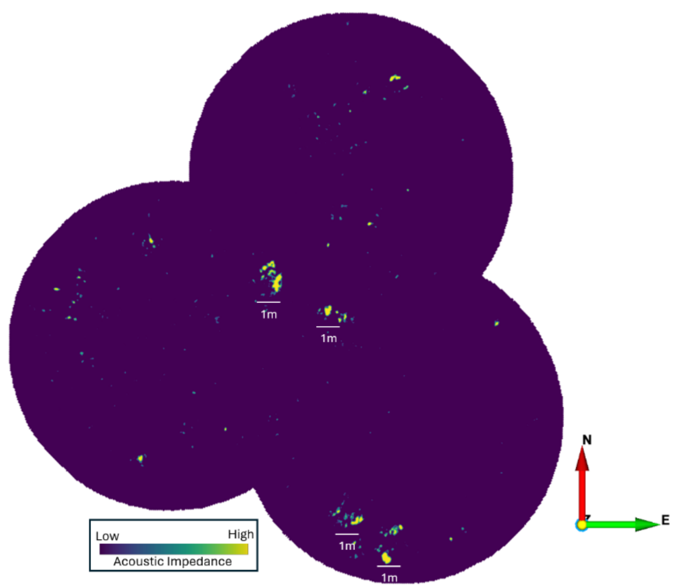

Fig. 7. Plan-view image of four identified anomalies from one of the triple SAS datasets, suggestive of boulders or cobbles at a depth of 1.65m.

and width were interpreted. Of these anomalies, 990 are present in the uppermost 5 m of the sub-seabed, 48 are interpreted between 5 m and 10 m below the seabed, and 19 are interpreted deeper within the sub-seabed between 10 m and 15 m. Fig. 7 shows one of the post-processed AC triple core data representing the subsurface at one of the legs of an OSS platform. A total of 71 anomalies were identified within this unified volume.

Since the AC acoustic data comprises specular and non-specular returns (Guigné, 2014), the AC data can also detect lithological layers/boundaries across the survey area. In this campaign, the geotechnical data was collected by the client and the interpretation was shared with Kraken Robotics. Fig. 8 shows the crossline image through the AC triple core SAS volume, where the observed layers are annotated, and the table shows the expected geological conditions given by the client. This provides a better understanding of how the AC interpretation is related to the geotechnical information.

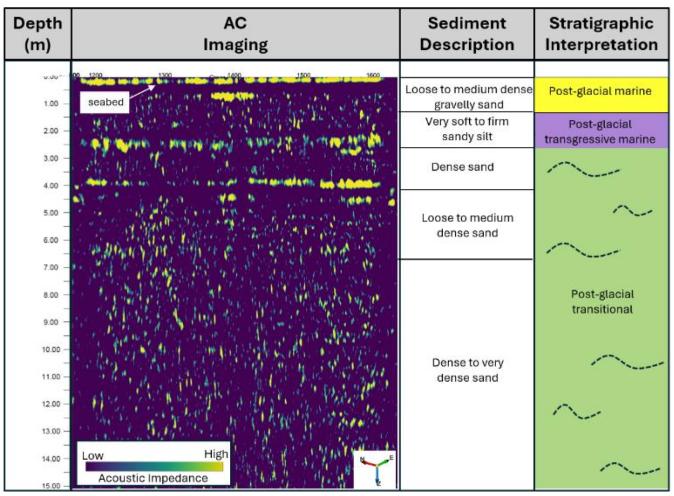

Fig. 8. The crossline image from the AC HF SAS data (on the left), the sediment description (centre), and the stratigraphic interpretation (on the right).

IV. CONCLUSION

Merging three cores at each leg footing of OSS platforms, which provided a bigger footprint over the survey area, requires precise positioning that plays a crucial role in AC surveys. Since a USBL system was used to position the AC in a shallow water environment, this caused an uncertainty of ±50 cm. A beacon was located on the seabed and was used as a reference point to shift the acoustic responses of the beacon for all acquired data laterally to the fixed position of the beacon. This unique method of AC surveying has been successfully implemented to increase the AC footprint to help Kraken Robotics interpret and report a total of 1057 acoustic anomalies within eight AC triple cores across two OSS platforms. In addition to this as the AC data was used to aid in the stratigraphic interpretation over each AC triple survey area.

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