Merging individual Acoustic Corer™ data sets into a unified volume to optimize the identification and interpretation of geohazards, obstructions and stratigraphy: Case studies from the Baltic Sea and Gulf of Mexico

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ABSTRACT: *The Acoustic Corer™ (AC) 3-D imaging technology comprises high- and low-frequency chirps and a parametric source with operating frequencies from 1.5kHz–15kHz through a stationary landed platform. Using multi-aspect acoustic imaging, it produces a 14m diameter volumetric image to a penetration depth of 60m below seabed, depending on the geological conditions. Recent multi-core AC surveys within the Baltic Sea and Gulf of Mexico proved that merging individual AC data sets into a unified volume greatly enhanced the data resolution and understanding of the sub-seabed stratigraphy and geohazards and obstructions present within. Specifically, this enabled a more cohesive representation and characterization of boulders, hard layers, and conductor pipes. The ability to merge data sets and maintain data quality suggests that optimal positioning, soil velocity and static corrections were obtained. These case studies, as applied to the renewables and oil and gas sectors, build on the value that the AC delivers for de-risking offshore infrastructure installations and remediation efforts.*

1 Introduction

Three-dimensional (3-D) investigations of the shallow sub-seabed for identifying and characterising geohazards, obstructions and stratigraphy require specular and non-specular returns with spatial accuracies exceeding those of current conventional seismic surveys (i.e., towed streamer-based methods). Advanced acoustic accuracies enable improved correlations between acoustic and geotechnical properties of near-surface soils. To effectively image geohazards and obstructions (e.g., boulders, pipes, etc.) and stratigraphic characteristics (e.g., small-scale sand/shale lenses) requires retention of the entire signal energy distributions, principally the diffuse diffracted signals and the dominating reflective energy and location calibrations. This can be accomplished by sub-seabed interrogation through a stationary transmitter and receiver spatial centimeter-spaced network with horizontal dimensions greater than 5m. Previous applications include Vardy et al. (2008) who used a 3-D chirp sub-bottom profiler to map the seabed and bedrock structure to identify buried discrete targets in a tidal basin on the southern coast of the United Kingdom. Wenau and Alves (2020) utilized 3-D seismic data to interpret the origins of a shallow tunnel valley in the southern North Sea and Römer-Stange et al. (2022) designed a marine acquisition system consisting of a sparker acoustic source and a hydrophone array and applied diffraction imaging to detect boulders in the North Sea.

The "Acoustic Corer™ (AC)" (Guigné et al., 2012) is an advanced high-resolution acoustic imaging technology that can detect buried targets, such as boulders and conductor pipes, up to 60m below the seabed, conditional to the geological conditions. It has a long history of successful applications, ranging from offshore windfarm pre-installation risk assessments to decommissioning and remediation of existing oil and gas infrastructure. This paper highlights two successful AC campaigns in the Baltic Sea and Gulf of Mexico during the Summer and Fall of 2022. The Baltic Sea campaign investigated the presence of sub-seabed boulders that could affect offshore windfarm (OWF) development, while the Gulf of Mexico campaign imaged buried conductor pipes to assist with remediation efforts of a toppled oil platform. In both of these campaigns, in which the OWF and oil and gas sites cannot be named, merging and uniformly migrating all AC cores resulted in enhanced resolution and coherency in the data sets, yielding accurate identification and representation of geohazards, obstructions and stratigraphy.

2 Acoustic Corer™ (AC)

2.1 *Technological Description*

The AC consists of two sonar heads attached to each arm of a 12m boom held and rotating off a set of tripod legs (Figure 1). This boom turns 180°, creating a 360° "acoustic core" product 14m in diameter down to a depth of 60m, depending on the geology. The sonar heads contain three collocated acoustic sensors: an HF chirp (operating across 4.5–12.5kHz), an LF chirp (operating across 1.5–6.5kHz), and a Parametric source (using a secondary frequency (f_s) of 8kHz) (Table 1 and Figure 1). The Parametric source (Innomar) has a narrower acoustic propagation pattern than the HF chirp, providing a more detailed, crisper imagery of the features. Together with the HF chirp, collocated confidence is derived, and critical imagery elements are confirmed in target picking.

Table 1: Acquisition parameters for the three AC sources

Setting	High-Frequency (HF)	Low-Frequency (LF)	Innomar/Parametric
Sampling Rate	50kHz	50kHz	100kHz
Samples Per Trace	5450	5450	7333
Penetration Depth	60m	60m	60m
Pulse Frequency Range	4.5–2.5kHz	1.5–6.5kHz	8kHz (f_s)
Pulse Segment (Chirp) Duration	15ms	15ms	N/A
Pulse Width (Innomar/Parametric)	N/A	N/A	0.07–1ms (User Selectable)
Pulse Taper Type (Waveform)	Rectangular	Rectangular	N/A
Pulse Type	Linear	Linear	Ricker
Match Filter Type	Hann	Hann	N/A
Ambient Noise Recording	ON	ON	ON

The AC is typically deployed on the seabed using a crane. Immediately after landing, the AC's depth, altitude, pitch, and roll are recorded, and stability tests are performed. Once it is determined that the system is stable in static mode, the AC is rotated and the acoustic payloads are moved out of the booms to their baseline positions while continually monitoring pitch, roll, and altitude via the onboard sensors located on the main frame and the acoustic payloads.

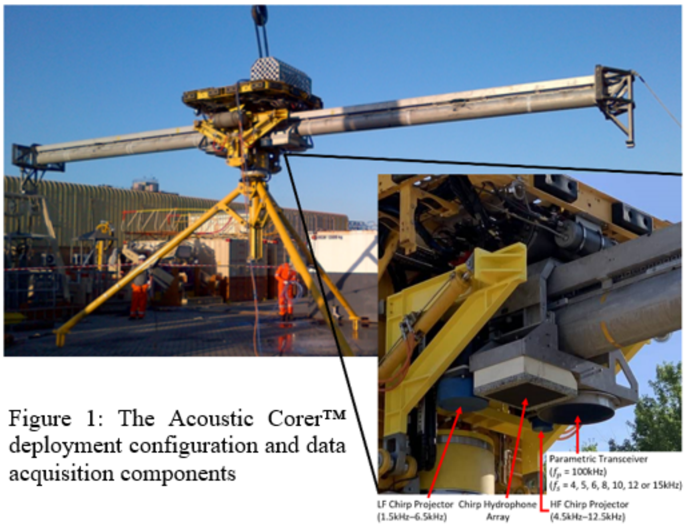

Figure 1: The Acoustic Corer™ deployment configuration and data acquisition components

2.2 *Data Acquisition*

The AC acquires two types of scans: JYG-Cross and 3-D synthetic aperture sonar (SAS). The JYG-Cross (Guigné et al., 2010) is a technique that resembles a high-precision seismic line that folds the data to accentuate sub-seabed stratigraphy, similar to multi-channel marine seismology. The outputs are two orthogonal 2-D lines. The SAS uses multiple frequencies to produce a high-resolution 14m diameter volumetric image of the sub-seabed.

For each JYG-Cross scan, the source and receiver packages acquire offset data in 10cm increments for a total of 5,000 positions along the booms. The total JYG-Cross scan time is approximately four hours, and the acquisition sequence is as follows:

1. low-frequency chirp on boom 1;
2. low-frequency chirp on boom 2.

For each SAS scan, the source and receiver packages acquire normal incidence data along each boom in 7cm increments, for a total of approximately 10,000 positions per scan. The total SAS scan time is approximately 10 hours, and the acquisition sequence is as follows:

1. innomar/parametric ping on boom 1;
2. low-frequency chirp on boom 1;
3. low-frequency chirp on boom 2;
4. high-frequency chirp on boom 1;
5. high-frequency chirp on boom 2;
6. innomar/parametric ping on boom 2.

2.3 *Data Processing*

The JYG-Cross data sets were used to perform 2-D semblance analysis to derive subsurface soil velocity profiles (V_{rms}) and subsequent velocity models (Figure 2) for the survey sites. Velocity models, or p-models, are 3-D volumes that are generated to provide the coordinates and soil velocities of the points that will be imaged. These p-models were then used in a gridded interpolation to generate a regional velocity model across the entire survey areas (Figure 2).

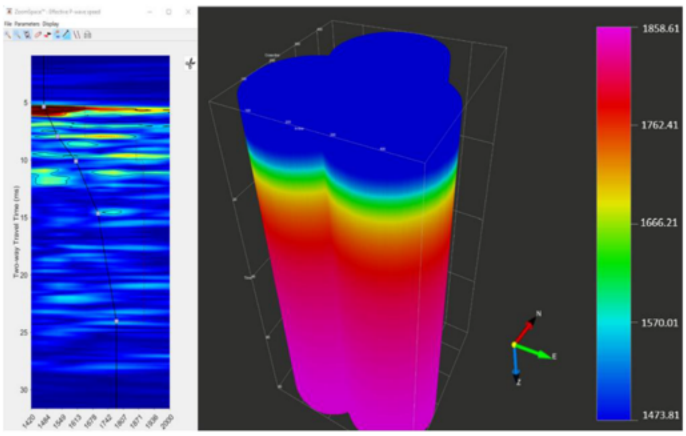

Figure 2: Semblance analysis (left) and velocity model generation (right) used for SAS data processing and depth conversion

All SAS volumes were processed through standard seismic processing steps using ZoomSpace™, an in-house software. The individual pre-processed volumes were merged and migrated into a single cohesive volume which was statically corrected to the same reference datum. This enabled a more unified identification and interpretation of geohazards, obstructions and stratigraphy. The detailed processing flow is shown below in Figure 3.

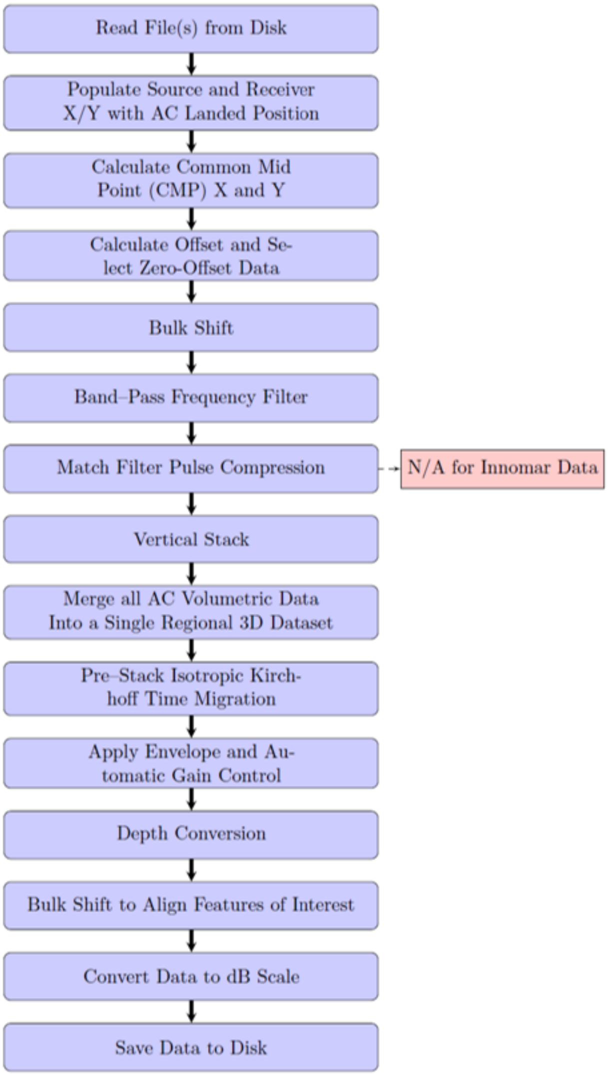

Figure 3: ZoomSpace™ processing workflow for HF, LF, and Innomar/Parametric AC (SAS) data

3 Case Study #1: Baltic Sea

3.1 *Objectives*

The purpose of this campaign was to investigate foundation conditions to interpret and map sub-seabed boulders, equal or greater than 0.50m in diameter, that may impede monopile emplacement.

3.2 *Survey Area*

In October 2022, Kraken was contracted to carry out an Acoustic Corer™ survey within the Baltic Sea, to aid in the understanding of the shallow soil conditions, with a particular focus on identifying anomalies suggestive of sub-seabed boulders. Specifically, 29 AC scans were completed at future wind turbine generator (WTG) locations. At one of the WTG locations, namely the "triple core" site, three AC scans were carried out. Each AC scan, apart from the triple core site (Figure 4), comprised both JYG-Cross and SAS scans. At the triple core site, JYG-Cross and SAS data was collected at one of the three scan locations, while SAS only data was acquired at the other two locations.

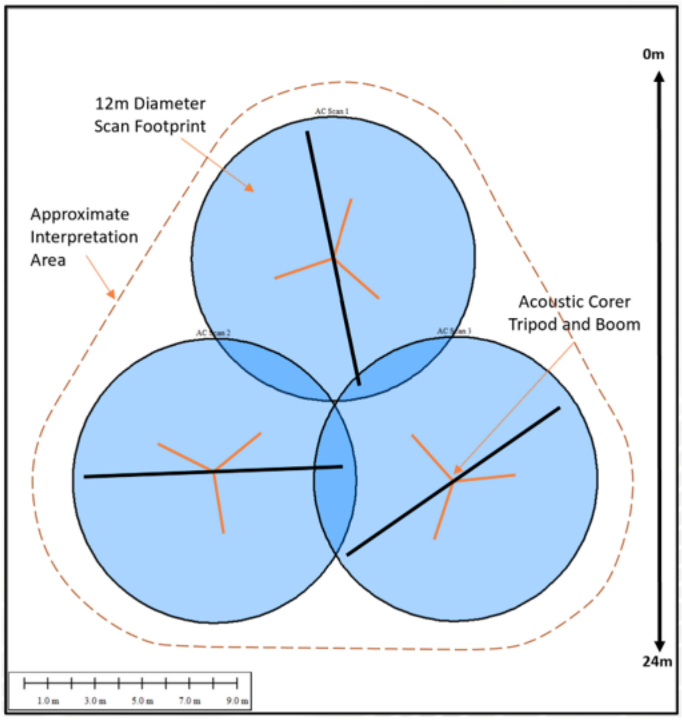

Figure 4: Triple acoustic core site layout and methodology

Previous geophysical and geotechnical information were used to produce a desktop study of the depositional settings and lithologies expected at each AC site, ahead of acquisition. The survey area exists within a region of previous glacial activity. Thus, the survey area is predominantly comprised of subglacial traction in the form of variable high strength gravelly, slightly sandy clay and very dense sand. In some areas, one or both post-lake deposits and outwash sediments are present to a maximum depth of 30m and 35m below seabed, respectively. The post-lake deposits consist of medium to very dense silty fine sand while the outwash sediments comprise loose to very dense sand, medium to very dense slightly sandy silt or medium to very high strength silt and low to high strength clay (Table 2).

3.3 *Results and Interpretation*

A total of 579 acoustic anomalies, equal or greater than 0.50m in diameter, were identified within the OWF locations. Of these, 446 were observed in the uppermost 5m of the sub-seabed, while 84 were detected between 5–10m below seabed and 49 were imaged deeper within the sub-seabed, between 10–25m. Additionally, 39 hard layers were identified. Of these, 14 interfaces were observed to be continuous across the entire core, while 24 were partial interfaces and one comprised a boulder field.

3.3.1 *Triple Core Site*

To increase the footprint for geohazard detection at the WTG locations and maximize data interpretation, three adjacent, partially overlapping, AC scans were completed at one WTG location (Figure 4). Semblance analysis using the acquired JYG-Cross data produced a water to soil velocity profile (V_{rms}) from approximately 1475–1860m/s (Figure 2). This V_{rms} profile was used to generate a regional p-model encompassing all three scan locations, which was subsequently used to migrate the three SAS data sets into a single, triple core footprint for interpretation. The desktop study summary of the expected geological conditions given the existing geotechnical and stratigraphic information for the site is shown below in Table 2, where the AC signal penetration of 32m can be seen to exceed the maximum depth of CPT data.

Table 2: Expected geological conditions for the triple core site

Sediment Description	**Depth (m below seabed)**	**Stratigraphic Interpretation**	**AC Signal Penetration**
Soft clay	0.00 – 0.30	Holocene veneer	↑
Very dense sand	0.30 – 0.50	Outwash sediments	
Very stiff to hard clays	0.50 – 3.50	Glacial traction till	
Very dense sand	3.50 – 9.20		
End of CPT	9.20		
Note – AC signal penetration extends beyond CPT data			

3.3.1.1 *Anomaly Summary*

A total of 36 acoustic anomalies were identified within the unified cores (Figure 5), down to a depth of 6.40m below seabed. These anomalies varied in size from 0.50–3.00m long to 0.30–1.10m wide and were indicative of a boulder or group of boulders.

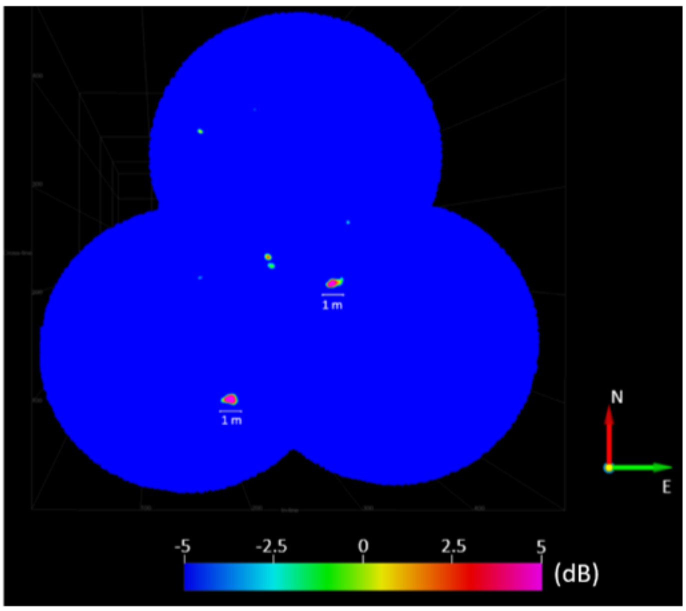

Figure 5: Plan-view image of two identified anomalies, suggestive of boulders, within the triple core SAS footprint

3.3.1.2 *Sediment Depositional Environment and Lithological Layers*

Two lithological (hard) layers were identified within the merged AC volume at 0.30m and 3.10m below the seabed, respectively (Figure 6).

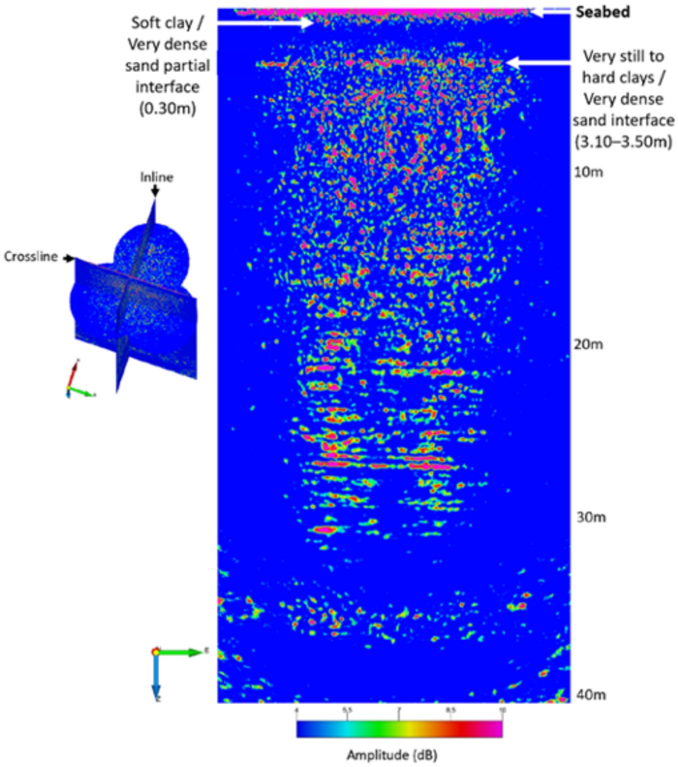

Figure 6: Crossline slice through the combined SAS volume in which continuous and partial hard layering were observed. The strong reflector at the top of the section represents the seabed (and depth = 0m) as the water column was removed during a post-processing bulk shift

In comparison with the stratigraphic interpretations in Table 2, these hard layers were interpreted as a partial interface between the Holocene veneer and Outwash sediments and a continuous interface from the Outwash sediments into the glacial till. A summary and detailed description of the interpreted lithological layering and present anomalies is given in Table 3.

Table 3: Lithological layer interpretation

Lithological Layer	**Depth Below Seabed (m)**	**Description**
Holocene veneer to Outwash sediments – P	0.30	Partial interface between soft clay and very dense sand. Seven anomalies were observed within the Holocene veneer.
Outwash sediments to Glacial traction till	3.10 – 3.50	Interface between very stiff to hard clays and very dense sand. Sixteen anomalies were observed within the outwash sediments.
Note – P = Partial interface not seen across entirety of core		

4 Case Study #2: Gulf of Mexico

4.1 *Objectives*

The primary objective of this campaign was to process and interpret the acquired AC data to identify the full expanse of conductor pipes that were buried and lost within the sub-seabed after a 2004 mudslide.

4.2 *Survey Area*

The study area is located within the Gulf of Mexico, which had previously experienced a toppling event after a hurricane. In May 2022, Kraken was contracted to carry out a sub-bottom/below mudline (BML) survey, where 63 AC scans were completed to determine the extent, expanse, orientation, and characteristics of conductor pipes. The survey area was 205m x 60m, comprising six JYG-Cross and 63 SAS scans (Figure 7).

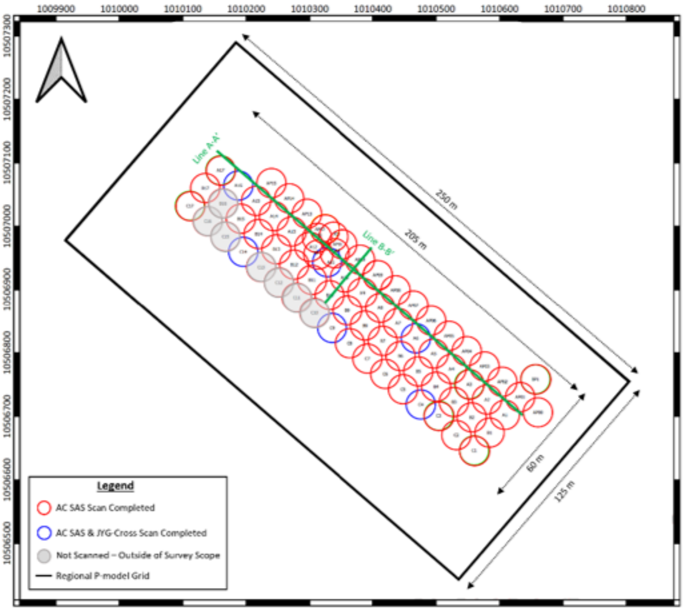

Figure 7: Gulf of Mexico Acoustic Corer™ survey layout

To better understand the seabed and sub-seabed characteristics at the survey area, previous geotechnical information was reviewed prior to acquisition. The uppermost seabed (7.3m BML) is characterised by soft sediments with low shear strength (<10kPa). These conditions required close stability monitoring during the deployment of the AC using a crane. The survey area is largely comprised of clay with the top 18–21m suggestive of mass flow deposits. As a result, this material is highly variable with undrained shear strengths approaching zero near the mudline (i.e., seabed surface), increasing to about 26.3kPa around 23m BML. However, harder material could still be encountered at shallower depths depending on whether blocky material exists within the mass transport deposits. Below 23m, the soil is less variable but underconsolidated with undrained shear strengths ranging from 28.7–33.5kPa between 24–61m BML. These shear strengths are nearly 3 times lower than those typically encountered in other regions of the Gulf of Mexico.

4.3 *Results and Interpretation*

For the interpretation and picking of the seabed, conductors and basement horizons, the post-processed migrated volume was analysed using the OpendTect software. Initial interpretation began with the seabed, where a grid was generated using the inline/crossline data. Each grid line was tracked along the seabed horizon, appearing as a continuous bright reflector within the data (Figure 8). A similar approach was used to construct a series of grid lines, representing the basement surface. Once completed, a gridding technique was applied using an inverse distance weighted algorithm. The grids were filtered and smoothed using an average-type weighting scheme and the 3-D horizon surfaces were created.

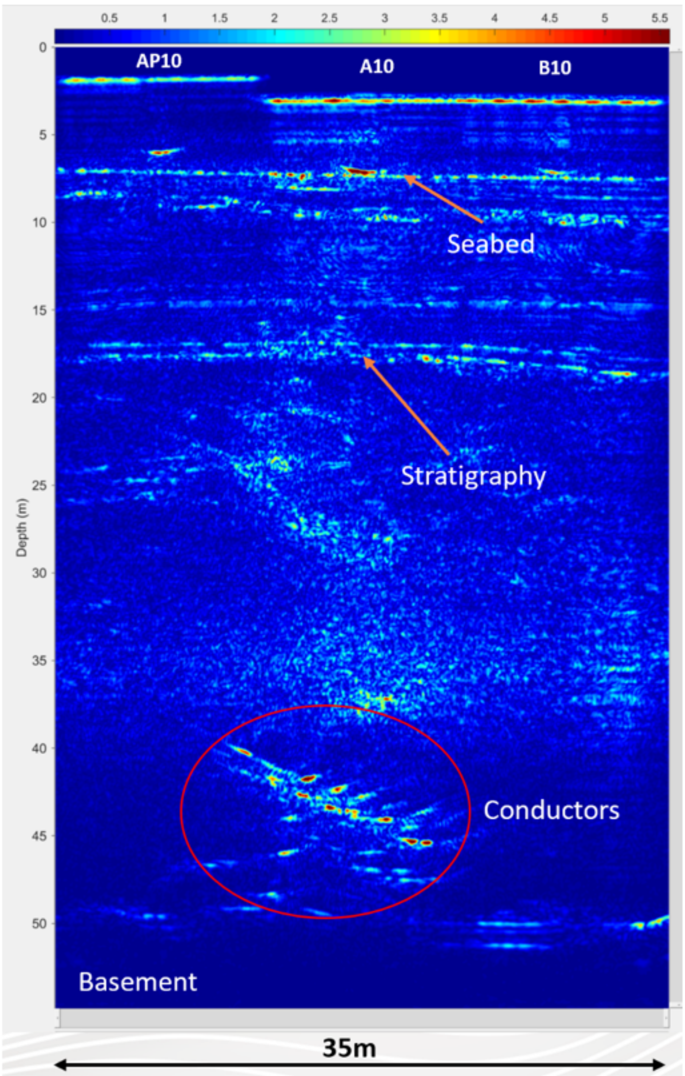

Figure 8: Vertical section across Row 10 (Line B-B' in Figure 7) showcasing seabed, stratigraphy, and conductor reflectors.

The conductors were evaluated in cross-section (inline) view, tracking the bulls-eye response of each feature along the unified dataset (Figure 8). A location point was marked for every visible conductor at each inline interval. This procedure was repeated throughout the migrated volume until the full extent of each conductor had been identified. A total of 18 conductors were interpreted, comprising a digitisation of approximately 40–50 location points per conductor. The 18 conductors and the inferred seabed and basement horizons were then imported into EIVA's NaviModel visualisation software for further analysis (Figure 9).

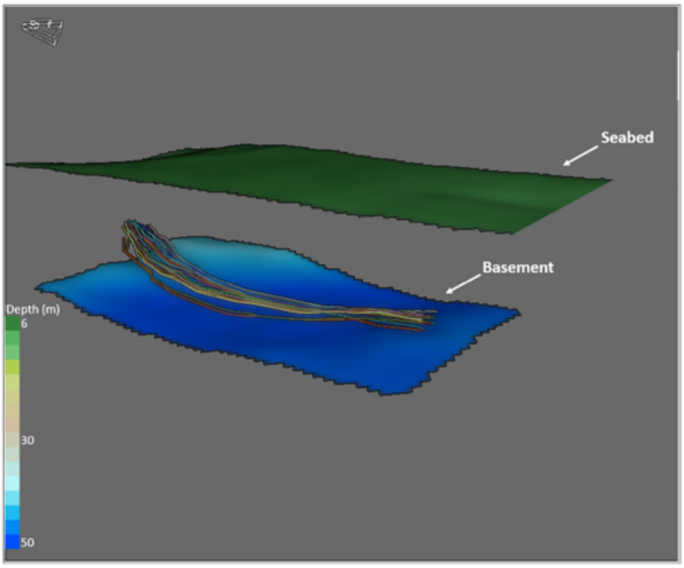

Figure 9: NaviModel 3-D visualization of the inferred seabed, basement and 18 conductor bundle

The AC data sets accurately captured both the specular returning sedimentary signals and the non-specular returns of the conductors. They delivered a volumetric image of the conductors' presence characterising their depth, shape, size, and form.

In the upper region of the sub-seabed, namely the upper 18m, the composition is characterised by an unconsolidated chaotic nature, at times blocky, associated with a flow event. Clay-based linear diffractors are present within a weak non-cohesive sediment matrix in this region.

The conductors appear as a bundle primarily in Lines AP and A running NW-SE where an apparent, abrupt termination is observed (Figure 10). These conductors are found at depths between 27.7–48.1m, with the greatest concentration appearing between 39.6–47.2m. The shallowest conductor appears at 27.7m trending downwards from the toppled jacket (Figure 11). The cross-sectional analysis of the conductor bundle (Figure 10) positively identified 18 individual conductors (Figure 11). By migrating all the cores together, the spatial resolution was improved. This provided additional clarity on the continuity of the conductors and enabled discrimination with a high degree of confidence.

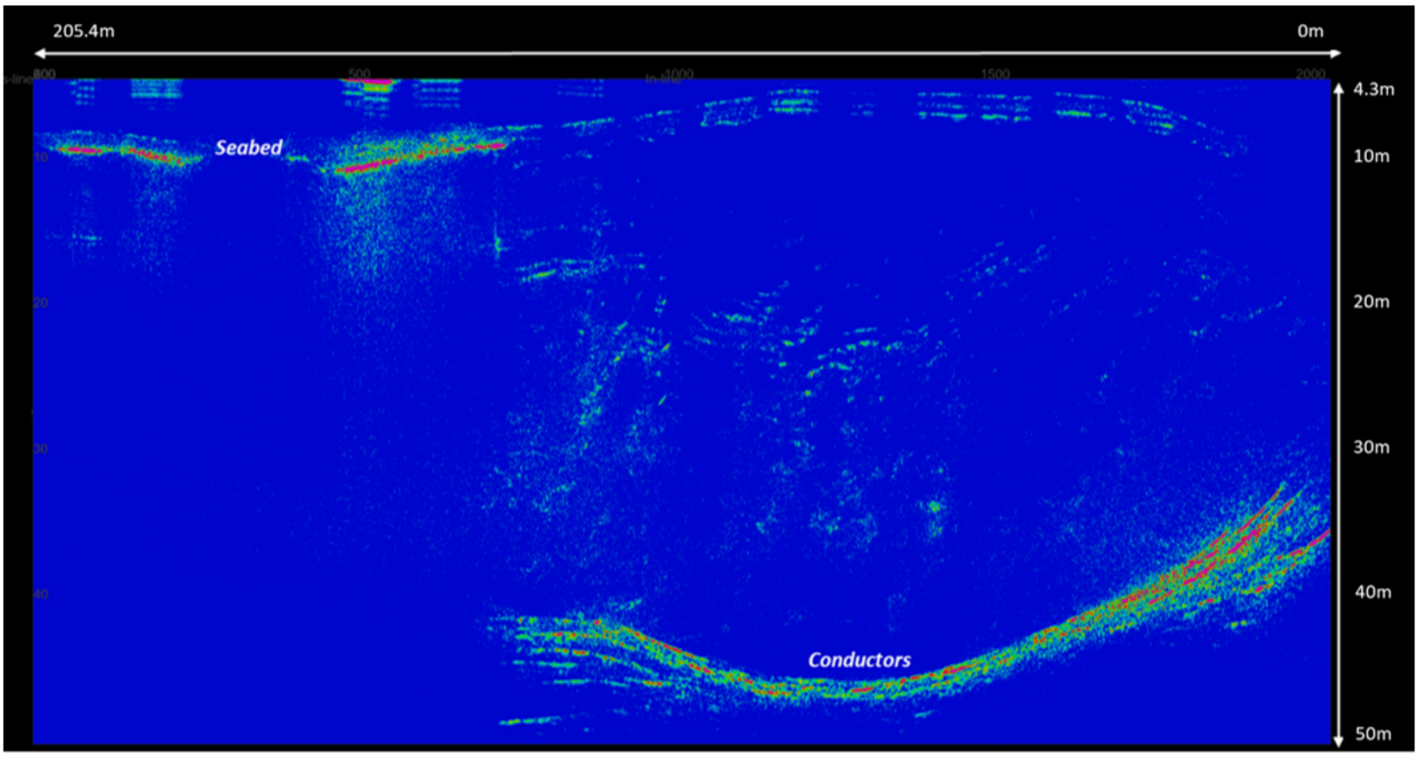

Figure 10: Crossline 335 (Line A-A' in Figure 7) of the unified migrated volume highlighting important features of interest

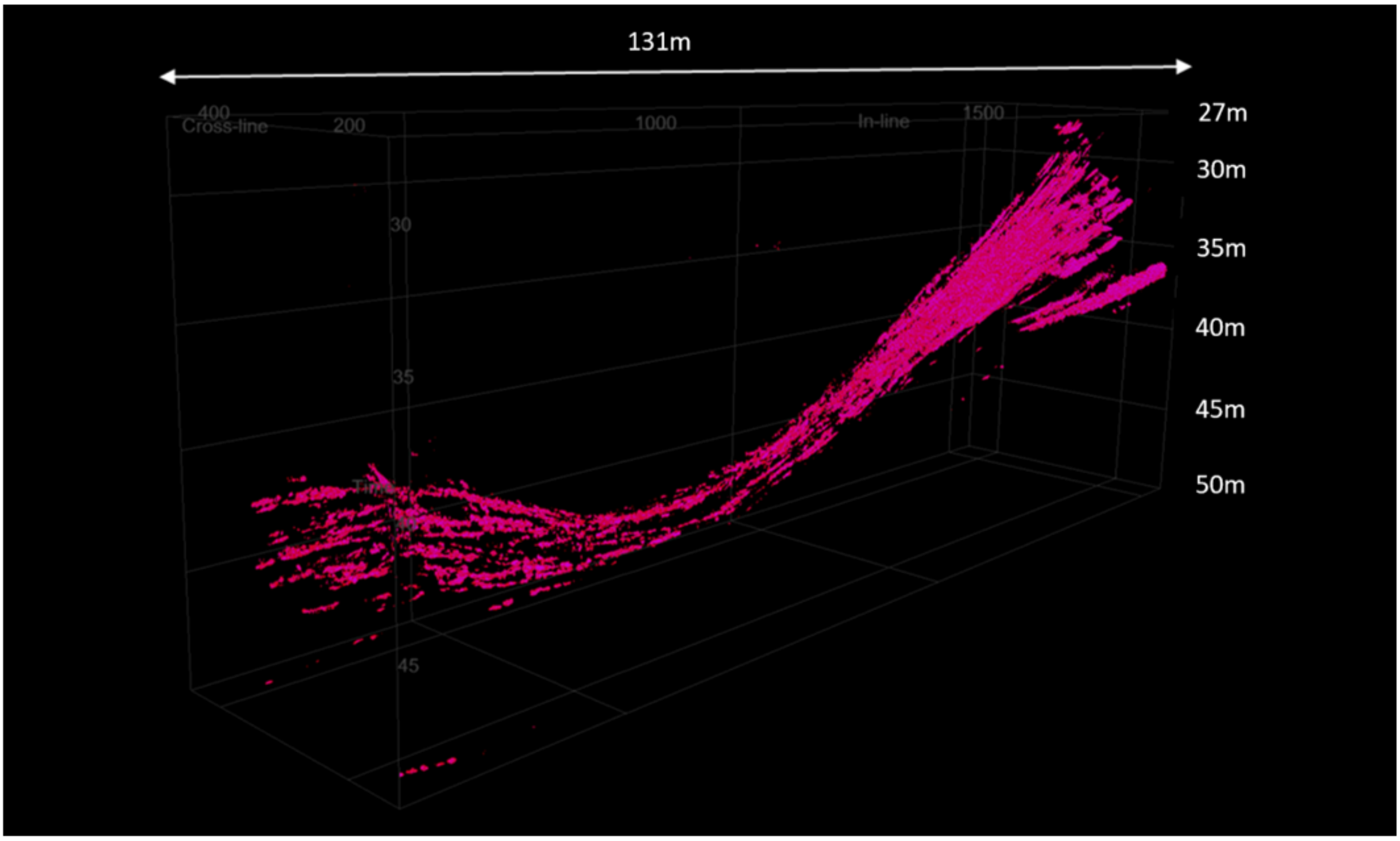

Figure 11: Identified conductors as seen in the unified migrated volume

5 Conclusions

The increase in development of offshore windfarms in complex seabeds has led to greater risks during foundation installation. The AC mitigates those risks by identifying geohazards pre-installation, thus providing confidence in foundation design and placement. Similarly, the growing number of producing hydrocarbon fields creates an increased risk of oil spills and the need for remediation. The AC can assist in identifying the infrastructure and associated characteristics that may have led to the oil spill.
As shown throughout this paper, the AC technology has been successful at detecting and imaging buried boulders and conductor pipes, particularly through the advanced resolution and interpretation footprint achieved in merging and migrating the individual cores into a single unified volume. Herein, the high confidence set of deliverables from the AC allowed the respective clients to move forward with their development and remediation plans.

6 Acknowledgements

The authors would like to thank the offshore Geoscientists and Operations team of Kraken Robotics for the collection and initial handling of these data sets. Additional thank you to Dillon Hoffmann and Kevin Kennelley of Couvillion Group for their support throughout the Gulf of Mexico campaign.

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