Near Surface Sub-Seabed Boulder Detection Using a 3D Acoustic Profiler

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ABSTRACT: In 2021, Kraken Robotics (formerly PanGeo Subsea) was contracted to conduct a Sub-Bottom Imager (SBI) survey to support a harbour deepening campaign. To perform the dredging safely and effectively in the harbour, all subsea boulders and other obstructions must be identified to minimise the risk of impeding the operation or damaging the dredging equipment. The SBI data was acquired to support the bathymetry data within the channel approach and inner harbour in areas where water depth was recorded under 16 m. Since the channel deepening campaign will dredge up to 2 m below the seabed, the bathymetry data alone is insufficient to identify boulders that lie below the seabed, which introduces a danger of potentially excluding a significant number of obstructions. Data interpretations were performed in four sections based on a priority system, and approximately 36,600 discrete anomalies were interpreted. Using GIS techniques, 11 “blocks” of dense boulder accumulations, >100 boulders per ha at 3 m depth of burial (30,000 m³), were analysed.

1 Introduction

Boulders and other obstructions in the shallow subsurface can cause challenges to offshore dredging operations. Dredging the seabed is a common technique to maintain or increase the depth of navigational channels to accommodate larger vessels and ensure safe passage. In addition, with larger ships carrying the bulk of goods imported and exported, dredging is essential in today’s economy. However, as per Hosier (2016), obstructions such as bedrock, debris, or underwater structures, can cause deviations in the dredge path and limit the ability to control sediment re-suspension, negatively affecting the performance of the dredging operation. To detect obstructions on the seabed, initially bathymetry data was acquired and processed, however as per Kozaczka (2013), classic hydroacoustic devices such as side scan sonar and multibeam echosounder proved to be ineffective at detecting objects buried below the seabed.

This paper aims to illustrate the importance of 3D acoustic profiler data to support offshore dredging operations and how to effectively communicate the interpretations made.

This paper will briefly outline the equipment and calibrations, then go onto an extensive review of Subbottom Imager (SBI) data, quality control, interpretation, and reporting techniques for the acoustic profiler data and how it is used to support decisions and operations in offshore dredging campaigns. Due to the sensitivity of the project the survey area and the end client will not be mentioned.

2 Equipment & System Verification

2.1 *Equipment*

Figure 1. SBI system mounted to the SeaKite platform on the back deck of a vessel.

Kraken Robotic’s (formerly PanGeo Subsea) SBI was mounted to an EIVA platform called the SeaKite, as presented in Figure 1. The SBI system consists of five hydrophones, each containing eight channels (40 channels in total) and 3 Neptune parametric projectors, and the appropriate subsea and topside equipment. In addition, to support the functions of the SBI, several other sensors were mounted to the platform, including:

- Intelligent Pressure Sensor (IPS);
- Sound Velocity Sensor (SVS);
- Inertial Navigation System (INS);
- Ultra-Short Baseline (USBL) receiver; and
- Doppler Velocity Log (DVL).

2.2 *System Verification*

The system verification is known internally as the SBI acceptance test. The SBI acceptance test starts with deck, and wet tests, completed before the positional verification is performed. The purpose behind the deck and wet tests are to ensure the SBI is performing to the project-specific settings. The frequency range of the SBI is similar to that of other industry standard sub-bottom profilers (SBP) allowing the SBI's signal to penetrate the seafloor. The typical SBI settings are presented in Table 1.

Table 1. SBI Data Acquisition Parameters

Setting	Value
Sampling Rate	50 kHz
Pulse Repetition Frequency	45 Hz
Record Length	800 samples
Frequency Range	4.5 kHz to 12 kHz
Pulse Length	4.5 ms
Pulse Taper	0.5 ms

Once the functionality of the SBI is confirmed, the positional verification test can be performed. The positional verification test aims to ensure that the interface with the survey team is functioning and that offsets have been measured and implemented correctly. The positional verification test involves the collection of five datasets over the SBI acceptance frame, presented in Figure 2. The SBI acceptance frame has a USBL mounted to the disk on the left of the frame, and offsets from the beacon to each disk are accounted for. All five lines of SBI data are interpreted to ensure that the target appears in the same position measured from the USBL position, as shown in Figure 3. Once all the above procedures were performed and the results calculated and confirmed as passed, the SBI system was ready to start the survey.

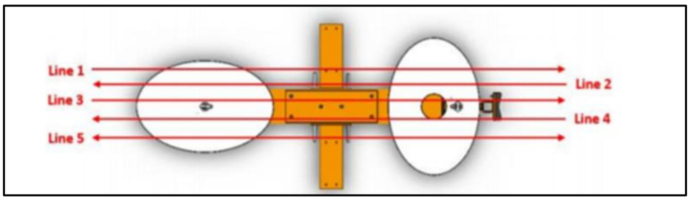

Figure 2. Plan view image of the SBI acceptance frame and the line plan for the positional verification test.

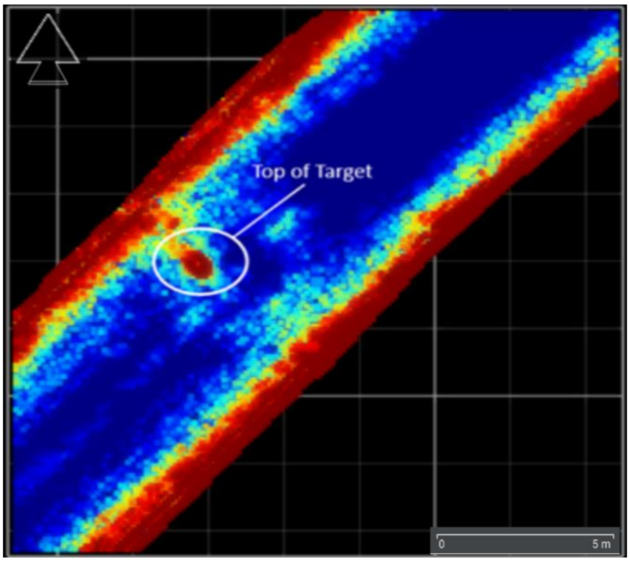

Figure 4. Plan view image of the SBI acceptance frame in SBI data.

2.3 *Velocity Analysis*

The final step before the survey begins is to determine the velocity of the shallow soils to convert from two-way travel time to depth. Using an in house software, called Zoomspace^{TM}, this allows semblance to be performed on segy data sets in the 2D velocity analysis. Using the 2D velocity analysis tool, presented in Figure 4, the interval velocity can be determined for the shallow soils while the water velocity is determined from the sound velocity profiler (SVP), These velocities are then input into the SBI data renderer to be visualized by the geoscientist.

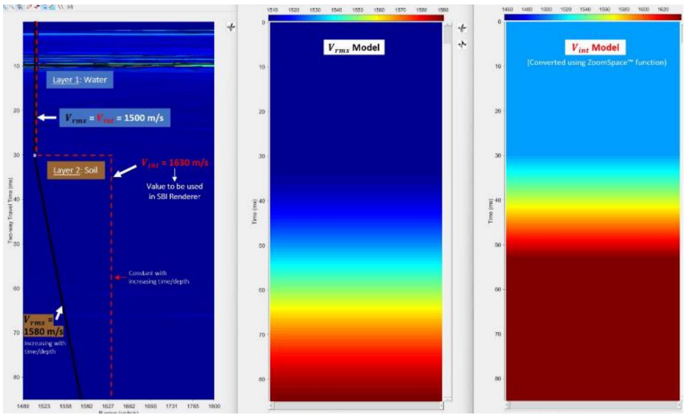

Figure 3. 2D Semblance window in Zoomspace.

3 Survey Methodology

The SBI is one example of a 3D acoustic profiler that can resolve buried features with a high acoustic impedance, such as a boulder. The SBI uses synthetic aperture sonar (SAS) and beam forming technology to better visualize anomalies in the along and across track views, respectively, which produces a 7 m wide data swath that can visualize variations in acoustic impedance up to 5 m below the seabed. The SBI data undergoes quality control and various stages of interpretation and reporting.

3.1 *Quality Checks*

The offshore team follows a rigorous QC process to ensure data is suitable for interpretation. The quality assurance starts during acquisition, where the INS system is interfaced with Kraken's data acquisition software so that the Technician can observe the stability parameters and make sure the SBI system is within the set platform stability range, which is presented in Table 2. In addition to viewing the data from the INS system, the data is also viewed in EIVA NaviModel to conduct a secondary check of the data.

Table 2. Regular SBI Stability Guidelines.

Parameter	Optimal Range
Fly height	3.5 ± 0.5 m
Fly height variation	< 0.6 m over a 3.5 m distance travelled
SeaKite Forward speed	>3 knots
Station Keeping	± 0.5 m of the intended survey line
Pitch	± 5 degrees
Roll	± 8 degrees
Pitch Variation	< 5 degrees over a 3.5 m distance travelled
Roll Variation	< 5 degrees over a 3.5 m distance travelled
Surge	± 0.5 m
Sway	± 0.5 m
Heading (crabbing)	± 15 degrees

After the platform stability is deemed acceptable, the data coverage of good quality data is confirmed using an in-house GIS plugin, which plots the swath width as a function of fly height. For this project, SBI data coverage requirements were 100% in the designated survey area to identify buried discrete anomalies.

3.2 *Data Interpretation*

The SBI data interpretation is broken down into two parts to represent the discrete anomalies found effectively. The two parts of the SBI data interpretation are:

- Individual discrete anomalies; and
- Dense accumulations of discrete anomalies.

All variations of the SBI data took place in EIVA NaviModel.

3.2.1 *Individual Discrete Anomaly Interpretation*

The individual discrete anomalies were interpreted in NaviModel using the "Eventing Tool" feature. The eventing tool is an interpretation tool which allows the user to enclose an anomaly in a polygon and extract the information on the anomaly based on the location and shape of the acoustic response. In addition, each reported anomaly required reporting of the X-Y position, burial depth and effective diameter.

The discrete anomaly X-Y position is taken from the centre of the polygon in the project geodesy. Since the anomalies are initially reported in raw depth from the pressure sensor, the burial depth is calculated with the tool "Subtract DTM from Depth," which requires a bathymetric surface in the form of a Digital Terrain Model (DTM). To use this feature, SBI data must already be converted to the same vertical datum as the DTM otherwise; the calculation will present inaccurate values. The measurement of each discrete anomaly's effective diameter (longest dimension) was classified using the standards shown below in Table 3. To standardise the measurements of discrete anomalies, a 6 dB approach is used to narrow the gain window to calculate the diameter of the feature accurately. The difference between the average gain for interpretation and the 6 dB gain for measuring the effective diameter is presented in Figure 6. The 6 dB method has been developed from previous survey experience and has been shown to provide reliable discrete anomaly measurement results in shallow soils.

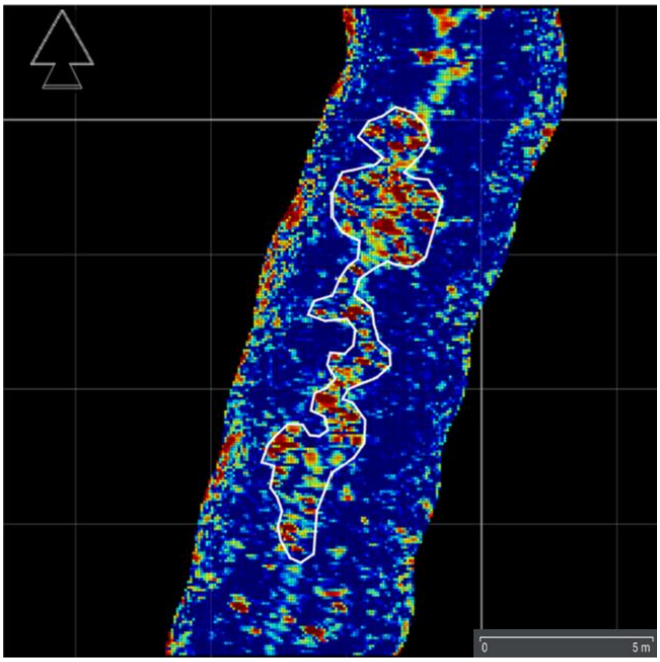

Figure 5. Anomaly cluster in SBI data enclosed in a polygon.

Table 3 - Size Classification for Effective diameter of Acoustic Anomalies.

Size Classification	Size Range
A	0.4m-1.0m
B	1.1m – 1.5m
C	1.6m – 2.0m
D	2.1m – 3.0m
E	3.1m – 4.0m
F	>4.0m

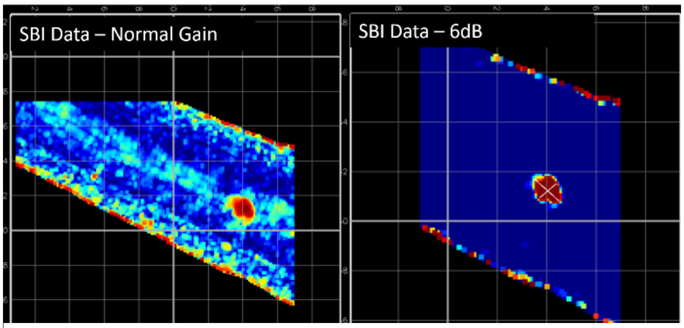

Figure 6. SBI discrete anomaly in 'normal' gain range and 6dB gain.

The eventing tool output can be customised to export a .csv file containing information such as Easting (m), Northing (m) and absolute depth in the set geodesy for each interpreted discrete anomaly. The exported .csv files are easily imported as shapefiles into GIS software packages for QC purposes and charting.

3.2.2 *Anomaly Cluster Interpretation*

Anomaly cluster interpretation is a technique used to interpret areas of dense anomaly accumulations where it is not feasible to differentiate between individual discrete anomalies. Areas which contain dense anomaly accumulations typically relate to boulder-bearing units such as glacial deposits related to outwash, traction till, and fluvial depositional environments. An example of an area of dense anomaly accumulations in SBI data is presented in Figure 5.

The polygons that digitize areas of dense anomaly accumulations contain geodetic information for the polygon's vertices along with the absolute depth.

The interpretation techniques stated in Section 3.2 are suitable for most SBI scopes such as Unexploded Ordnance (UXO) and decommissioning surveys. However, for sub-seabed boulder surveys to support dredging campaigns, additional, more complex deliverables are required to communicate the characterisation of the sub-seabed conditions effectively. To communicate the deliverables more meaningfully, a workflow was produced in a GIS software package to develop a sub-seabed boulder density map, like the one presented in Figure 7. A sub-seabed boulder density map illustrates the concentration of boulders per volume measure; this can be set to dredging equipment limitations or other specifications from the end user. An example of specific boulder density parameters is provided in Table 4.

Table 4. Anomaly Density Classification.

Ranking	
Low	<50 boulders per block
Medium	50-100 boulders per block
High	>100 boulders per block

Generating a boulder density map follows a 9-step process requiring several tools in a GIS software package and the in-house GIS coverage tool plugin. The nine steps for the generation of a boulder density are:

- Load in the 1x Coverage output from the SBI coverage tool to show where 100% data coverage exists.
- Subtract the exclusion zones from the data coverage so that these areas are not included in the volume calculation.
- Break the coverage plot into a unique 100 m x 100 m grid. This cell size can be adjusted to end-user specifications.
- Clip the grid to the coverage plot. Each 100 m x 100 m square in the survey area has a unique ID in the attribute table.
- Use the field calculator to add a column and calculate the area (m^2)
- Add a column for the signal penetration depth; for this example, a constant depth of signal penetration 3 m below the seabed is assumed.
- Multiply the penetration depth by the area to get the volume of each 100 m x 100 m square.
- Run the “Count Points in Polygon” tool to calculate the number of discrete anomalies within 100 m x 100 m squares.
- The field calculator calculates the average anomaly density for each block. Conditional polygon symbology set to colour was based on the density classification presented in Table 4 provided by the end user.

Many of the above options are set to client-specific standards such as grid size, depth of signal penetration, and rule-based colour coding. These parameters can be adjusted in a GIS software package to fit specific parameters of dredging equipment, project parameters, or end-user specifications.

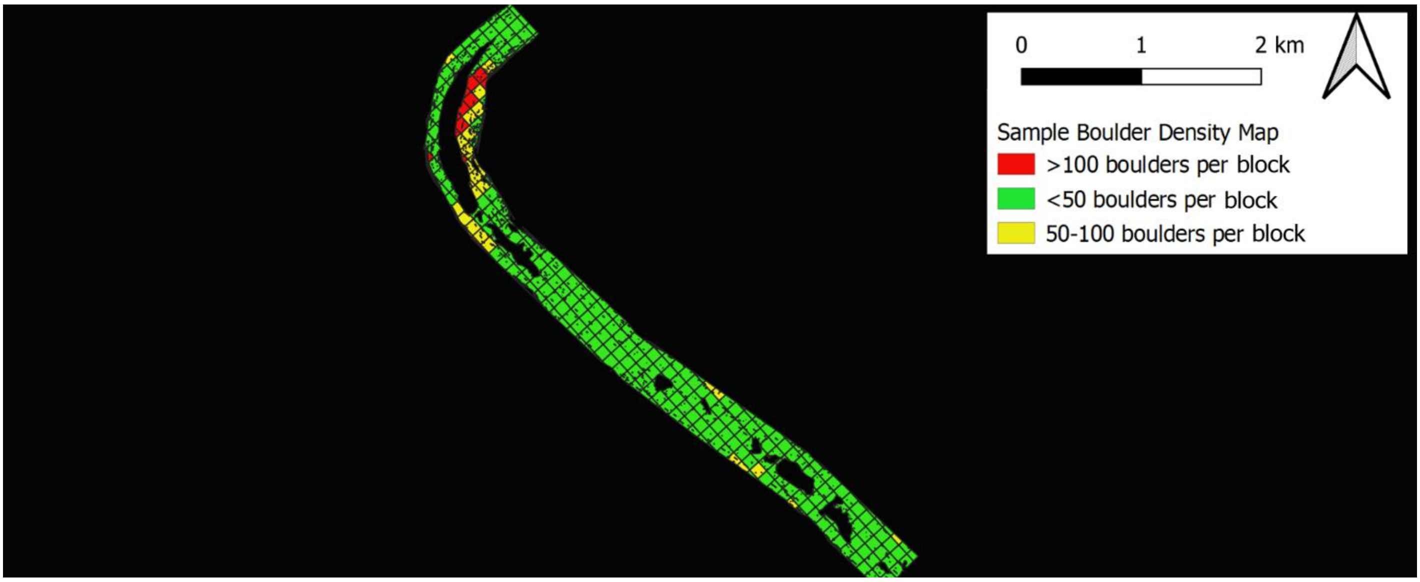

Figure 7. Sample of the boulder density map produced using the specified parameters for the project.

4 Results

The deliverables included results from the individual discrete anomalies, areas of dense anomaly accumulations and the boulder density map. Approximately 36,600 discrete anomalies were interpreted within the 18 km^2 survey area.

The distribution of the burial depth for the discrete anomalies can be found in Table 5.

Table 5. Acoustic anomaly depth of burial summary.

Depth of Burial (m)	Quantity
0 – 0.5	19752
0.5 – 1.0	8690
1.0 – 1.5	5369
1.5 – 2.0	1998
2.0 – 2.5	593
> 2.5	222

The distribution of the discrete anomaly effective diameters can be observed in Table 6. While the shape of each discrete anomaly was not a formal deliverable for the project, Geoscientists noted that the discrete anomalies were linear or irregular in form, which is more indicative of manmade debris as opposed to boulders.

Table 6. Acoustic Anomaly effective diameter summary.

Size Range (m)	Quantity
0.4 – 1.0	22804
1.1 – 1.5	7997
1.6 – 2.0	3094
2.1 – 3.0	1653
3,1 – 4.0	529
> 4.0	547

Results of the areas of dense anomaly accumulations interpretation included the delivery of all polygons in the form of ESRI shapefiles. In total 1,427 areas were reported within the SBI data indicating the presence of glacial deposits.

The final deliverable was the boulder density map, conditioned to display the classification shown in Table 4; the breakdown of the classification results is presented in Table 7.

Table 7. Anomaly Density Summary

Size Range (m)	Quantity
Low	754
Medium	47
High	11

The data interpretation results identified discrete anomalies indicative of boulders and areas of dense anomaly accumulation. All the above indicate regions and features that would impact dredging progress by either slowing down or damaging the equipment.

5 Discussion

The SBI data interpretation revealed many discrete anomalies, which were used to determine the density of anomalies in locations throughout the survey area. As presented in Table 5, most discrete anomalies are of shallow burial. However, only 12% of the discrete anomalies were located on the seabed, which was detected using traditional bathymetric survey equipment. Therefore, even when discrete anomalies are identified on the seabed, the dimensions may need to be accurately determined from not just bathymetry data alone. For example, in Figure 8 a boulder is identified on the seabed; however, in Figure 9, a profile view of the same discrete anomaly in the SBI data shows that it is much larger in size below the seabed, which could be classed as a more significant obstruction than previously thought with the bathymetry data alone.

With such a high number of discrete anomalies interpreted, it is essential to ensure that deliverables provide a detailed characterisation of the subsurface so that the end user can effectively make decisions based on the results of the interpretations. For example, the boulder density map can be tailored, as it was for this project, to highlight areas that may impede dredging operations or damage the equipment itself.

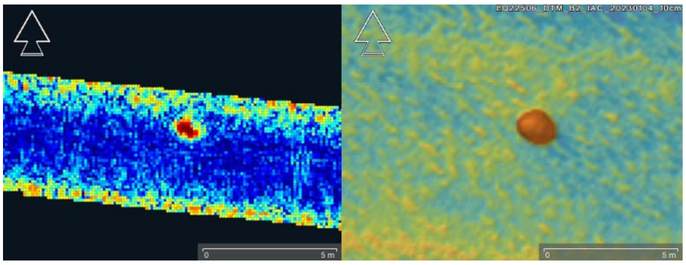

Figure 8. Interpreted boulder on the seabed in the SBI data (left) and bathymetry data (right).

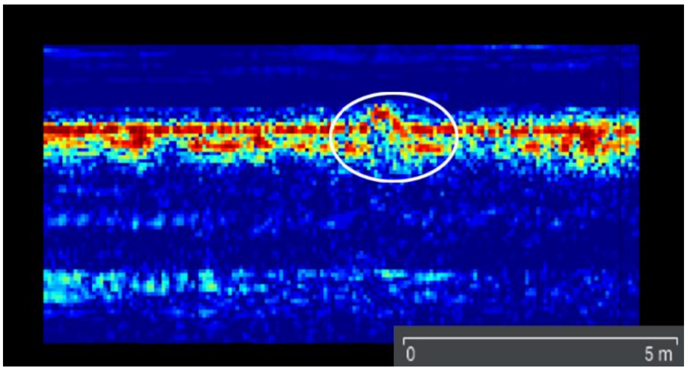

Figure 9. Profile view of anomaly imaged above in Figure 7.

As stated by Notteboom et al. (2022), the dredged material can vary greatly (peat and organic soils, cobbles, clays, boulders, silts, broken rock, sands, rock, and gravels, cemented soils and corals) and understanding what obstructions the shallow soils contain can help in planning. When areas of numerous discrete anomalies interpreted to be sub-seabed boulders, coupled with known boulder-bearing shallow soil units, are characterised, end users can make informed decisions on which dredging techniques are most suitable. Dredging can be performed by four primary methods, which include:

- Mechanical Dredging;
- Hydraulic Dredging;
- Hydraulic/Mechanical Dredging; and
- Hydrodynamic Dredging.

The scope of this SBI campaign was a sub-seabed boulder survey. However, the discrete anomaly listing included discrete anomalies with an effective diameter of 0.4 m or more significant. In addition, many discrete anomalies had an irregular or linear shape, which is not typical of boulders. Therefore, they were interpreted as artificial debris, and according to a study published by the government of Canada and written by Han et al. (2019) stated that 21% of debris on the seabed found within harbours is metal debris, including household debris appliances, cans, vehicle parts, and fishing gear. With the acoustic characterisation of the subsurface, objects in the shallow soils with a higher acoustic impedance than the surrounding sediment and within the resolution constraints will likely be detected by a 3D acoustic profiler and reported if the size criteria are met. While the survey was a sub-seabed boulder survey, the SBI was also influential in locating other objects which could impede dredging.

Including other available geophysical and geotechnical datasets can improve confidence in the SBI interpretation through data and interpretation integration. This survey used a 100% data coverage methodology; however, utilising a 200% data coverage methodology enables a discrete anomaly to be checked for repeatability on adjacent datasets, meaning all discrete anomalies are verified. This process can potentially reduce the number of discrete anomalies reported as “false positives.” The differences between 100% and 200% data coverage surveys are a decision to be made by the end-user based on the quality of deliverables versus the cost, as 200% coverage surveys have a denser line spacing, therefore increasing survey and interpretation time. Integrating magnetometer data with SBI data enables sub-seabed boulders and buried ferrous metal objects to be characterised, as you would expect a ferrous metal object to produce a magnetic anomaly. The SBI detects variations in acoustic impedance. However, it cannot differentiate between sub-seabed boulders and ferrous metal objects. As presented in Figure 10, UXOs can take on spherical and elliptical shapes, making them impossible to distinguish in the SBI data.

Figure 10. UXOs recovered before the dredging campaign.

Future projects would benefit from simultaneous magnetic data collection in the gradiometer setup flying from the aft of the SeaKite. With magnetic data, the SBI data can differentiate between sub-seabed boulders and UXOs with higher confidence. As an example, the North and Baltic Seas have a known presence of UXOs. As stated by Kölbel et al. (2015), UXO preparation is part of risk assessment for dredging projects. To avoid unexpected UXOs, a thorough and professional investigation of the given area is recommended. The confidence in SBI boulder interpretation would also benefit from analyzing the ground-truthed results, if they could be provided. Ground truthing data has been provided in the past for UXO campaigns, which has been used to establish a confidence ranking scheme for interpretation. With sufficient ground thruthing data, boulder interpretations made with the SBI would have improved confidence.

While the SBI survey discussed was limited by 100% data coverage and the lack of available supporting data to integrate with the SBI data for anomaly differentiation, the SBI data still was an effective method for characterising the subsurface to support dredging operations. For example, the location of discrete anomalies such as boulders and man-made debris can highlight obstructions to help end users make informed decisions before dredging.

6 Conclusion

Before dredging operations commence, it is essential to consider surface features and accurately characterise the subsurface. Outside of the SBI, other systems such as 3D chirp and 3D ultra-high resolution (UHR) seismic solutions can be used as long as resolution requirements are adequate. The SBI data interpretation revealed approximately 36,600 discrete anomalies and 11 sites containing a high concentration of discrete anomalies, including interpretations of sub-seabed boulders and man-made debris. While ~36,600 discrete anomalies were identified, less than ~4,600 were located on the seabed, leaving over ~32,000 acoustic anomalies left unidentified when using only bathymetric data. By performing 3D acoustic surveys to characterise the shallow soils, informed decisions can be made on dredging operations and which equipment will fit the specifications effectively. With an understanding of what obstructions are present in the shallow soils and using the appropriate equipment, dredging operations can be performed with fewer delays and in a more cost-efficient manner. To further support dredging projects, magnetometers mounted to an acoustic profiler to help differentiate between boulders and ferrous metal debris and potential UXOs will bring more value to the interpretation and enhance the safety and cost efficiency of dredging campaigns.

7 References

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