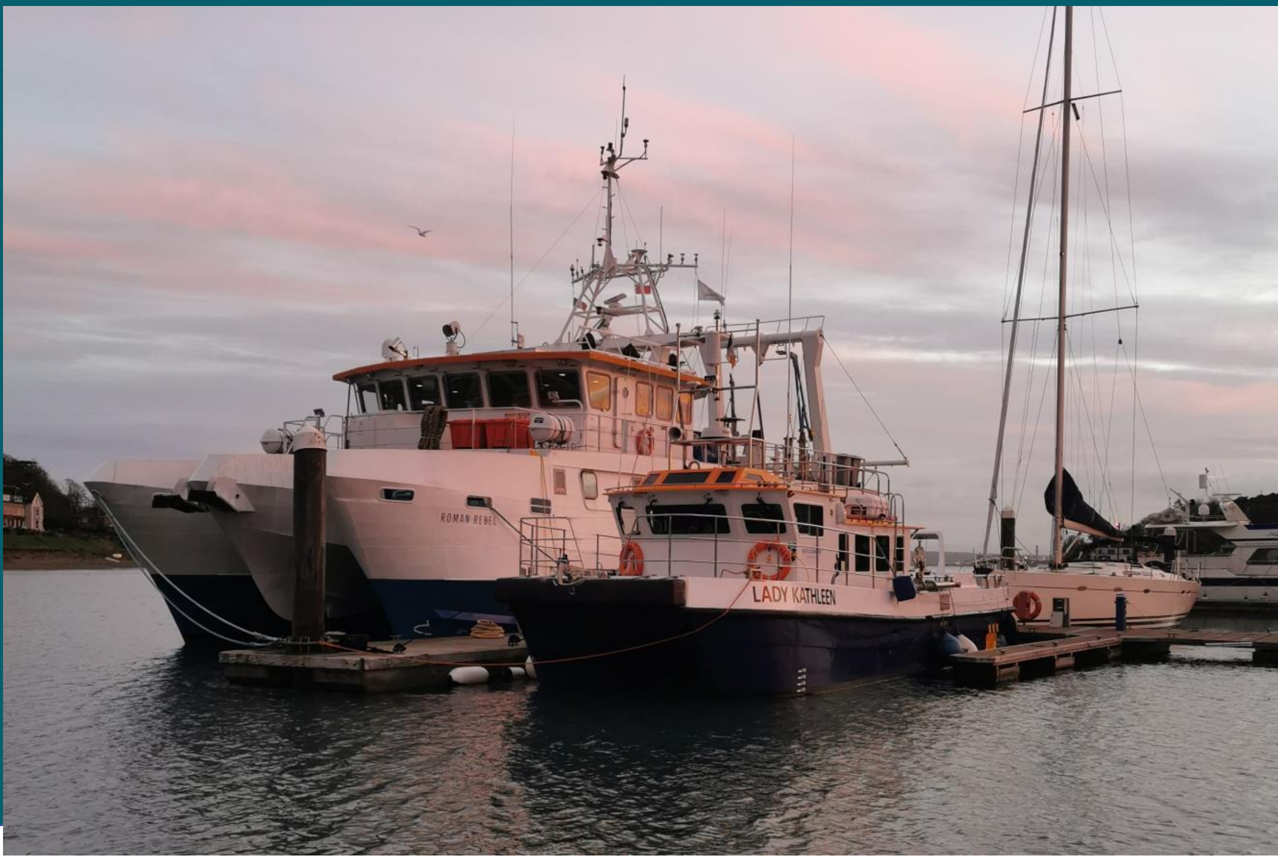
Processing Report

SSE Arklow Bank

GR-GEO-REP-24G02

Confidential - Draft prepared for Client review



Prepared for:

sse

GREEN REBEL

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Executive Summary

Green Rebel Ltd was contracted by SSE Renewables (referred to herein as 'the client') to complete a geophysical and hydrographic investigation at Arklow Bank, in the Irish Sea, approx. 10 km East of Arklow Town, Co. Wicklow. The investigation consisted of the acquisition of Multibeam Bathymetry, Sub-Bottom Profiler, and 3D Multichannel ultra-high resolution seismic (UHRS) data. This report outlines the processing and interpretation of multibeam bathymetry. The site was surveyed by two of Green Rebels vessels, the Roman Rebel (27.5m catamaran purposed built survey vessel) and the Lady Kathleen (14m shallow draft catamaran purposed built survey vessel). The purpose of the investigation is to underpin and support the development potential windfarm array site:

- The identification and mapping of potential geohazards.
- The facilitation of the development of a ground model.
- The provision of data and information to inform Cable Burial Risk Assessment (CBRA).

To this end, the Roman Rebel commenced geophysical and hydrographic survey operations after mobilisation, calibrations and sea trials on the 7th of July 2024. Arklow Bank Roman Rebel survey operations, before demobilisation were completed on the 3rd of August 2024. The Lady Kathleen commenced geophysical and hydrographic survey operations after mobilisation, calibrations and sea trials on the 13th of July 2024. Arklow Bank Lady Kathleen survey operations, before demobilisation were completed on the 5th of August 2024. Data were processed, analysed, and interpreted; the results are presented herein.

This report presents background information that includes a summary of the Arklow Bank project objectives and variations from the scope of work. Following this, the acquisition and subsequent processing steps for each multibeam bathymetry are described. Finally, the results of the data analyses are documented.

Note: This report is to be treated separately to the pending 3D UHRS Processing and Interpretation report from the project sub-contractor GeoSurveys.

Table of Contents

Definitions, Symbols and Abbreviations

AOI	***Area Of Interest***
CTI	Chesapeake Technology International
DEM	Digital Elevation Model
DoD	DEM of Difference
WGS84	World Geodetic System 1984
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Geographic Positioning System
IHO	International Hydrographic Organization
LAT	Lowest Astronomical Tide
MAG	Magnetometer
MBES	Multibeam Echosounder
NaN	Not a Number
QC	Quality Control
QINSy	Quality Integrated Navigation System
SBP	Sub-bottom Profiler
SoW	Scope of Works
SSS	Side-scan sonar
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty
USBL	Ultra-short Baseline
UXO	Unexploded Ordnance
VORF	Vertical Offshore Reference System

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1 Introduction

Green Rebel acquired data for the Arklow Bank project in one phase. The geophysical survey consisted of multibeam bathymetry, sub-bottom profiler, and 3D ultra-high resolution seismic (UHRS) data acquisition, surveyed by the Roman Rebel and Lady Kathleen. The survey was carried out between the 7th of July and 5th of August 2024. The survey mobilised and departed from Cork, Ireland and sea trials began on 5th of July for the Roman Rebel and 10th of July for the Lady Kathleen. Survey demobilisation finalised on the 5th of August at Dun Laoghaire harbour, Dublin, Ireland.

During Arklow Bank geophysical survey, a total length of 808.44 km was surveyed including infills and reruns, of which the Roman Rebel acquired 715.1 km and the Lady Kathleen acquired 93.4 km. The survey area is approximately 64.7 km^2. Approximately 3.198 TB of hydrographic and SBP data were acquired during the full survey.

1.1 Survey objectives and Scope of Work

Table 1: List of main data deliverables (Additional deliverables specified in the data matrix)

Type	*Description*	*Resolution (m)*	*File*
MBES Processing project	Generated in QPS Qimera v. 2.6.2	NA	Folder structure
Positioning Navigation	Corrected navigation files – vessel tracklines	NA	*.shp,
Bathymetric soundings	Cleaned and corrected to LAT. Ungridded.	NA	*.geotiff, *.csv (xyz)
Bathymetric DEM LAT datum	Digital Elevation Model Reduced to LAT	0.25 m, 1 m	*.geotiff, *.csv (xyz)
Bathymetric contours LAT datum	Contour interval of 1 m	NA	*.shp
Total Vertical and Horizontal Uncertainty Surfaces (TVU and THU)	Covering the entire survey grid	1 m	*.geotiff, *.csv (xyz)
Bathymetric derivatives	Micro-elevation, gradient, multidirectional hillshade, roughness	0.25 m	*.geotiff ,*.txt (xyz)

Type	Description	Resolution (m)	File
Daily bathymetric DEM(s)	Digital Elevation Models reduced to LAT and created for each survey day	0.25 m	*.geotiff
Sub-Bottom Profiler Raw Data	Raw SBP SEGY data	NA	*.sgy

1.2 Variations from the SoW

Table 2: Summary of variations from the SoW

Reference Number	Description	Cause
Var – 001	Acquisition of Raw SBP data – no processing	To gather more near surface seismic data while acquiring MBES and 2D M-UHRS
Additional data deliverable request	Creation of daily .geotiff of MBES DEM data	To understand sediment mobility and migration between survey days

1.3 Reference Documents

Table 3: Summary of referenced documents

File name	Title	Author
BK-SSE-000-GEP-SPF-0004	Arklow Bank UHR Seismic Geophysical Survey 2024	SSE
BK-SSE-000-GEP-SOW-0003	Arklow Bank 2D UHR Seismic Geophysical Survey 2024	SSE
GRM_24G03_RR_SSE	Arklow Bank Ops Report	Green Rebel

1.4 Summary of Findings

Table 4: Summary of findings, including metadata, quality, results, interpretations, and potential hazards.

Acquisition	
Survey Dates: 1st of March to 28th of April 2024	
Geophysical systems used: Two hull-mounted Reson SeaBat T50-R multibeam echosounders (Roman Rebel); single-head, hull-mounted Reson SeaBat T50-R (Lady Kathleen)	
Bathymetry	
Complex bathymetric relief related to a dynamic sand bank geomorphology	Depth range (mLAT): -9.79 to -51.04
Seafloor Morphology	
Medium and large sandwaves, sand bank geomorphology	
Seafloor sediments	
Not assessed (not in the SoW)	
Seabed Targets and Potential Site Specific Hazards	
No side scan data acquired for waterfall picking.	
Geological Features	
Banks, seafloor sedimentary features (bedforms): medium and large sandwaves	
Potential Hazards	
Steep gradients	Associated with medium/large sandwaves and sand bank geomorphology
Boulders	Fields of boulders and individual boulders present and delineated as point contact shapefiles
Mobile sediments	High sediment mobility observed, sandwave migration observed in between survey lines

2 Data Acquisition and Processing

2.1 Surface and subsurface positioning

2.1.1 Surface positioning

2.1.1.1 Roman Rebel

All survey positioning and navigation data were recorded via a primary and independent secondary GNSS antenna for redundancy and QC. The primary antenna used was an Oceaneering C-Nav 3050 receiver which used Precise Point Positioning (PPP) via C-NavC2 corrections to achieve 5 cm horizontal and 20 cm vertical accuracy. PPP is a global precise positioning service using the available GNSS system. A PPP solution depends on GNSS satellite clock and orbit corrections, generated from a network of global reference stations. Once the corrections are calculated, they are delivered to the end user via satellite or over the Internet. These corrections are used by the receiver, resulting in decimetre-level or better positioning with no base station required. C-Nav data are logged and monitored continuously in QINSy as well as the C-Nav RINEX which provides a live display of height error. C-Nav logs files in a *.cnav 3050 format which can be subsequently interrogated by C-Proc, a software made to extract C-Nav QC statistics. Data was acquired, processed, delivered, and displayed in this report using WGS84 UTM30N projected coordinate system.

2.1.1.2 Lady Kathleen

All survey positioning and navigation data were recorded via a primary GNSS antenna. Two antennas used were a Trimble AT1675-540TS receiver which used VRS Now via Trimble corrections to achieve 2 cm accuracy. VRS is a provides real-time differential corrections to a GNSS system. A VRS solution depends on data from several permanent reference stations to compute corrections that are generally more accurate than corrections from a single reference station. Once the corrections are calculated, they are delivered to the end user via satellite or over the Internet. VRS data are logged and monitored continuously in QINSy.

2.1.2 Sub-surface positioning

Towed sensors were positioned via Sonardyne Mini Ranger II USBL with an accuracy of ± 0.2% - 1.3% of the slant range. Overall, the USBL tracked the positions of towed bodies well. However, isolated, localised deviations were observed. Minor navigation wobbles and inconsistencies (causing up to 20 m offsets) are common with USBL systems and easily influenced by environmental factors (cf. Li et al., 2018). This is typical and can be rectified in post-processing to ensure that geographic accuracy of 2 m can be attained in accordance with project specifications.

Sub-surface position navigation data were parsed online with the associated survey files (*.jsf and *.txt). These navigation data were processed as initial processing steps for each specific workflow separately (details in sections 2.6.2).

2.1.3 Tidal Reduction Methodology

Vertical corrections were applied to the data in real-time via Quality Integrated Navigation System (QINSy) using the PPP system. All data were then reduced specifically to Lowest Astronomical Tide (LAT). To do this, the UCL and UKHO product, Vertical Offshore Reference Frames (VORF) system was used. The VORF project allows to seamlessly transform vertical height information to other common coastal and offshore levels within the Irish and UK nautical zones.

2.1 Multibeam bathymetry data (including tidal reduction methodology)

2.1.1 Data acquisition

2.1.1.1 Roman Rebel

Bathymetric and acoustic backscatter data were acquired using two hull-mounted Reason SeaBat T50-R multibeam echosounders (MBES). Each MBES transceiver produces 1,024 beams per ping and can operate from 190 to 420 kHz. During the Arklow Bank survey operations, the MBES was typically operated at a frequency of 400 kHz. Opening beam angles were adjusted dynamically throughout the survey to maximise the coverage to sounding density ratio. The sonar heads were integrated with a real-time sound velocity sensor, an iXBlue HYDRINS inertial navigation system and two independent GNSS antennas (C-Nav and Hemisphere).

Data were acquired in a boustrophedonic, gridded survey design (Figure 1) with the general, main line spacing of 15 m for the Roman Rebel scope and 7-8m for the Lady Kathleen scope. Survey speed was approximately 4 - 4.5 knots. Sound Velocity Profiles were acquired at a minimum of every 12 hours but always whenever clear changes were observed in sound speed recordings (QINSy alarm set to sound velocity changes greater than 2 m/s). A Valeport Swift sound velocity profiler was used for SVP casts and a total of 31 profiles were recorded during acquisition. Data acquisition was managed in QINSy which was also used to visualise raw data and save *.db files with raw multibeam data. All data were stored on a dedicated offshore data server.

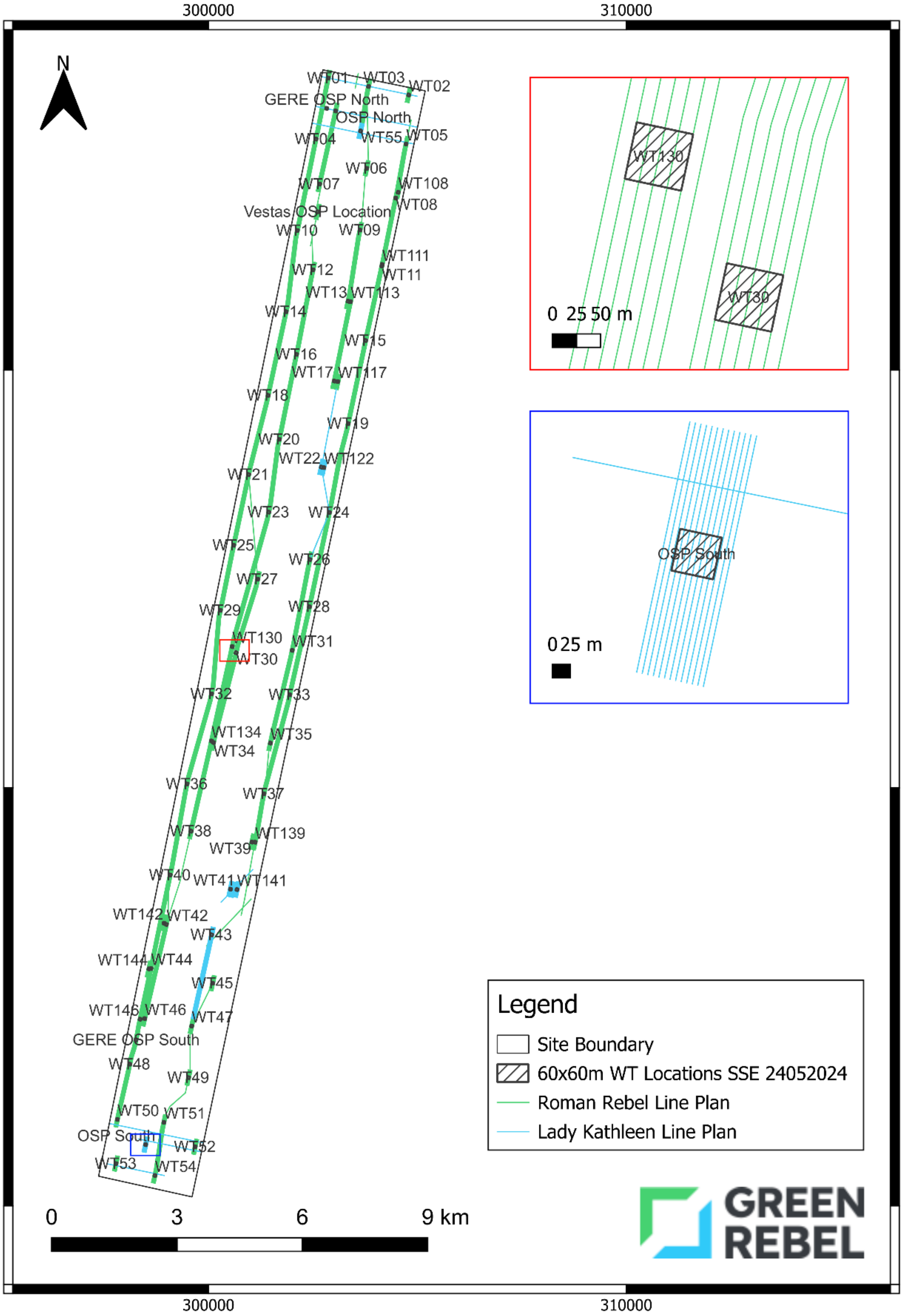

Figure 1: Overall map displaying the lineplan for both the Roman Rebel and the Lady Kathleen (see inset images of line spacing and colour coded to each vessel)

2.1.1.2 Lady Kathleen

Bathymetric data were acquired using a single hull-mounted Reason SeaBat T50-R multibeam echosounder (MBES). The MBES transceiver produces 1,024 beams per ping and can operate from 190 to 420 kHz. During the SSE ABWP 2 survey operations, the MBES was operated typically at a frequency of 400 kHz. Opening beam angles were set to 60–65 degrees (or adapted for shallow depths). The sonar head was integrated with a real-time sound velocity sensor, a Teledyne Type-30 IMU and integrated Applanix INS (inertial navigation system) and two independent GNSS antennas (Trimble AT1675-540TS).

Data were acquired in a boustrophedonic, gridded survey design, roughly parallel to depth contours, along the NE-SW axis of the Arklow Bank sand bank with the line spacing of 8 m for the main lines (Figure 3). Survey speed was approximately 4.5 knots. Sound Velocity Profiles were acquired at a minimum of every 12 hours but always whenever clear changes were observed in sound speed recordings (QINSy alarm set to sound velocity changes greater than 2 m/s). A Valeport Swift sound velocity profiler was used for SVP casts and a total of 20 profiles were recorded during acquisition. Data acquisition was managed in QINSy which was also used visualise raw data and construction of *.db files with raw multibeam data. All data were stored on a dedicated offshore data server.

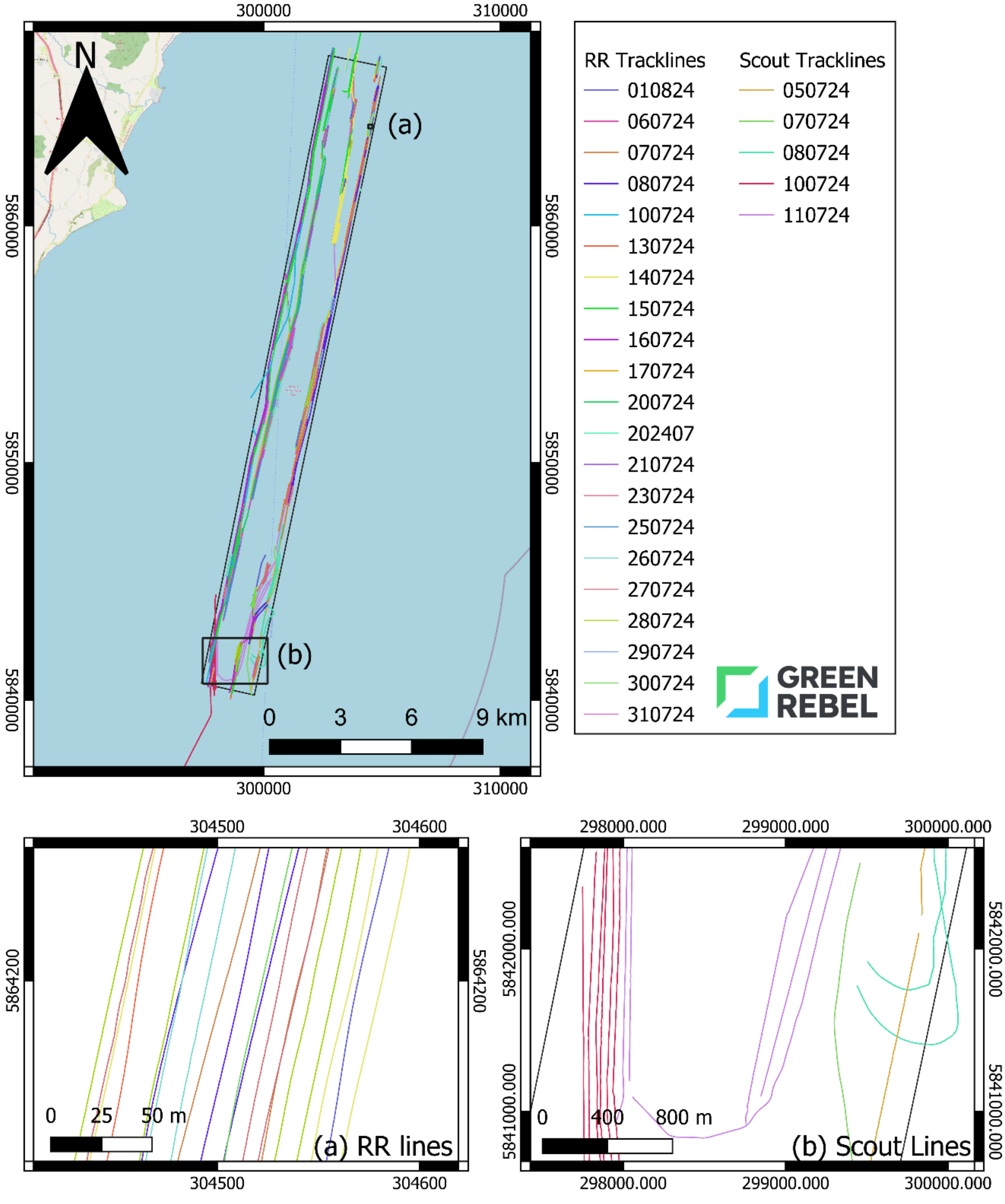

FIGURE 2: ROMAN REBEL AND SCOUT TRACKLINES COLOURED ACCORDING TO THE DATES AT WHICH THEY WERE SURVEYED.

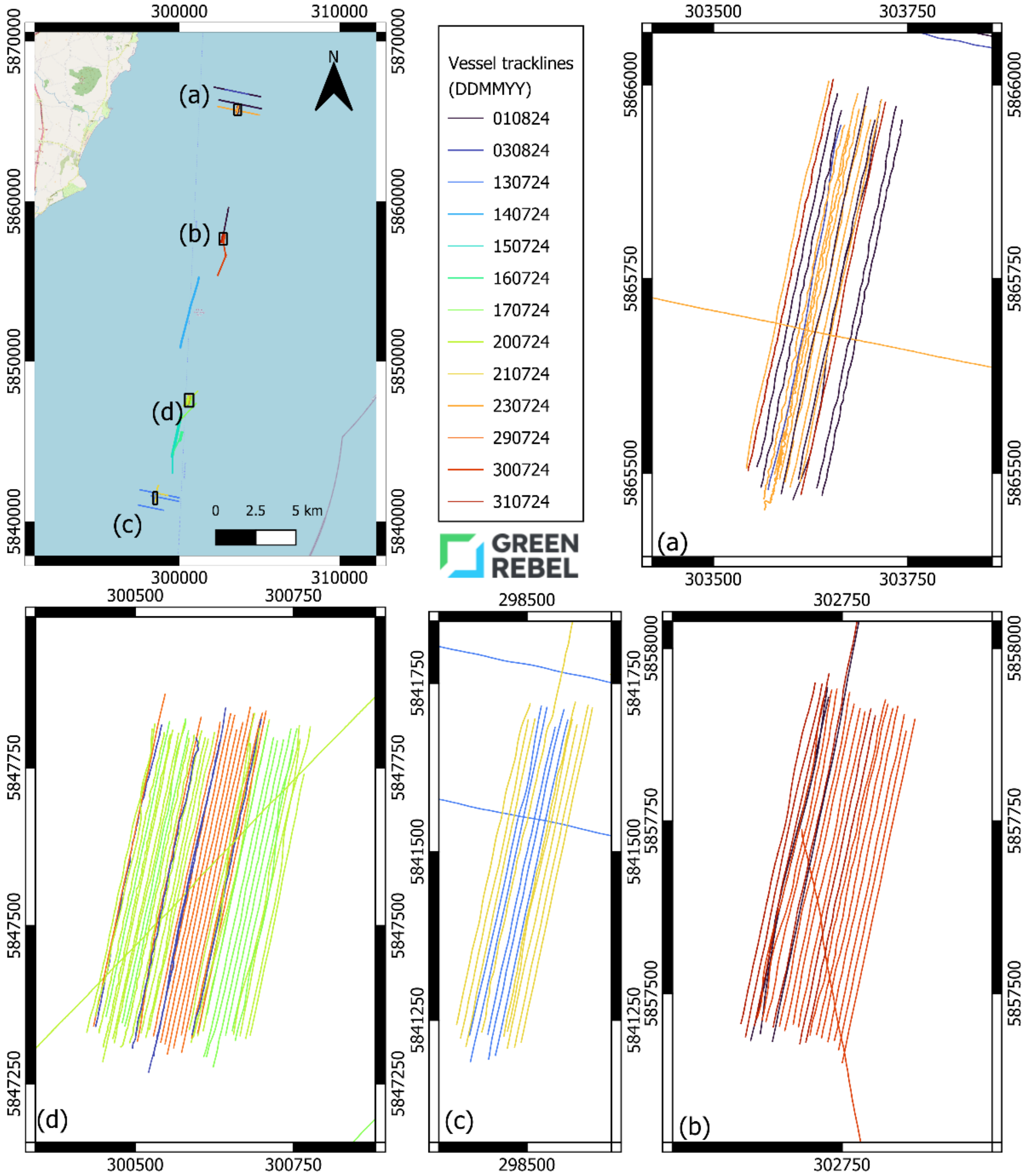

FIGURE 3: LADY KATHLEEN'S TRACKLINES COLOURED ACCORDING TO THE DATES AT WHICH THEY WERE SURVEYED.

2.1.2 Processing workflow

Multibeam bathymetric data are interpreted to accurately measure water depth, capture seafloor features, geomorphology and other objects like shipwrecks. Raw multibeam echosounder data were acquired and stored in a series of QPS *.db files. These files contain the raw sounding, GNSS, altitude and applied sound velocity data. As such, data processing was required to merge these data, remove or correct anomalous data, create a bathymetric surface corrected to a defined vertical reference system, confirm that the data conforms with IHO standards and export the data in a GIS-compatible format.

The *.db files were imported to QPS Qimera which converts the data to a proprietary (*.qpd) file format. From the *.db files, sound velocity, vessel and offset values are automatically read into the project. The processing parameters were defined to ensure that the sound velocity strategy is in accordance with the surveyed strategy, that the altitude values are applied from the correct source from the *.db file as well as GPS tide and the correct separation model. A raw surface was then created using these processing parameters, representing the average value of soundings within each cell. Vessel configuration was checked for any clear deviations from those set during acquisition. Nearest in time or nearest in distance sound velocity profile casts were selected for refraction corrections in Qimera, depending on the observed sound velocity variations.

Surface and profile sound velocity data and vertical positioning were then inspected for anomalous data values and spikes which were subsequently removed. Although vertical errors within the GPS heights were low (± 15 cm), navigation data were smoothed in QPS Qimera where appropriate. The raw bathymetric surface was then colour coded based on uncertainty (95% confidence interval) with a standard range of 0 to 0.4, to view areas where accepted soundings have considerable standard deviation. Mild filters (e.g., spline) were applied locally to areas with evident noise, ensuring that no possible contacts or bathymetric features were removed during the process. This was confirmed by performing visual inspections on each line or area before and after applying the filter. This strategy allows for a detailed examination of the dataset while at the same time removing the erroneous measurements.

Subsequently, the data were cleaned using the swath and slice editors, depending on the morphology of the seabed and the distribution of the anomalous data. In areas with complex natural or anthropogenic seabed features like wrecks, pipelines, infrastructure, the 3D editor is also implemented.

If high standard deviation values remained in the outer beams or line overlap, then the data were interrogated further. If this error was related to sound velocity, a series of checks were performed: i) re-inspection the surface and profile sound speed data and smoothing/despiking if required; ii) application of a refraction edit (± 1 ms-1 at 1 m water depth) and/or; iii) application of QPS's TU Sound Speed Inversion algorithm which utilises neighbouring soundings to determine the 'best-fit' sound speed refraction solution that minimises sounding mismatch in areas where there is sufficient overlap.

All data were corrected to LAT using the VORF separation model. Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU) were computed for each sounding within the dataset. These were used for quality control purposes to ensure that the data is within client-specified limits. Another surface was created to ensure adequate sounding density (showing hit count per 1 m pixel). Finally, cross lines, which are independent of the surface grid were cross checked with the grid. This check, carried out in Qimera's cross check tool, generated a table of statistics that provide the results of the analysis of beam footprint values within the processed surface.

On inspection of the data and ensuring that the data meet the required IHO survey specifications, the data were exported. Initially, *.tif and *.xyz (or *.csv) files were exported comprising the backscatter and bathymetric surface data, respectively. The LAT-reduced, denoised bathymetric data was then inspected using GIS.

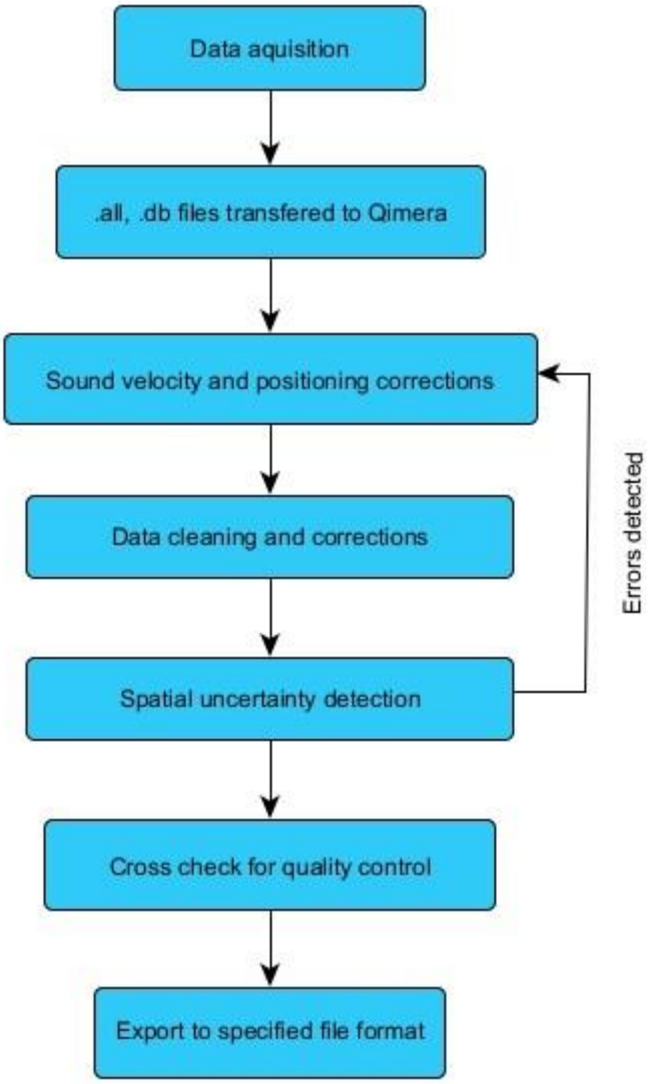

FIGURE 4: GENERAL MULTIBEAM ECHO SOUNDER DATA PROCESSING WORKFLOW FOR CORRECTED BATHYMETRIC GRIDS

2.1.3 Coverage

Multibeam echosounder swath coverage was optimised for sounding density to ensure that depth-induced swath width changes do not cause unnecessary fluctuations to sounding density. This ensures that all pixels on the final bathymetric surface were binned based on a similar number of soundings. Furthermore, it facilitates consistent data quality when sea state is less favourable.

To do this, an alarm was set in QPS QINSy to note considerable sounding density changes, and the swath was subsequently adjusted based on the discretion of the senior surveyor. Given that water depth throughout the Arklow Bank survey ranges from -11.66 mLAT to -51.04 mLAT for the Roman Rebel survey area and -9.79 mLAT to -49.38 mLAT for the Lady Kathleen data, swath width was generally highly variable. Figure 5 and Figure 6 demonstrates swath width and water depth in cross track data for the Roman Rebel and Lady Kathleen, respectively.

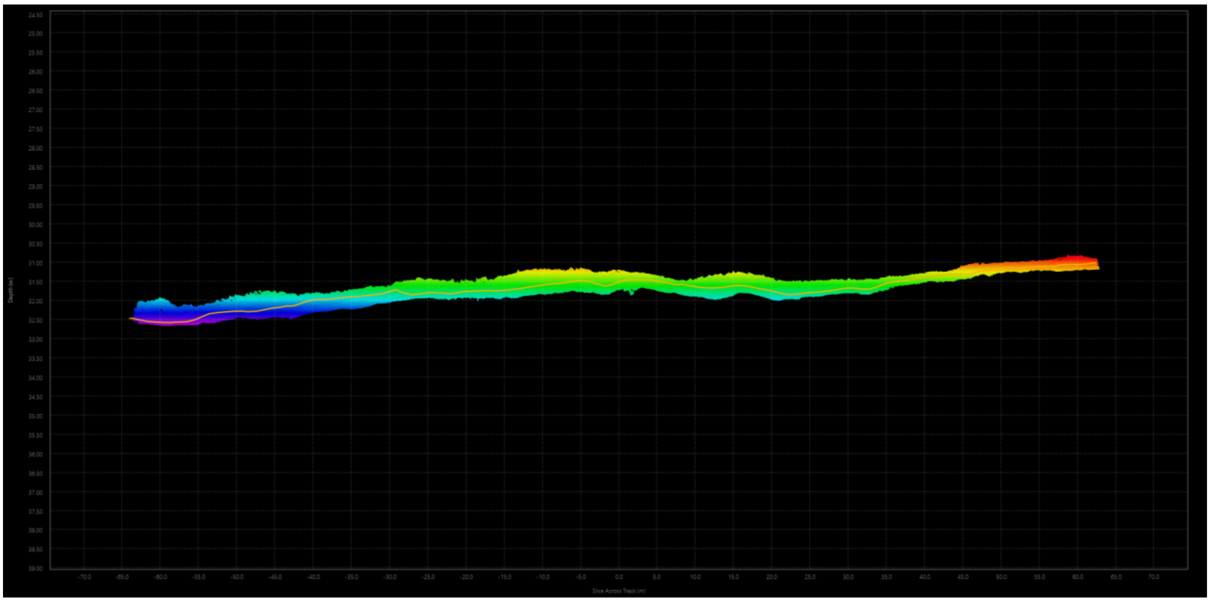

Figure 5: Plot showing typical cross track profile from the Roman Rebel's multibeam echosounder pings during the Arklow Bank survey. Note: Water depth (32.50m). Data are colour coded by depth.

Using the swath coverage strategy outlined above, an area of c. 20.88 km^2 and c. 2.67 km^2 was surveyed by multibeam in the Arklow Bank survey area by the Roman Rebel and Lady Kathleen, respectively (Figure 7).

Line spacing for the survey was designed to ensure consistent data coverage with respect to the 3D UHRS spread.

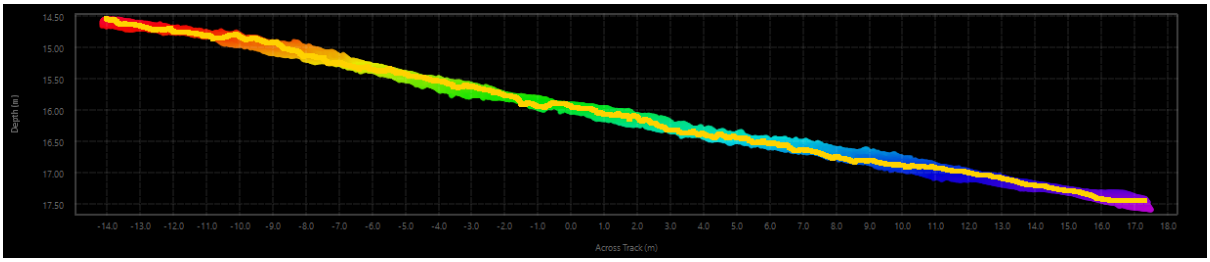

Figure 6: Plot showing typical cross track profile from the Lady Kathleen multibeam echosounder pings during the Arklow Bank survey. Note: Water depth (16.00 m). Data are colour coded by depth (Vertical Exaggeration: x2).

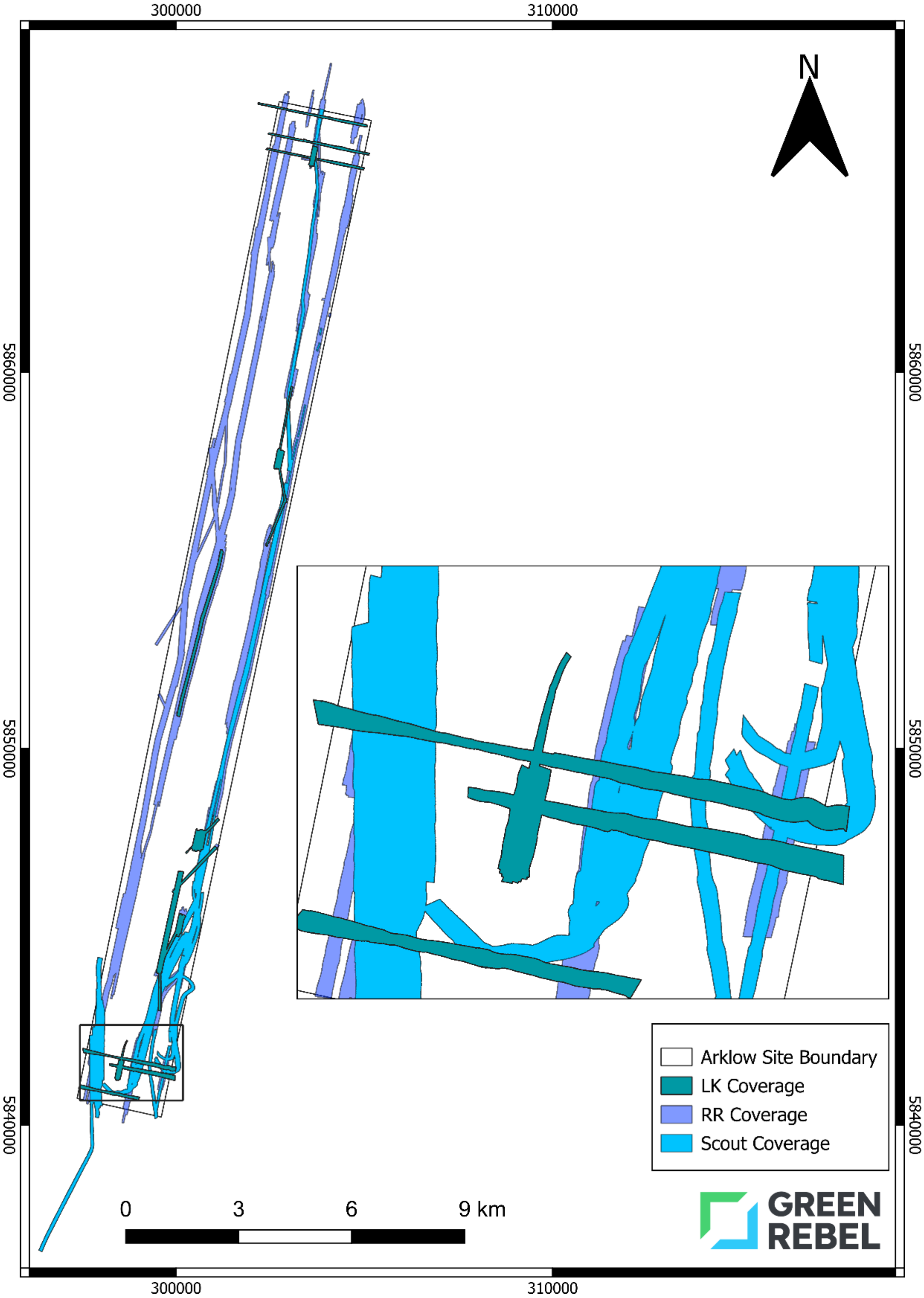

FIGURE 7: MAP SHOWING THE TOTAL AREA SURVEYED IN THE ARKLOW BANK SURVEY BY THE ROMAN REBEL AND LADY KATHLEEN.

2.1.4 Positioning accuracy

The surface positioning quality during field operations achieved the required project's specifications, as documented in the Operations Report (Table 3) and these data provided positioning for the multibeam systems. The accuracy of the Roman Rebel and Lady Kathleen MBES systems is apparent with visual inspections of neighbouring lines in the raw data. This assessment shows consistent vertical alignment of sounding overlap (Figure 8 and Figure 9). Some misalignments visible between the adjacent lines is related to the dynamic nature of the seabed, where consecutive, neighbouring/infilling/rerun profiles were surveyed at time intervals spanning a few days (as outlined in the geohazard assessment in section 3.3.1)

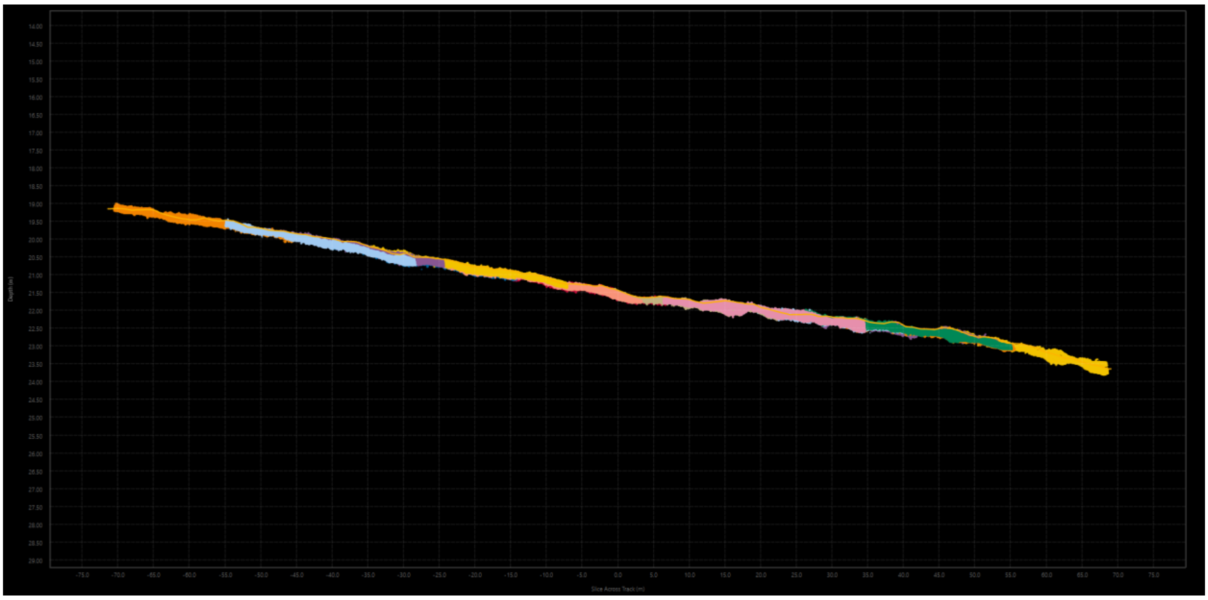

Figure 8: Plot showing across track bathymetric data (Roman Rebel) to highlight the vertical 'matching'/positioning of the raw data acquired with the primary GNSS antenna (Vertical Exaggeration: x5)

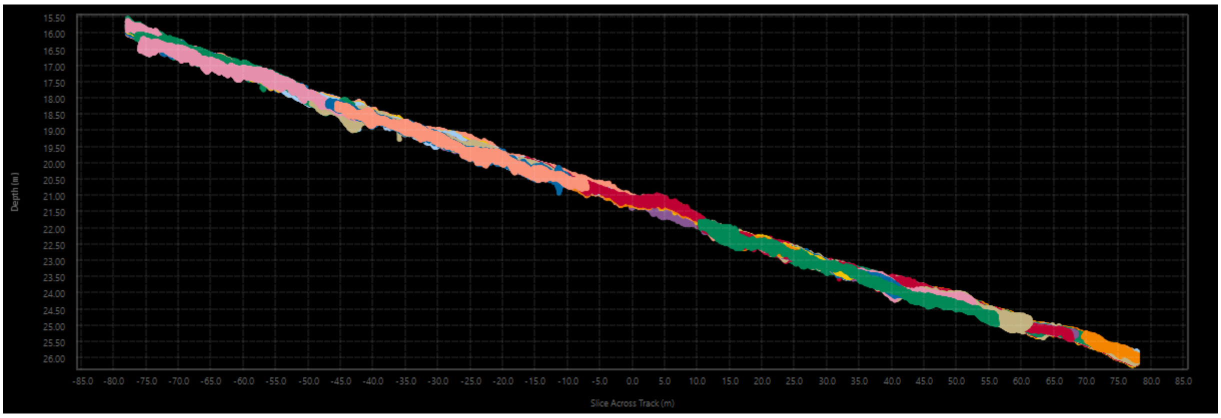

Figure 9: Plot showing across track bathymetric data (Lady Kathleen) to highlight the vertical 'matching'/positioning of the raw data acquired with the primary GNSS antenna (Vertical Exaggeration: x5)

2.1.5 Sound velocity control

Sound velocity was measured both at the multibeam transducer as well as through the water column via sound velocity profiles. Sound velocity profile values are required to calibrate the multibeam-derived sounding values for speed of sound in water. These data enabled accurate calculation of bathymetric values.

Sound velocity profiles were recorded at a minimum of every 12 hours or by the discretion of the senior surveyor. A total of 31 and 20 sound velocity profile casts were acquired during the survey operations onboard the Roman Rebel and Lady Kathleen, respectively. Surface sound velocity values measured at the multibeam transducer head were continuously measured and monitored by the acquisition software (i.e. QPS QINSy). When QINSy measures a difference between the sound velocity at the transducer (Figure 10) and in the profile, an alarm is set off. When this happens, a new sound velocity profile is recorded. This cautionary procedure ensured that the sound velocity value was updated whenever there was any considerable change in the physio-chemical properties of the underlying water mass. Care was taken in environments/situations that were likely to influence sound velocity changes (e.g. heavy rain fall, nearby estuaries, harbours, surface water influx).

Figure 11 shows a sample of typical sound velocity values recorded during the Arklow Bank survey. Sound velocity profiles measured during the survey period reveal minor fluctuations in these profiles with depth, indicating that local variation is abundant in the upper layers. Note: Profiles that are substantially out of the survey area are (i.e., mobilisation and calibration profiles) excluded from this figure.

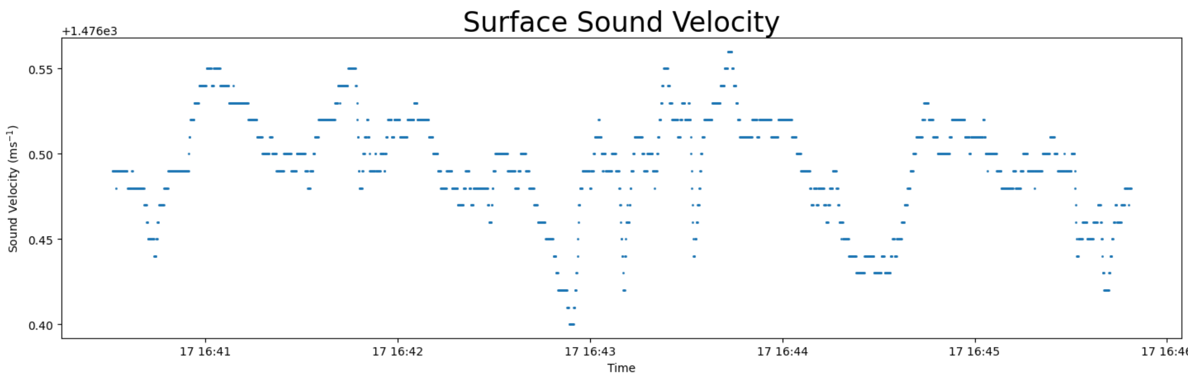

FIGURE 10: REPRESENTATIVE EXAMPLE OF SURFACE SOUND VELOCITY MEASUREMENTS RECORDED DURING SURVEY OPERATIONS (±0.25 MS-1 VARIATION OVER A SINGLE SURVEY FILE)

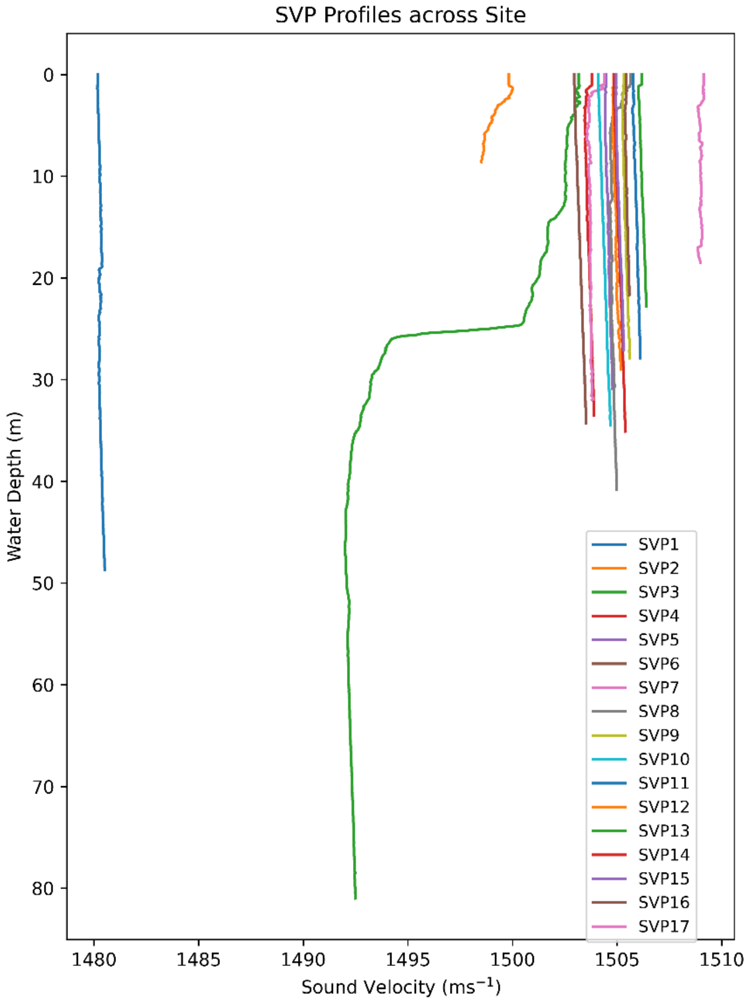

Figure 11: Representative sound velocity profiles acquired during the Arklow Bank survey – Roman Rebel.

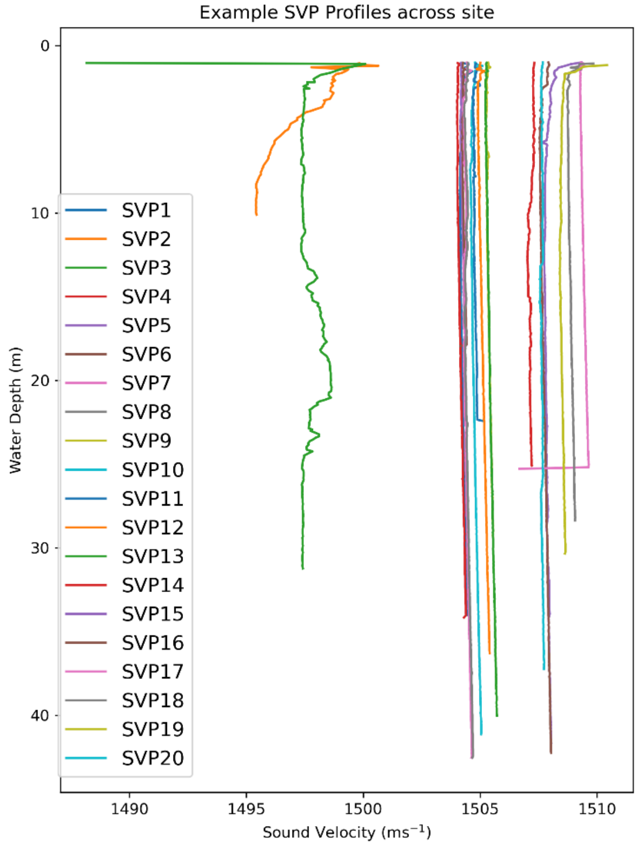

FIGURE 12: REPRESENTATIVE SOUND VELOCITY PROFILES ACQUIRED DURING THE ARKLOW BANK SURVEY – LADY KATHLEEN.

A mean water column velocity of c. 1500 m/s was apparent across the site, observed on both the Roman Rebel and Lady Kathleen. This value is estimated from the combined SVP casts from both vessels.

2.1.6 Sounding quality

Multibeam echosounders transmit and record acoustic energy using a transducer. As such, they are sensitive to noise that can be expressed in the resulting raw data. This is a common phenomenon and can be the result of direct impact between air bubbles and the transducer when sea states are less favourable, biofouling, or interference by acoustic energy that is similar in frequency to that of the multibeam (400 kHz). Green Rebel has completed testing to optimise survey parameters for minimal across-sensor interference. However, it is impossible to eliminate these artefacts completely. Noise and artefacts expressed in the raw multibeam bathymetric data during the survey operations are uncommon and when they do occur, they are minor (Figure 13). These anomalous soundings are clear and obvious in the raw datasets and can be removed when the data are processed.

One possible measure of multibeam data quality is sounding density. To access this, the density of soundings per 1 m cell were measured and values range from 1 to 304258 soundings per 1 m cell for the Roman Rebel data, for both RR and Scout lines, and 1 to 30557 soundings per 1 m cell for the Lady Kathleen data. The mean number of soundings in the raw bathymetric data are 16692.09 per 1 m cell for the Roman Rebel data and 685.37 per 1 m cell for the Lady Kathleen data. As specified by SSE, the coverage shall be no less than 3 good quality samples per specified grid size (0.25m) for 95% of the survey area and the survey should achieve IHO standard Order 1a. As such, the average sounding density is well within the range (it exceeds it significantly) to achieve the final product specification after post-processing.

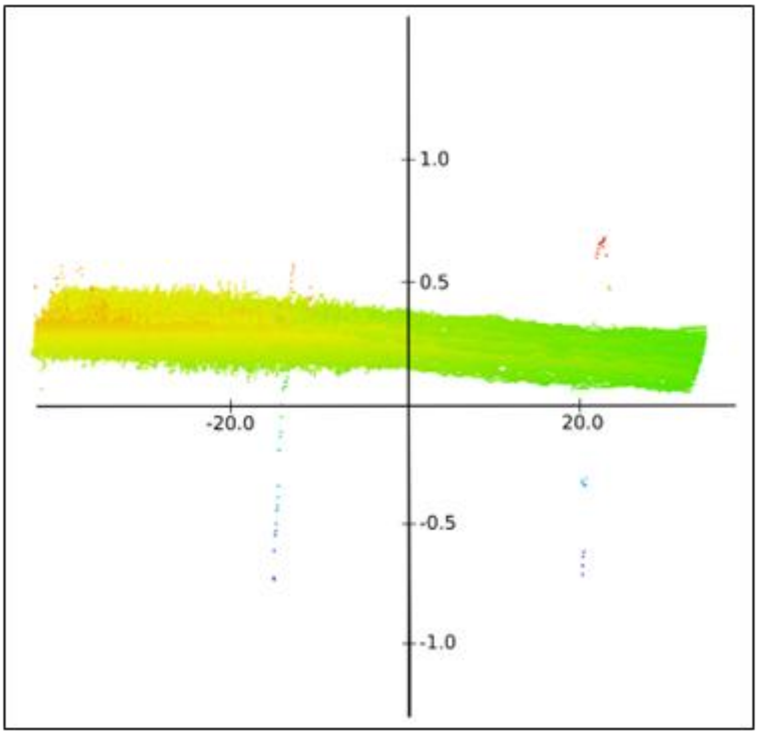

Figure 13: Sample of typical noise artefacts recorded by the multibeam echosounder and expressed in the sounding data. Note: units in meters and vertical exaggeration of x22.78.

2.1.7 Data quality

The processed multibeam echosounder-derived bathymetric data achieves the required specifications IHO Order 1a. Criteria for Order 1a standard include feature search (100%), bathymetric coverage (100%) and maximum allowable total vertical uncertainty (TVU). To calculate TVU, (Equation 1 is utilised:

(Equation 1)

$$TVU_{max}(d) = \sqrt{a^2 + (bd)^2}$$

Where *a* is the proportion of the uncertainty that does not vary with depth (0.5 m), *b* is a coefficient which represents that portion of the uncertainty that varies with depth (0.013) and *d* is the measured water depth (m). Table 5 shows the test results used to determine if the data acquired during the Arklow Bank survey achieved the level of accuracy required for IHO Order 1a. To generate these values, Qimera, the QPS MBES processing software utilises survey crosslines as cross check to evaluate TVU values and other statistics for IHO Standard assessment (Table 5).

TABLE 5: MULTIBEAM BATHYMETRIC DATA IHO S-44 ORDER 1A CHECK RESULTS – ROMAN REBEL LINES

Attribute	Value
Error Limit	0.609224
Number Rejected	408828
P-Statistic	0.004842
Test	ACCEPTED
Number Of Points	84438381
Grid Cell Size	1.000
Difference Mean	0.029415
Difference Median	0.025424
Difference Std. Dev	0.170276
Difference Range	[-51.15, 2.05]
Mean + 2*Stddev	0.369967
Median + 2*Stddev	0.365976
Data Mean	-26.745335
Reference Mean	-26.774750
Data Z-Range	[-76.09, -16.45]
Reference Z-Range	[-44.93, -16.93]

Table 6: Multibeam bathymetric data IHO S-44 Order 1a check results –Scout lines

Attribute	Value
Error Limit	0.642166
Number Rejected	477359
P-Statistic	0.011104
Test	ACCEPTED
Number Of Points	42989579
Grid Cell Size	1.000
Difference Mean	0.040782
Difference Median	0.036019
Difference Std. Dev	0.203225
Difference Range	[-45.52 23.01]
Mean + 2*Stddev	0.447232
Median + 2*Stddev	0.442468
Data Mean	-30.956162
Reference Mean	-30.996944
Data Z-Range	[-66.40, -12.80]
Reference Z-Range	[-46.94, -17.01]

Table 7: Multibeam bathymetric data IHO S-44 Order 1a check results – Lady Kathleen

Attribute	Value
Error Limit	0.623757
Number Rejected	7
P-Statistic	6.42713e-07
Test	ACCEPTED
Number Of Points	10891339
Grid Cell Size	0.250
Difference Mean	0.010
Difference Median	0.011
Difference Std. Dev	0.043

Attribute	*Value*
Difference Range	[-0.566, 1.215]
Mean + 2*Stddev	0.096
Median + 2*Stddev	0.097
Data Mean	-28.697
Reference Mean	-28.687
Data Z-Range	[-35.499, -22.421]
Reference Z-Range	[-35.418, -22.431]

Online quality control inspections were performed during acquisition by a dedicated QC person to ensure a high-density of soundings per 1 m cell. This was confirmed in post-processing where the final sounding grid acquired by Roman Rebel had a minimum of 1 sounding per 1 m bin (observed only in the edges of the swath), a maximum of 304258 soundings per 1 m bin, and a mean of 16692.09 soundings per cell. For the Lady Kathleen data, these values were: 1 (minimum number of soundings per 1 m bin), 30557 (maximum soundings per 1 m bin) and 685.37 (average soundings per 1 m bin). For transparency, this is visualised below (Figure 14 and Figure 16) and highlights the quality of the final bathymetric data.

Navigation data were logged in standard C-Nav format which were integrated within the raw QINSy database files. Real-time positioning data quality from C-Nav was of sufficient quality to exceed IHO Order 1a standard requirements. Vertical errors within GPS heights were low (± 7 cm) and provide a robust solution for computation of GPS tide. GPS tide was computed using the separation model between World Geodetic System 1984 (WGS84) datum and VORF LAT.

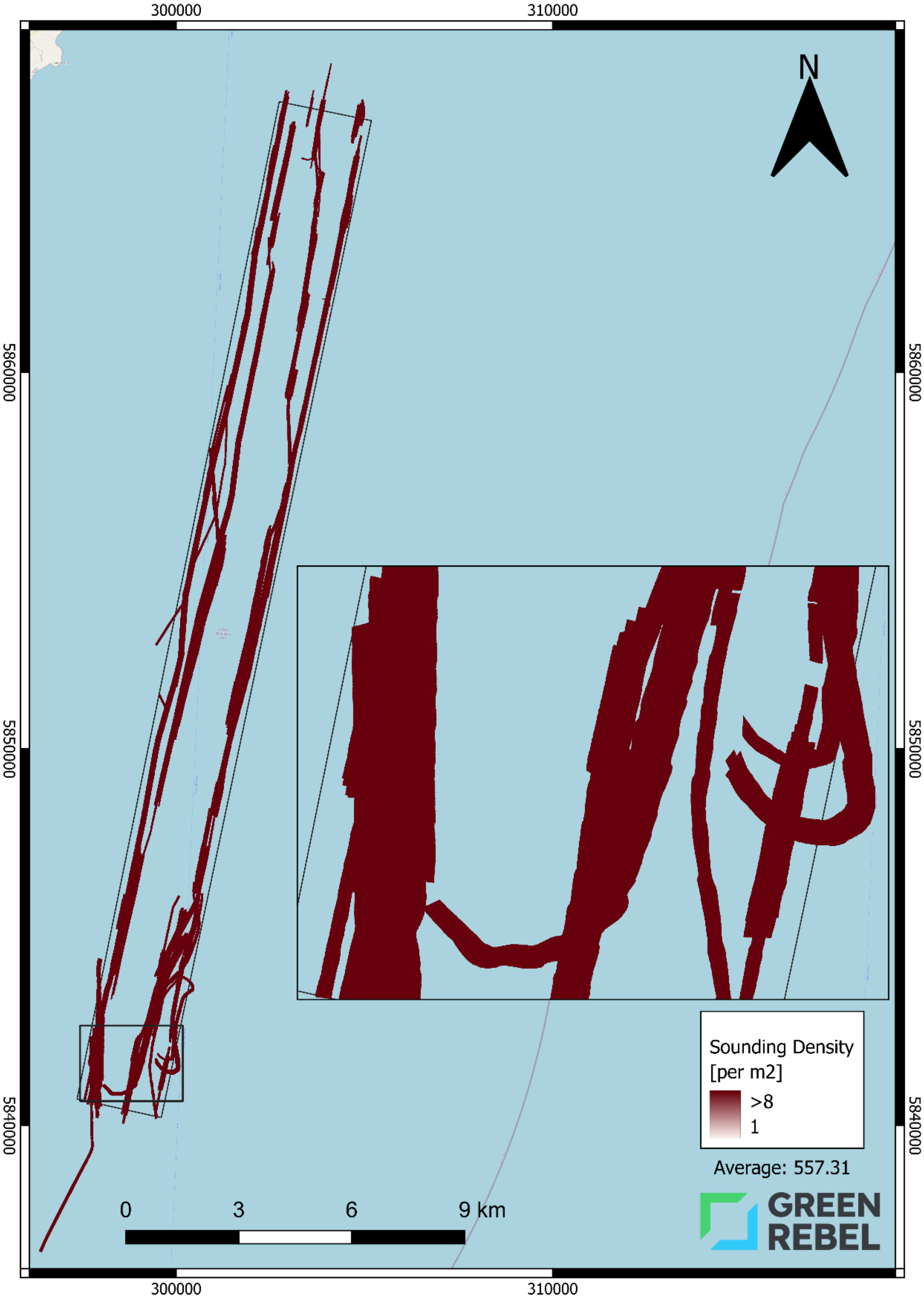

FIGURE 14: ROMAN REBEL'S MBES SOUNDING DENSITY MAP (SOUNDINGS MEASURED PER 1M BIN).

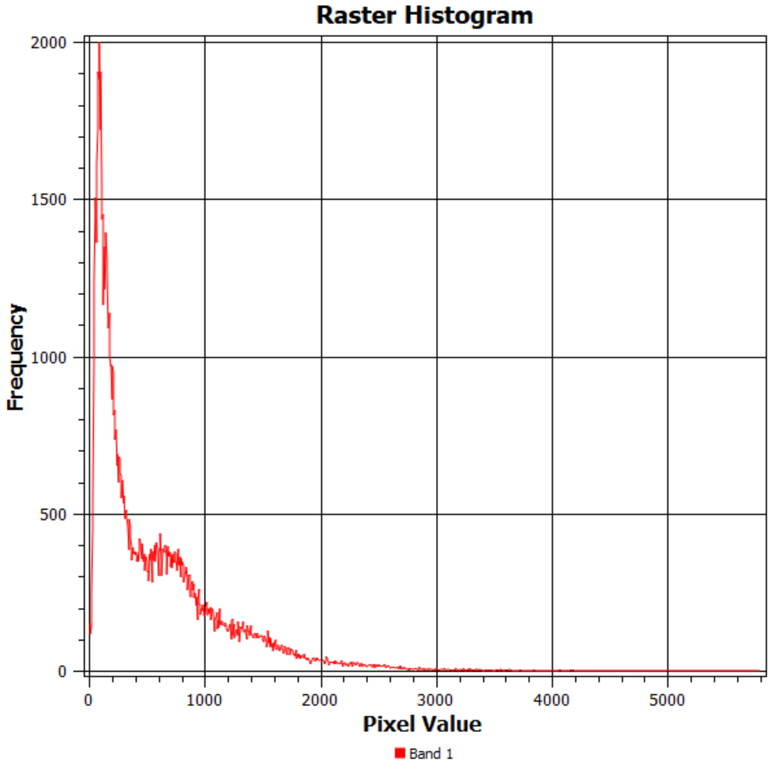

Figure 15: Histogram showing the number of soundings per 1 m cell within the final bathymetric surface – Roman Rebel.

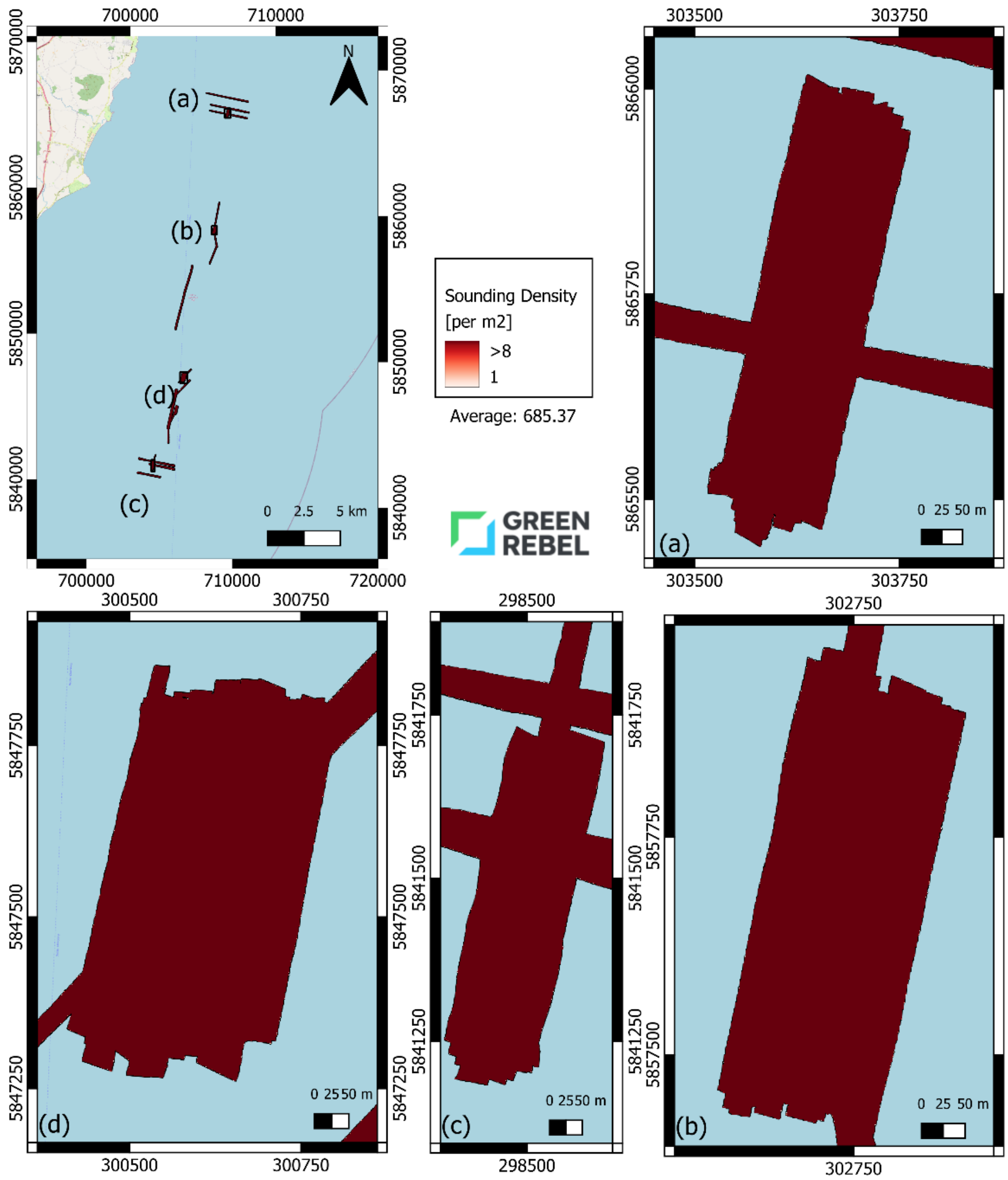

Figure 16: Lady Kathleen's MBES Sounding density map (soundings measured per 1m bin). (a), (b), (c) and (d) represent close ups of the areas shown in the main map (top left).

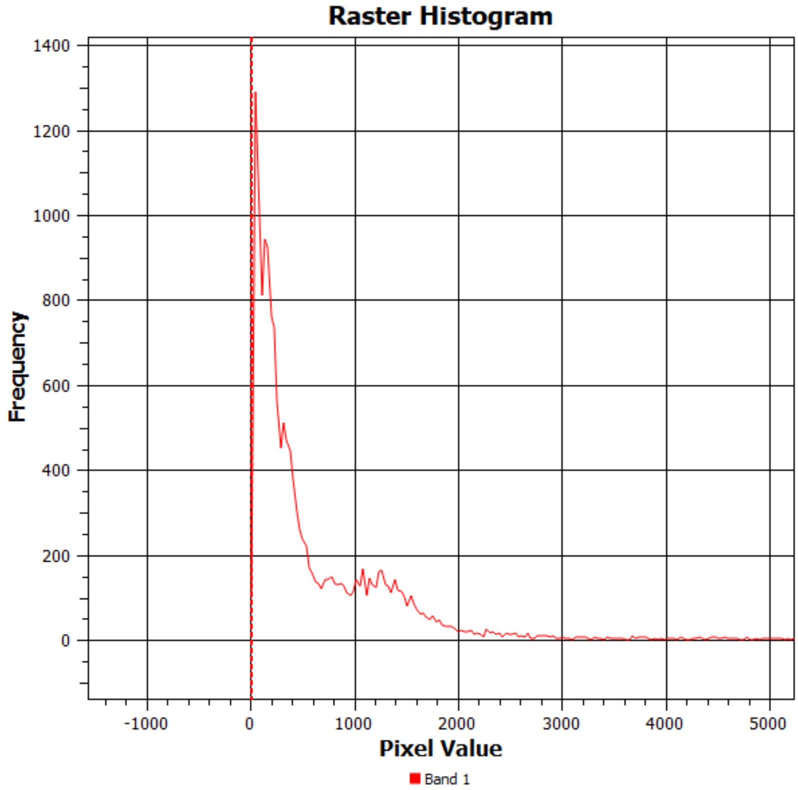

FIGURE 17: HISTOGRAM SHOWING THE NUMBER OF SOUNDINGS PER 1 M CELL WITHIN THE FINAL BATHYMETRIC SURFACE – LADY KATHLEEN.

Overall quality control of the data was completed by generating a QPS Qimera Dynamic surfaces from all MBES sonar data within the Arklow Bank survey area. The dynamic surface was created with a range of parameters used to assess the data and ensure it falls within specification. The uncertainty at 95% confidence interval was assessed in order to highlight areas where the vertical spread of soundings within a DEM grid are high and checks can be made to determine the cause. Areas within this layer that coincide with high standard deviations can occur where there are sound velocity errors, errors in the navigation, or when acquiring data in heavy weather and where there is a change in seabed relief – for example on top of sandwaves. Naturally, standard deviations for measurements are high also where the seabed exhibits rapid geomorphic change causing seabed movement during the acquisition of the data for adjacent, overlapping survey lines.

Figure 18 and Figure 20 show the uncertainty of the final bathymetric sounding grid at the 95% confidence interval for the Roman Rebel and Lady Kathleen data. These data show that the uncertainty is typically < 0.08 m although under certain circumstances there are higher standard deviations – mostly at the highly dynamic sandwave fields present in the Arklow Bank area. These sandwaves moved significantly during data acquisition (as shown in Figure 32 of section 3.3.1) causing high uncertainty in the final bathymetric grids. Nevertheless, the mean uncertainty is 0.23 for the Roman Rebel data and 0.08 m for the Lady Kathleen data, which demonstrates the quality and consistency of the grids. This is also plotted on histograms in Figure 19 and Figure 21, which show the spread of the uncertainty data between 0 and 0.4 m for the two vessels. No obvious, equipment-induced vertical artefacts were observed.

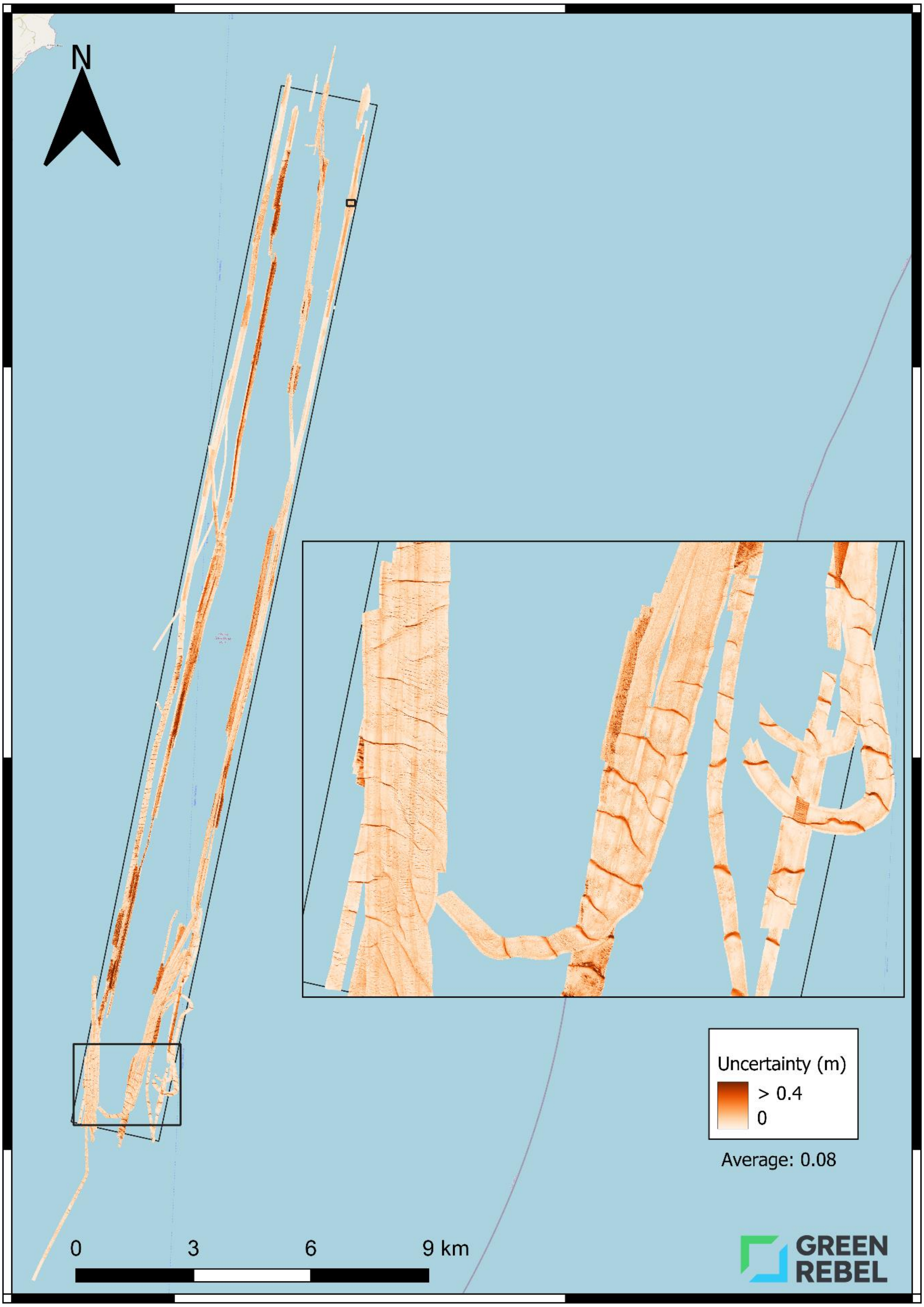

Figure 18: Roman Rebel's MBES Uncertainty raster.

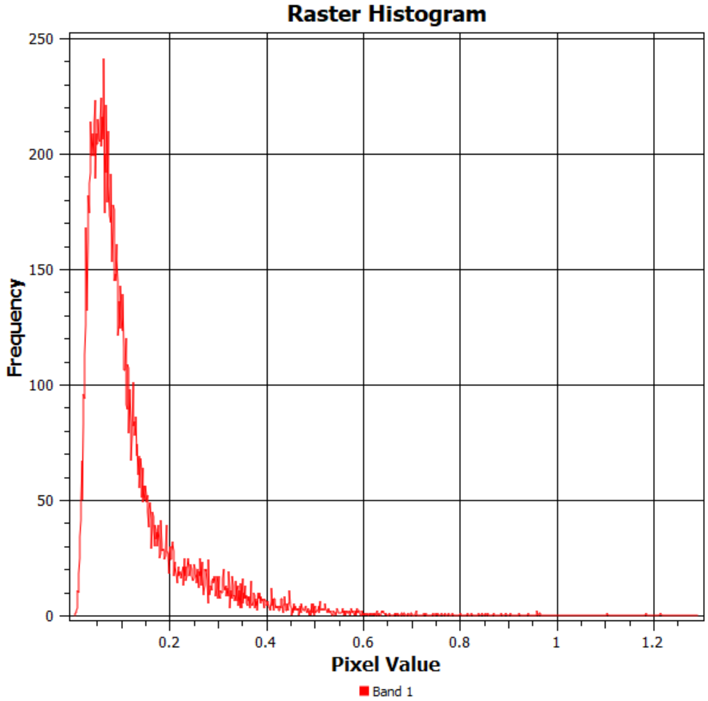

Figure 19: Histogram showing the uncertainty of soundings binned every 1 m within the final bathymetric surface – Roman Rebel.

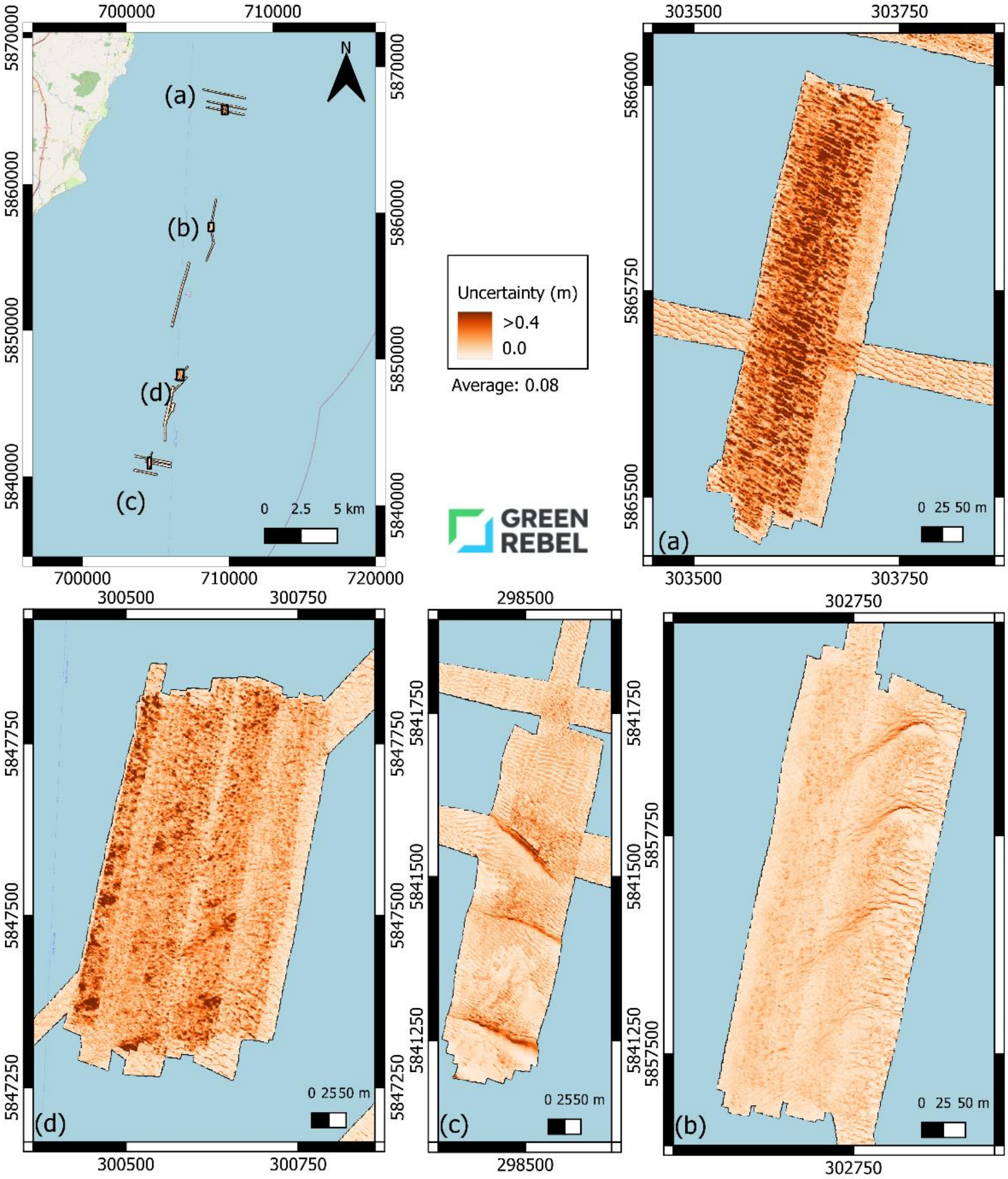

FIGURE 20: LADY KATHLEEN'S MBES UNCERTAINTY RASTER. (A), (B), (C) AND (D) REPRESENTS CLOSE UPS OF THE AREAS SHOWN IN THE MAIN MAP (TOP LEFT).

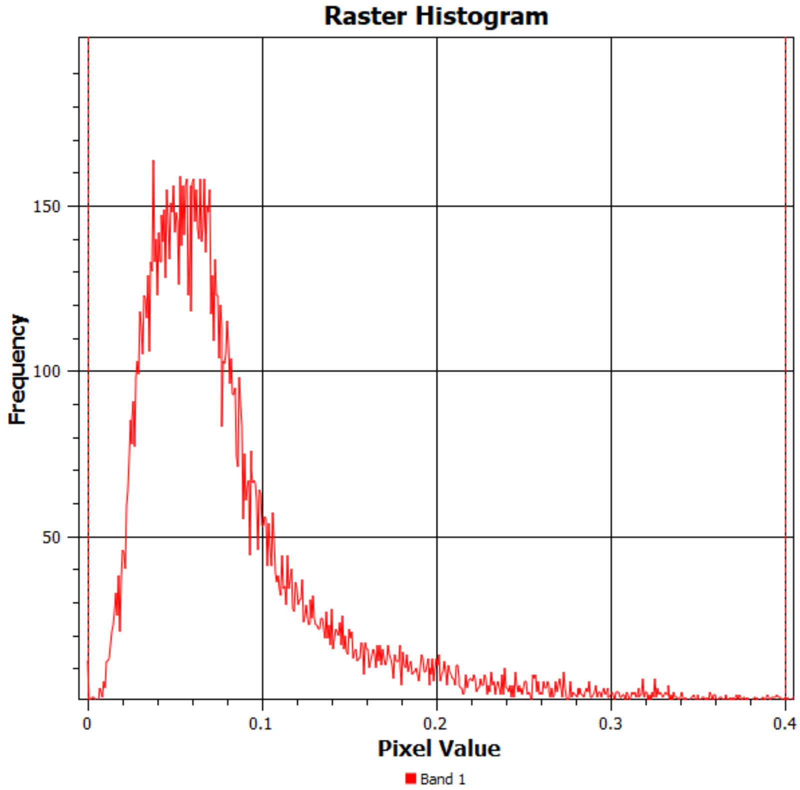

FIGURE 21: HISTOGRAM SHOWING THE UNCERTAINTY OF SOUNDINGS BINNED EVERY 1 M WITHIN THE FINAL BATHYMETRIC SURFACE – LADY KATHLEEN.

Given the high density of soundings, their vertical consistency as shown by low standard deviation and the cross validation with the IHO TVU test as well as the comparison with a well-known and established dataset, these data are deemed of high-quality and fit for purpose.

2.1.8 Final product

The final bathymetric grid was exported at 0.25 and 1 m per pixel as specified in the scope of works. The final bathymetric product was clean, meeting all industry standard tests as previously outlined. No artefacts or issues are observed with the final bathymetry product (Figure 22).

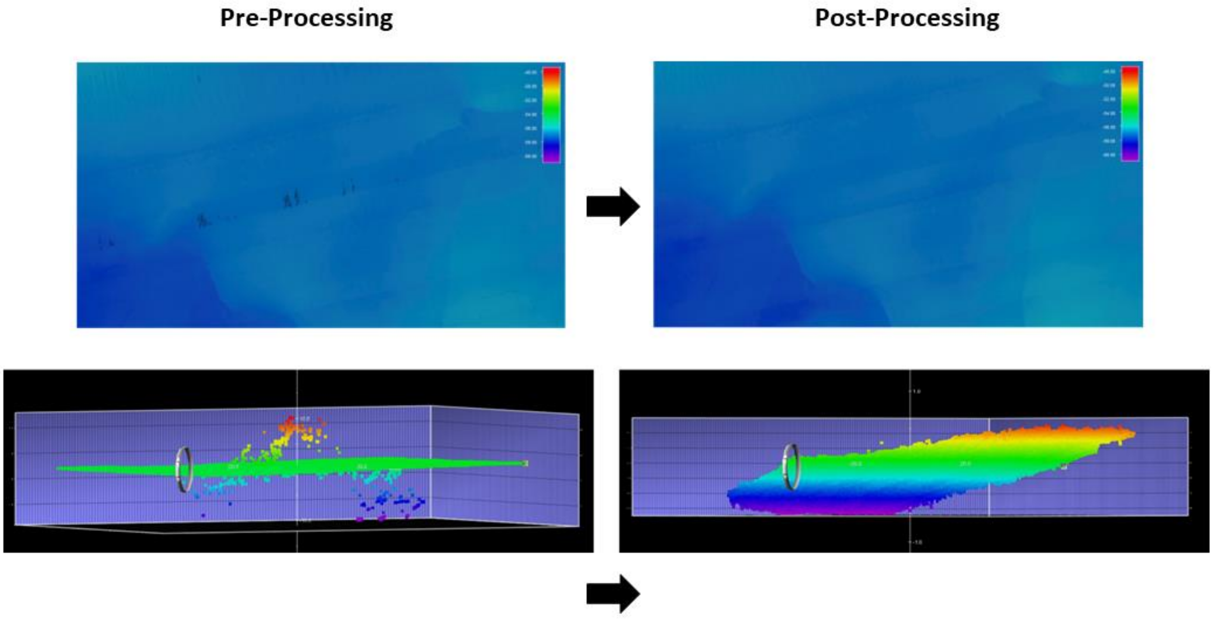

FIGURE 22: COMPARISON OF PRE- AND POST-PROCESSED ON A REPRESENTATIVE BATHYMETRIC SURFACE.

2.2 Sub-bottom profiler

Note: Sub-bottom profiler data was not processed or subsequently interpreted due to instruction from the client, SSE.

2.2.1 Data acquisition

2.2.1.1 Roman Rebel

Sub-bottom profiler data were acquired with a hull-mounted Innomar Medium-100 sub-bottom profiler. The primary frequency of 100 kHz was used to determine the bathymetry and the secondary frequency of 8 kHz was used to determine the sub-seafloor strata. All acquisition was managed via Innomar SESWIN software, which visualised raw sub-bottom profiles in real-time. Online data was quality controlled in SESWIN to ensure acquisition parameters were optimised during the survey operations. Raw data were recorded as *.ses3 files and subsequently converted to SEG-Y file format. Format handling procedure and the relevant trace header byte information are included in Appendices

Appendix 1. The SBP lines for the area were surveyed with a proposed main line spacing of 15m for the Roman Rebel.

2.2.1.2 Lady Kathleen

The Lady Kathleen is out fitted with a pole mounted Innomar standard 100 parametric sub-bottom profiler. Similar to the Roman Rebel, the primary frequency of 100kHz was used to determine the bathymetry and the secondary frequency of 8 kHz was used to determine the sub-seafloor strata. Acquisition was managed using Innomar SESWIN software, which visualised raw sub-bottom profiles in real-time. Online data was quality controlled in SESWIN to ensure acquisition parameters were optimised during the survey operations. Raw data were recorded as *.ses3 files, heave-corrected, and subsequently converted to SEG-Y file. Format handling procedure and the relevant trace header byte information are included in Appendix 1. The geophysical lines were surveyed with a line spacing of 7-8 m for the Lady Kathleen vessel. Additionally, the Lady Kathleen was used to connect boxes between areas.

2.2.2 Tidal and datum control

The sub-bottom profiler was hull mounted and received its ellipsoidal absolute position from the iXBlue HYDRINS (a Global Navigation Satellite System inertially aided), with centimetric accuracy vertical positioning corrections. Subsequently, the SBP transducer data needed to be reduced to the survey datum: LAT. This was achieved by correcting the bottom-tracked SBP data to datum-corrected bathymetry during post-processing using the SBP vertical offset tool available in SonarWiz.

2.2.3 Resolution and penetration

The theoretical vertical resolution depends on the physical parameters of the used frequency and pulse length. It can be calculated as:

$$\lambda = \frac{vT}{4},$$

Where the pulse length, $T = \frac{1}{f}$, f is the centre transmitted frequency, and v is the sound speed in a medium. The Innomar sub-bottom profiler was operated using a transmitted frequency of 7.7kHz, thus providing a vertical resolution of up to 0.0487 m.

The Innomar Standard = SBP has a transmit beam width of c.4° (±2°) for all frequencies), which corresponds to the footprint of c. 7% water depth. This means that at 1 m water depth, the horizontal resolution is 0.07m. The average depth at the survey site, calculated from the MBES bathymetry, equals 31.64 m. Hence, the mean SBP beam footprint during the survey operations was 2.21m. The typical sample frequency was 96,000 samples, with a mean of 1920samples per echo recorded. The signal pulse length was 120 µs.

The range length for the recorded Innomar SBP data was adjusted when needed during the survey operations according to the observed water depth and sub-seabed penetration and spans between 5 and 80m. The parameters above optimise the Innomar sub-bottom profiler to capture a range of up to 10 m below the seabed. However, the penetration depth largely depends on the acoustic properties of encountered substrates.

2.2.4 Raw Data quality

Sub-bottom profilers (SBP) are essential tools for defining and characterising sediment structures in the shallow subsurface, primarily focusing on unlithified sediments. Under favourable conditions, SBP systems can also detect the surface of the underlying bedrock. The raw data collected from the Innomar SBP system meets project specifications and is fit for its intended purpose, as subsurface features are well delineated across the survey area. For this report only Raw Segy data have been provided without any post processing or filtering applied.

Sub-seabed reflectors show strong, continuous signals. However, some datasets exhibit burst noise, introduced by the sparker, appearing as vertical stripes in the data (Figure 23). This noise is likely caused by cross-talk between the survey instruments. Despite these artefacts, the seabed reflectors remain visible and continuous, and the noise does not affect the penetration depth. A clear example of data without burst noise is shown in Figure 27.

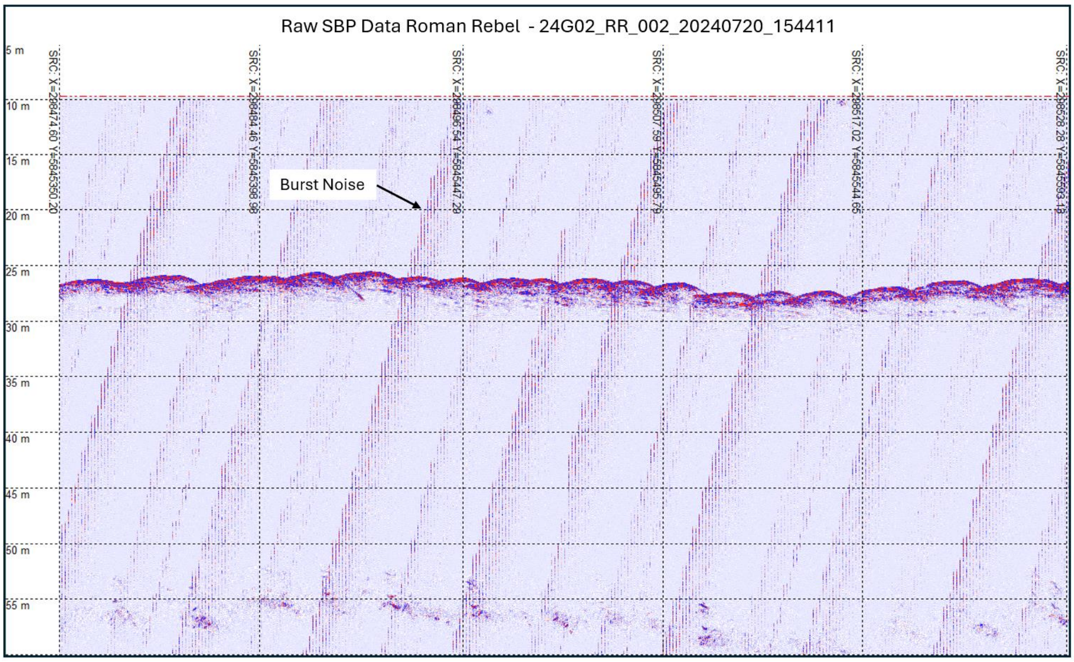

FIGURE 23: EXAMPLE OF RAW SBP DATA ACQUIRED ON THE ROMAN REBEL DISPLAYING BURST NOISE INTERFERENCE FROM THE SPARKER

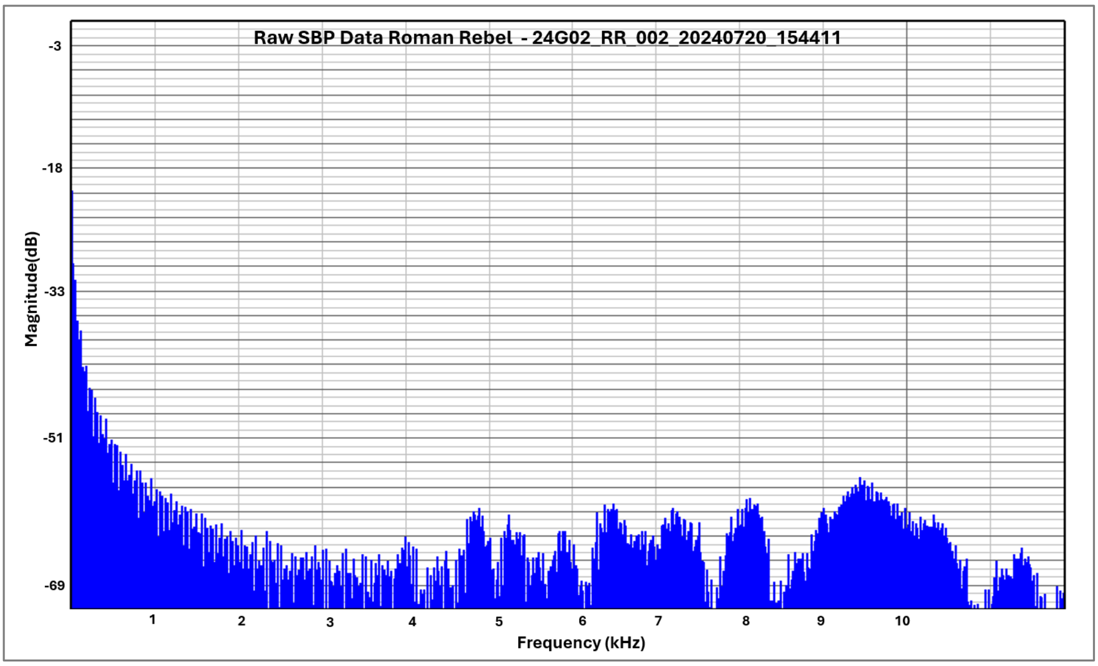

FIGURE 24: AN EXAMPLE SPECTROGRAPH REPRESENTING ONE TRACE OF THE INNOMAR MEDIUM-100 ON THE ROMAN REBEL

The spectrographs provide further insight into the noise patterns. The spectrograph in Figure 24 corresponds to the sub-bottom profile from the Roman Rebel (Figure 23), where low-frequency noise is observed up to approximately -18 dB at frequencies below 5 kHz, with significant noise concentrated between 1–2 kHz. Additionally, interference near 10 kHz suggests the presence of high-frequency noise, likely originating from other survey instruments.

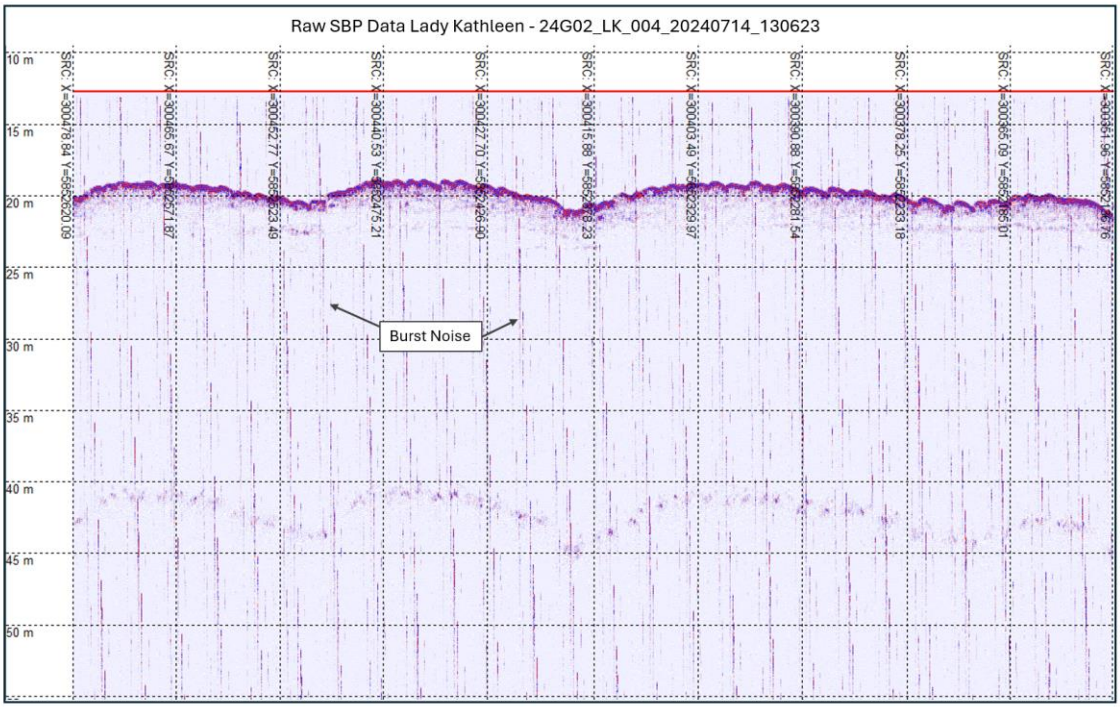

FIGURE 25: EXAMPLE OF RAW SBP DATA ACQUIRED ON THE LADY KATHLEEN DISPLAYING BURST NOISE INTERFERENCE FROM THE SPARKER

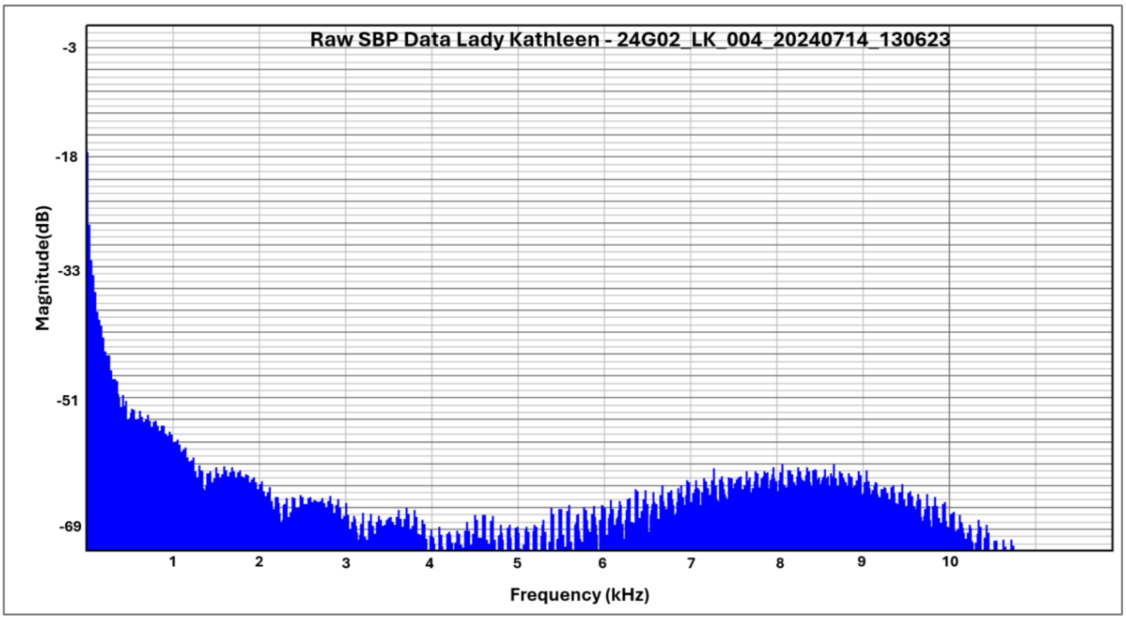

FIGURE 26: AN EXAMPLE SPECTROGRAPH REPRESENTING ONE TRACE OF THE INNOMAR STANDARD ON THE LADY KATHLEEN

In Figure 25, which correlates with the sub-bottom profile from the Lady Kathleen (Figure 25), similar low-frequency noise is evident, with levels again reaching up to -18 dB, predominantly concentrated below 5 kHz. Significant peaks between 1–2 kHz are apparent, suggesting that this low-frequency noise is generated by the MC UHRS equipment (sparker) and vessel activity. The high-frequency noise above 10 kHz is also visible, likely introduced by other survey equipment, such as the multibeam echosounder.

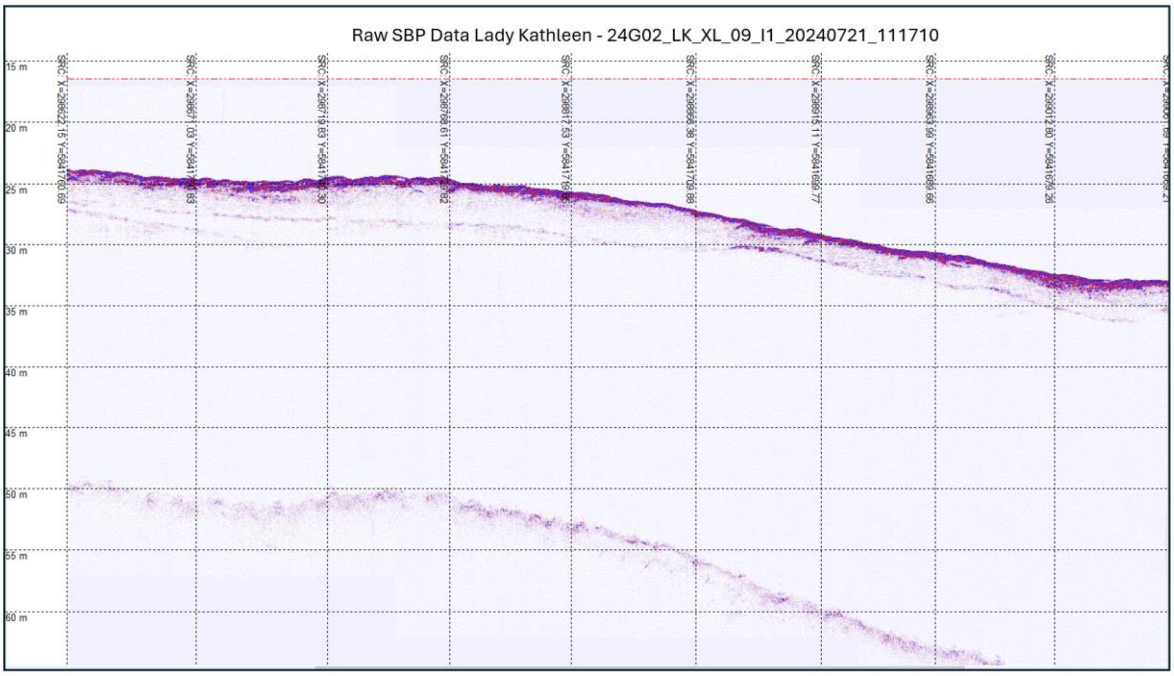

FIGURE 27: EXAMPLE OF RAW SBP DATA ACQUIRED ON THE LADY KATHLEEN WITH NO BURST NOISE INTERFERENCE FROM THE SPARKER WHEN SURVEYED WITHOUT SPARKER SOURCES TOWED BEHIND THE VESSEL

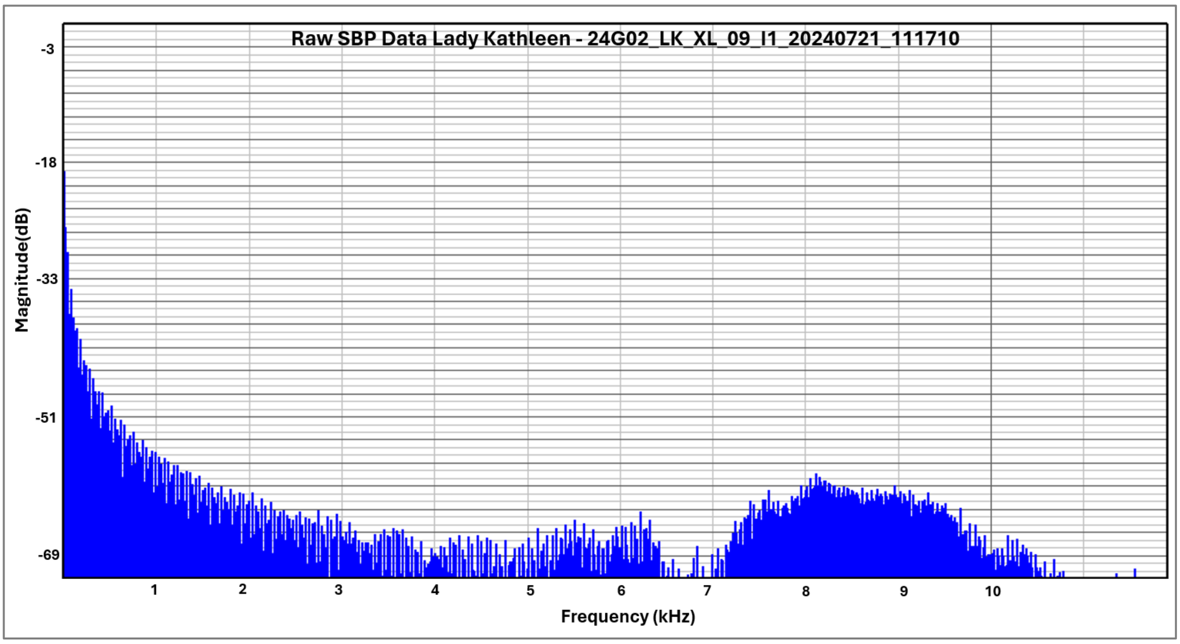

FIGURE 28: AN EXAMPLE SPECTROGRAPH REPRESENTING ONE TRACE OF THE INNOMAR STANDARD ON THE LADY KATHLEEN

In contrast, Figure 28 corresponds to the clean sub-bottom profile from the Lady Kathleen (Figure 27). This spectrograph shows less prominent noise, with low-frequency interference still concentrated below 5 kHz but at a slightly lower intensity. Minor peaks above 10 kHz are also observed. This interference can be mitigated through post-processing by applying a bandpass filter and burst noise filter to remove excess low- and high-frequency signal components, resulting in cleaner data.

3 Results

3.1 General narrative on the survey results

Multibeam bathymetry acquired in the Arklow Bank survey displays water depths ranging from -11.66 m to -51.04 m LAT for the Roman Rebel data and from -9.79 m LAT to -49.38 m LAT for the Lady Kathleen data. The water depths are relatively shallower near the main sandbank ridge, which runs along the north-east - south-west axis and intersects the centre of the survey area. From analysing the slope gradient and contours, in general the bathymetric slope is moderate to low with high slope values near crests of sandwaves.

3.2 Multibeam bathymetry

3.2.1 Final Bathymetric product – Roman Rebel

In line with the project's specifications, the bathymetry was gridded both at 0.25 m and 1 m spatial resolution, with average values of soundings within each cell. The bathymetry of the Arklow Bank displays a diverse topography, with the deepest readings (down to -51.04 mLAT) being measured in the southeastern and northeastern parts of the survey, while the shallower readings (up to –11.66 mLAT) are found in the southwestern area. Gaps are observed in the dataset due to the survey design prioritizing the geotechnical areas of interest, however, all these areas are fully covered.

Regarding the observed seabed morphology, pervasive sandwaves of various scales are observed in the bathymetry. Generally, two main types of sandwaves can be distinguished: large sandwaves with heights of c. 3 to 6 m and wavelengths of c. 100-200 m and medium sandwaves with heights of c. 0.2-0.5 m and wavelengths of c. 10 m. The two types are present both in Roman Rebel and Lady Kathleen datasets.

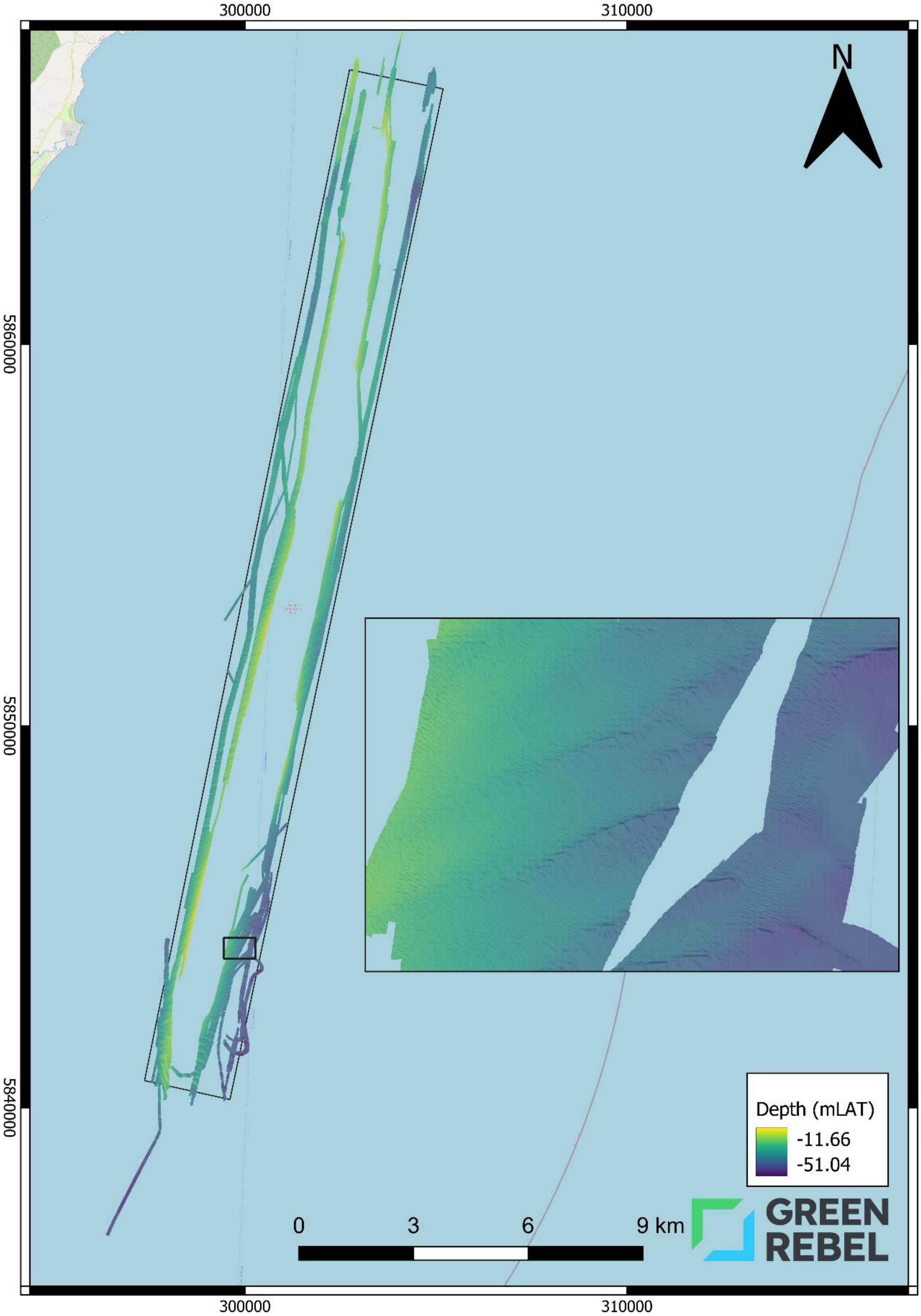

FIGURE 29: ROMAN REBEL'S MBES BATHYMETRY – OVERVIEW OF THE ENTIRE SITE. 1 M SPATIAL RESOLUTION.

3.2.2 Final Bathymetric Product – Lady Kathleen

The Lady Kathleen's bathymetric data (Figure 30) also display the diverse topography typical for large sand banks like the Arklow Bank. The deepest readings (down to -49.38 mLAT) are generally observed farther from the main ridge of the sand bank. On the other hand, the shallower readings (up to -9.79 mLAT) are found are associated with the shoal posed by the Arklow Bank's rising relief.

Large and medium sandwaves are observed in the Lady Kathleen data, characterized by the same morphology and patterns as those observed in the Roman Rebel data.

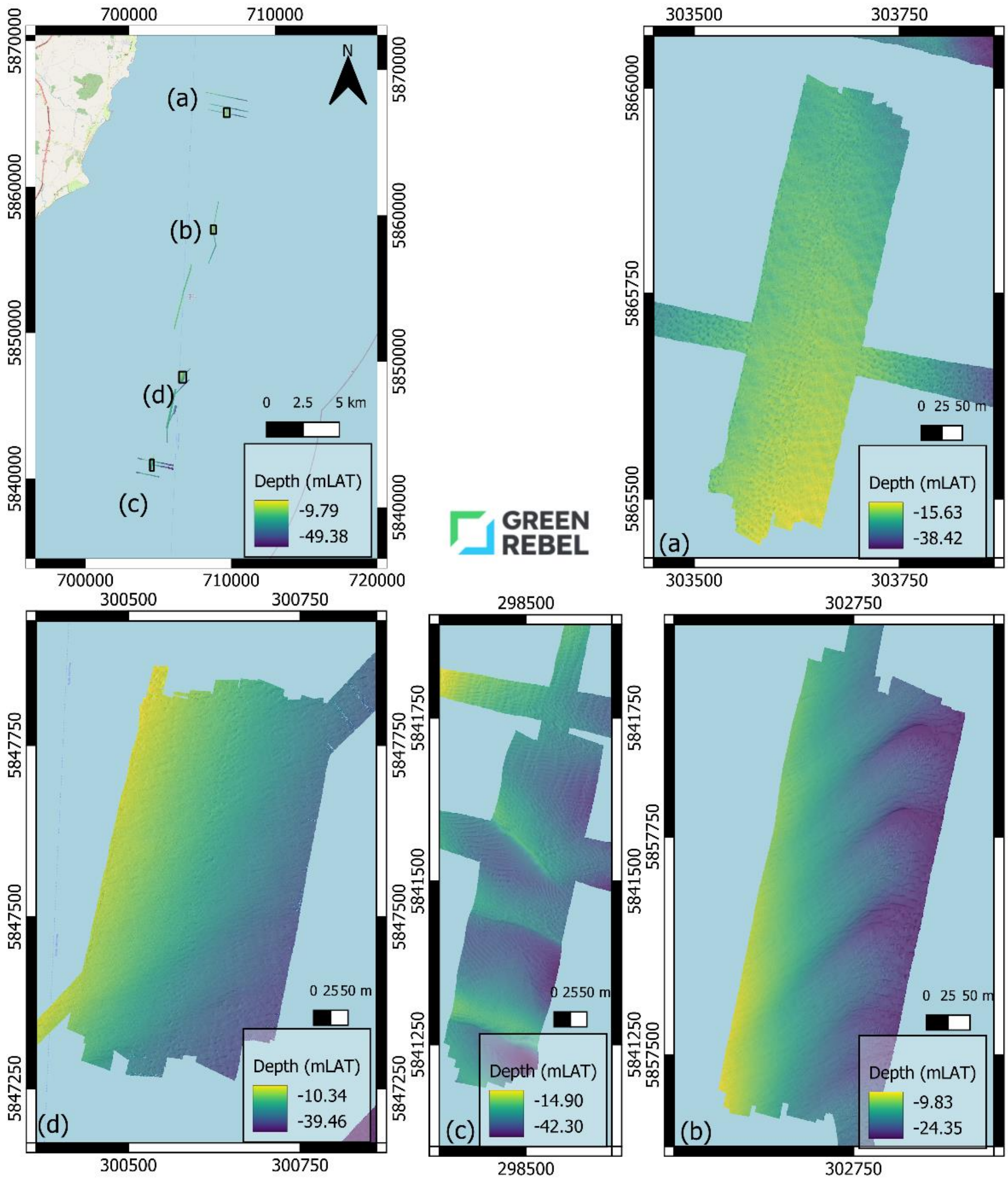

FIGURE 30: LADY KATHLEEN'S MBES BATHYMETRY – OVERVIEW OF THE ENTIRE SITE. 0.25 M SPATIAL RESOLUTION. (A), (B), (C) AND (D) REPRESENT CLOSE UPS OF THE AREAS SHOWN IN THE MAIN MAP (TOP LEFT).

3.3 Potential Engineering Geohazards

3.3.1 Surface Geohazards

Pervasive medium to large sandwaves were detected in both Lady Kathleen and Roman Rebel datasets, and as such the seabed can be deemed as highly dynamic. The upper sediment layer of the bank is renowned for its dynamism, driven by ebb and flood tidal current flows, creating complex hydrodynamic cells around the bank's main ridge (e.g. Creane et al., 2023). Recent studies indicate that on the southeastern side of the bank, sandwaves have an average height of 3 meters and a wavelength of 140 meters, migrating southward at an average rate of 23 meters per year (Creane et al., 2022). In contrast, sandwaves on the southwestern side of the bank have an average height of 2.3 meters and a wavelength of 123.5 meters, migrating northward at a rate of 32.7 meters per year (Creane et al., 2022).

During the survey conducted for this report, some of the adjacent/infill/rerun lines were acquired at time intervals of several days (as seen in the trackline figures: Figure 2 and Figure 3). This allowed to conduct difference modelling, i.e., subtracting consecutive datasets from each other to see how the seabed changes over relatively short time periods (5 days for the Roman Rebel and 6 to 14 days for the Lady Kathleen).

DEM of Difference (DoD) for the Roman Rebel lines Scouting_13 and RR_69 acquired at 5-day time interval is shown in Figure 31. Submeter geomorphic changes are present across the entire area of overlap between the lines utilised for the difference modelling. They are clearly periodical, with parallel, alternating stripes of cells indicating erosion and deposition. These difference patterns can be interpreted as moving sandwaves, and are not associated with equipment-induced uncertainties.

The results of the difference modelling conducted for the Lady Kathleen lines LK062 and LK062_I1 (upper figure panel, 14-day time interval) and LK088_I1 and LK088_I2 (lower figure panel, 6-day time interval) are shown in Figure 32. Pronounced geomorphic changes are visible in both DoDs, showing submeter values in the shorter, 6-day period and exceeding 1 m in the longer 14-day period. In both cases, the changes exhibit wave patterns similar to the Roman Rebel data-derived difference model, providing additional evidence to the active sediment transport related to sandwave migration at the site.

Highly mobile sediments should be considered as a potential geohazard as they may cause instability to the monopile fundaments, through local scour and/or sediment build up, and the related hide/exposure cycles of structures to hydrodynamic forcing, change in the distribution of loads (i.e., introduce dynamic loading) and other processes. This may result in the necessity to include scour mitigation/protection measures to the wind farm design.

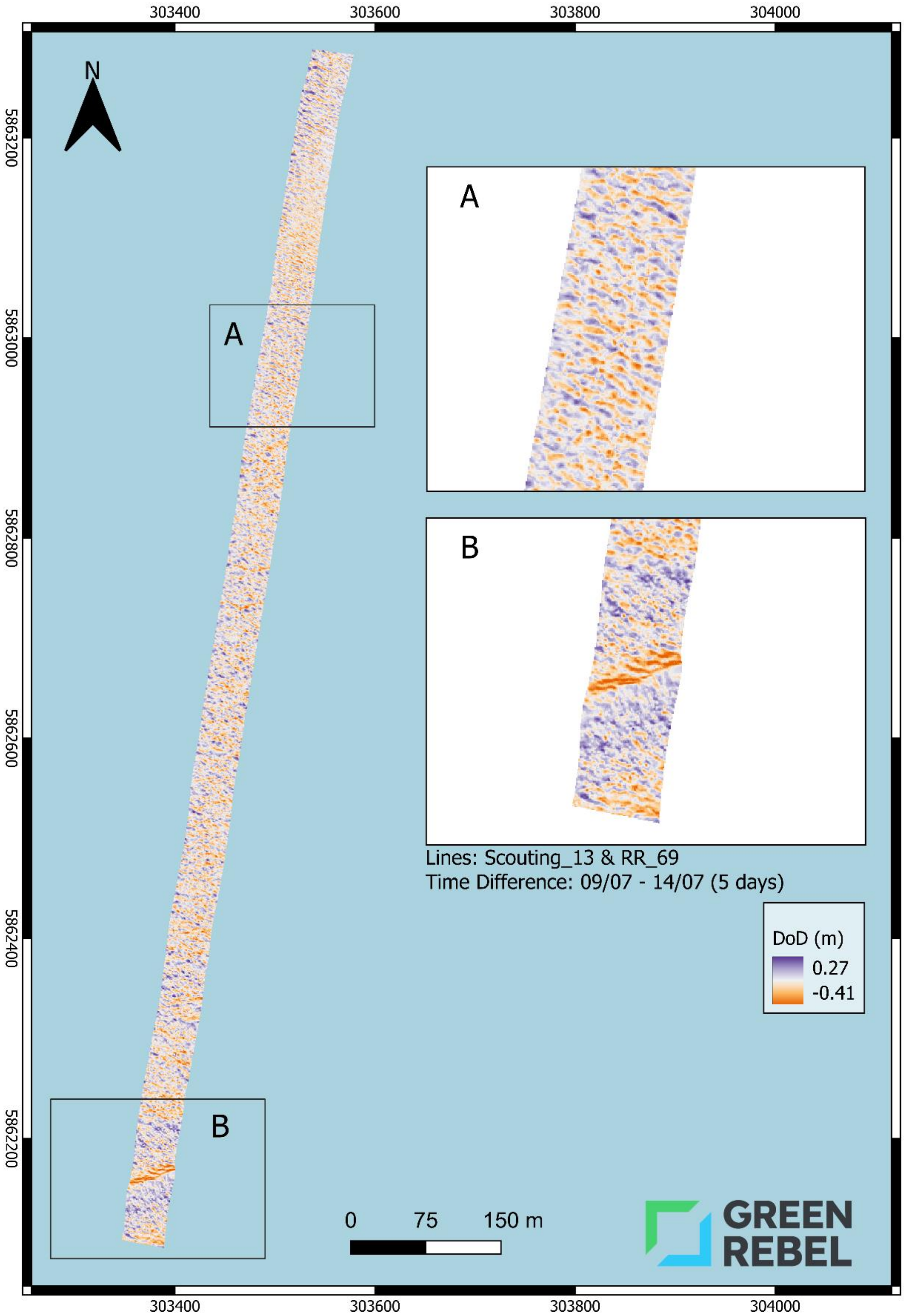

Figure 31: DEMs of Difference (DoDs) created using the Roman Rebel's bathymetric data. Upper panel shows differences in the overlapping data for lines Scouting_13 and RR_69.

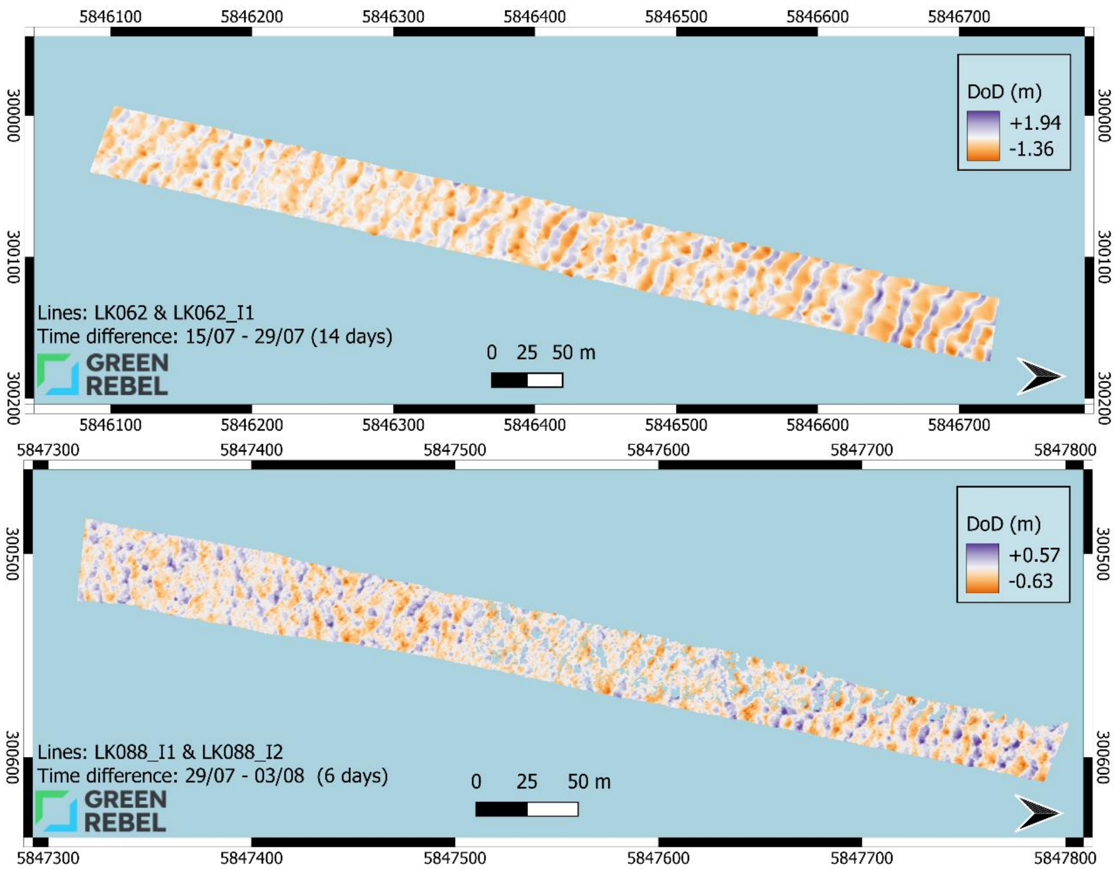

Figure 32: DEMs of Difference (DoDs) created using the Lady Kathleen's bathymetric data. Upper panel shows differences in the overlapping data for lines LK062 and LK062_I1. Lower panel shows differences between the overlapping data for lines LK088_I1 and LK088_2. Time intervals at which the consecutive line data were acquired were 14 and 6 days, respectively.

Additionally, boulders are treated as obstacles to offshore engineering and considered as a geohazard. Isolated instances as well as groups of boulders were detected in the 0.25 m resolution bathymetric grids and manually picked in GIS. Point shapefiles were generated representing their locations (1010 boulders), as well as other contacts – spudcan depressions (12) and unknown sonar contacts (2), as seen in the bathymetric DEMs.

4 Conclusions and Recommendations

MBES Bathymetry data provided a high-resolution insight into the topographic variability of the site, characterized by ubiquitous mobile bedforms (sandwaves) and steep reliefs typical for sand bank geomorphologies. MBES bathymetry reveals areas where seabed morphology varies and highlights where sediment mobility is present across the Arklow Bank 2 site. Difference modelling conducted using data acquired at time intervals of 5 to 14 days show active sandwave mobility, which should be considered as an engineering geohazard. Scattered individual boulders and boulder fields present in the area should be also taken into account when planning the wind farm development.

5 Appendices

5.1 Appendix 1

Seismic data handling

Raw Innomar sub-bottom *.ses3 and Raw S-UHRS *.cod data were converted to SEGY before processing. SEGY is a universal sonar format that can be edited and viewed in various software and programs. By importing the SEGY format, the trace headers were adjusted and edited within the software with additional gains, offsets and filters applied to the original file. Information pertaining to the handling of seismic data is provided below.

Relevant bytes for the processed Innomar SBP .sgy data

SEG-Y bytes	***Property***
All co-ordinates, depths and times multiplied by a scalar equal to 100. Big Endian byte order, IEEE Float 32 Bit	
1-4	Trace sequence number
9-12	Original Field Record Number
73-76	Source X co-ordinate, scalar=100
77-80	Source Y co-ordinate, scalar=100
109-110	Delay recording time (storing vertical corrections for the time domain data), scalar=100
181	Additional delay recording time
49-52	Source depth (storing vertical corrections for the depth domain data), scalar=100
	Velocities used for TWT/Depth conversion: 1500 m/s water, 1600 m/s sediments

References

Creane, S., Coughlan, M., O'Shea, M., & Murphy, J. (2022). Development and Dynamics of Sediment Waves in a Complex Morphological and Tidal Dominant System: Southern Irish Sea. *Geosciences*, *12*(12), 431. https://doi.org/10.3390/geosciences12120431

Creane, S., O'Shea, M., Coughlan, M., & Murphy, J. (2023). Hydrodynamic Processes Controlling Sand Bank Mobility and Long-Term Base Stability: A Case Study of Arklow Bank. *Geosciences*, *13*(2), 60. https://doi.org/10.3390/geosciences13020060