Sea Trial Report: Synapse 4-Magnetometer Array

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System Overview

Synapse is a new ultra-light, high-sensitivity marine magnetometer array system based on low-power rubidium optically-pumped scalar sensors.

The array is scalable from 1 to 30 units, with automatic time synchronization handled by the networking hardware in each towfish.

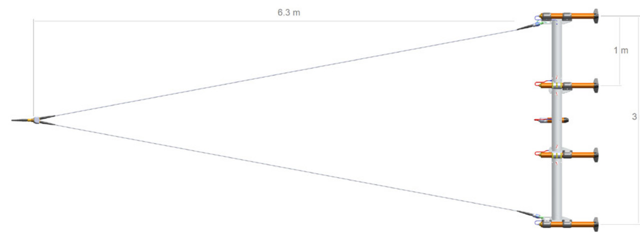


Figure 1 - Plan view of the 4-magnetometer Synapse array frame with a 6.3m Y-split cable for connecting to soft tow cable.

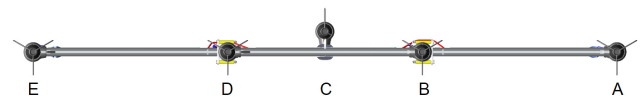


Figure 2 - Tail view of the streamlined 4-magnetometer Synapse array with nodes identified. Node C contains the depth, altitude and tilt sensors, while nodes A,B,D,E contain magnetometers.

The rubidium magnetometer sensor can sample at rates up to 20 Hz while maintaining low noise, excellent resolution and sensitivity, and having only one dead zone: equatorial. In contrast to traditional optically pumped magnetometers, which have both equatorial and polar dead zones.

Synapse towfish can be used as standalone magnetometers or combined into an array and feature flexible configurations that may include any combination of the following sensors: scalar magnetometer, pressure sensor, altimeter and tilt/IMU. Standard configurations include a 1000m pressure housing, a network status LED and a leak detector. Telemetry and power are supplied to all nodes via the same 2-conductor link from the vessel.

The Synapse evaluation system used for this demonstration included:

- A 4-magnetometer streamlined rigid and lightweight aluminum frame.
- The frame had an overall width of 3m and 1m magnetometer sensor spacing.
- An additional attitude node positioned in the center of the frame contained a pressure sensor, an altimeter (SBES) and a 3-axis gyro-compensated IMU for frame tilt monitoring.
- An 80m soft tow cable for towing the array, connected via a 6.3m Y-split adapter cable.

Sea Trial Survey

The purpose of the sea trial was to evaluate the performance of the Synapse 4-magnetometer array on a boat-towed survey at a location with a relatively flat bottom and an average depth of 20m, with the possible inclusion of a survey over a surrogate target of known size and magnetic properties. We selected a site meeting these criteria in The Solent, UK.

The 12 meter long towing vessel, equipped for nearshore geophysical survey, included state-of-the-art instrumentation, auto-pilot, Multi-Beam Echo sounder (MBES) and Differential GPS.

We'd selected a 50 kg iron surrogate target for this evaluation survey, but didn't deploy it due to limited time.

The sea trial occurred in the spring of 2023 at Gurnard Bay in an area with a historic wreck and an undersea cable.

Since the exact towing characteristics of the prototype test frame were unknown before test day, we dedicated time to evaluating the optimal towing deployment configuration and skipped the deployment of the surrogate target item. Towing configuration parameters included tow cable length and additional cable weights required to achieve the optimal survey altitude above the seafloor.

Details of frame configuration testing are outlined in Table 1.

Table 1- Operational timeline and notes on towing configuration

Time (UTC)	Notes	Eastbound Towing	Westbound Towing
09:45	Frame deployed. Calibrate depth sensor to 0.0m.	—	Depth: 2.9m, Alt: 18.9m, Speed 1.3m/s
10:00	Cable length increased to 40m.	Depth: 5.3m, Alt: 17.2m, Speed 2.7m/s	Depth: 4.5m, Alt: 18.4m, Speed 1.9m/s
10:50	Recover the frame and add a cable weight (2.8 kg) to 20m mark.	Depth: 7.5m, Alt: 14.8m, Speed 2.4 m/	—
11:03	Cable length increase to 80m.	Depth: 12.0m, Alt: 12.0m, Speed 2.1m/s	—
11:09	Recover the frame and add 2 more cable weights (lead wrap) for a total of approximately 8-9 kg.	—	—
11:35	Deploy the frame with 80m of cable.	—	—
11:42	Begin running survey lines without further changes to cable length or weights.	Depth: 16.8m, Alt: 7.9m, Speed 0.5 – 1.0m/s	Depth: 19.0m, Alt: 6.0m, Speed 2.7-3.1m/s
16:07	Complete survey. Recover the frame.	—	—

Figure 3 - Synapse 4-magnetometer array assembled on deck

Figure 4 - Connections between array nodes were routed through the frame to protect cables and reduce drag.

Figure 5 - Mechanical tow point featured a non-magnetic 2-axis swivel and a soft cable electrical connector

Figure 6 - Deployment of the array frame was accomplished by two deckhands and did not require a crane

Figure 7 - Marine Magnetics BOB data logging software was used to interface to the magnetometer array and monitor the real-time data including the frame orientation. Navigation was handled independently using the vessel's standard equipment.

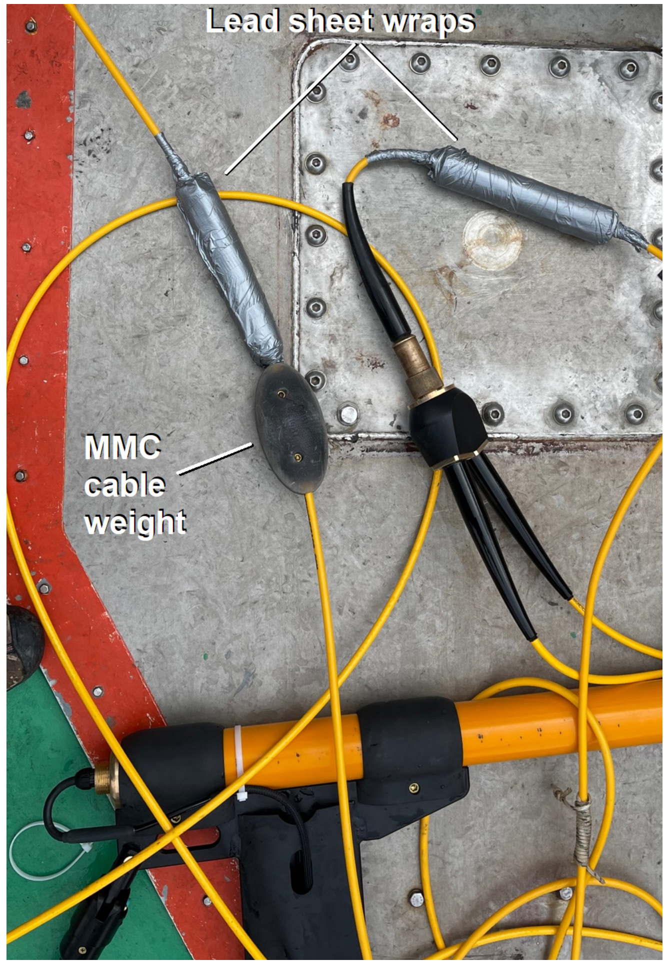


Figure 8 - Cable weights necessary to achieve the desired survey depth and altitude above seafloor included one 2.8 kg Marine Magnetics cable weight and two custom lead sheet wraps of approximately equal weight.

Results

16 survey lines were completed during the test, including 11 eastbound lines and 5 westbound lines. Of those, 8 lines were kept for the final data set based on their spacing, consistent altitude and lack of excessive overlap. The rest of the lines needed to be excluded because they either passed too far to the North of the main survey block, were not sufficiently straight or had altitude that was significantly different from the rest. Very strong tidal cross currents were observed in the area, up to 4kts, which made both navigation and consistent altitude control of the frame difficult.

The final set of survey lines with an average spacing of 10m is shown on Figure 9, in combination with MBES bathymetry data collected during the same survey. Green and red flags indicate the beginning and end point of each final survey line.

The position of the magnetometer array frame behind the vessel was computed in real-time by BOB software using an algorithm that takes into account the length of the deployed cable as well as the actual path of the towing vessel and the expected curve of the soft tow cable. The resulting path of the array frame was considerably smoother than the path of the vessel thanks in part to the long 80m cable which helped average out the vessel's maneuvers and course corrections.

It should be noted however, that the position of the frame was estimated without taking the tidal current into account, which probably added significant cross-track error at times.

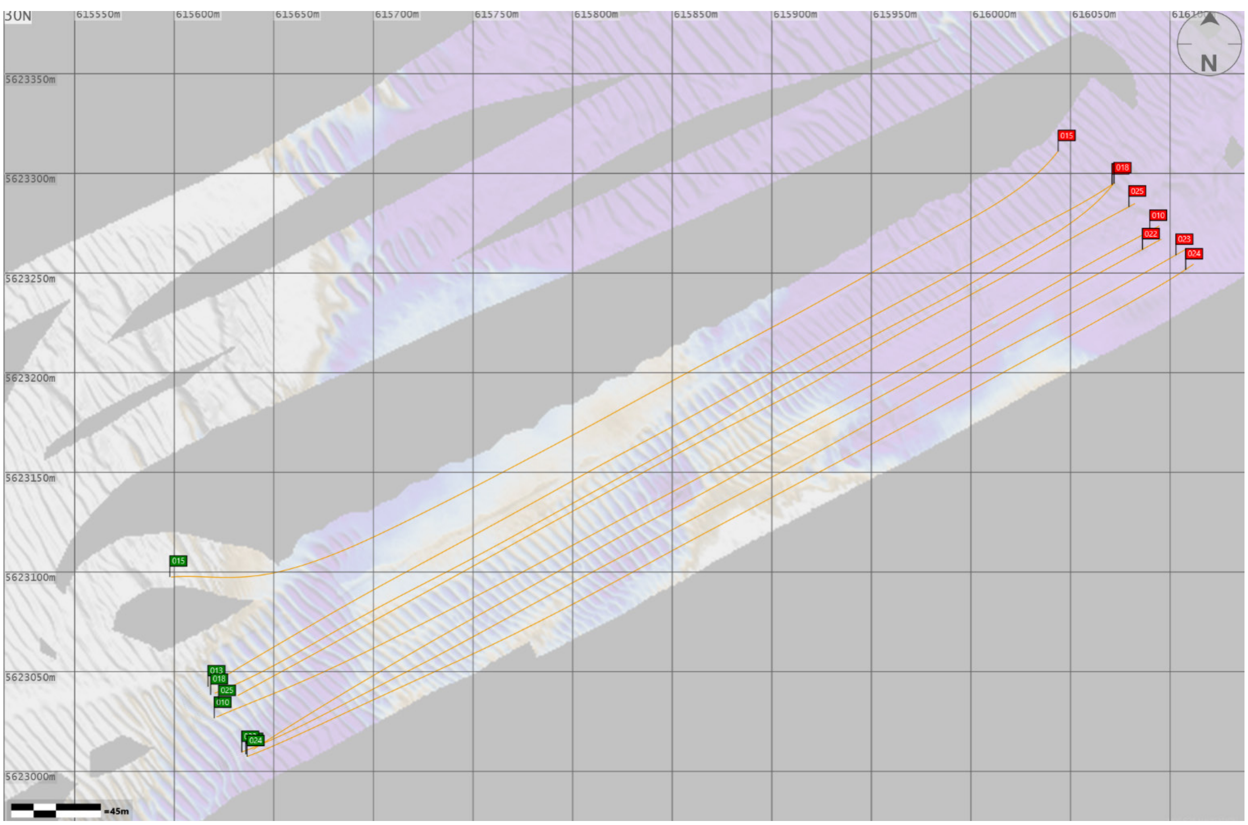


Figure 9 - Final set of survey lines with the background MBES data collected during the sea trial.

Data Processing

Data processing consisted of the following steps:

1. Layback correction to compensate for the errors in determining the combined offset between the vessel's reported GNSS position and the magnetometer sensors on the frame.
2. Base station correction to compensate for the temporal variation in the background ambient total field that occurred that day
3. Sensor levelling to compensate for any heading shifts or absolute level differences between the sensors on the frame
4. Generation of final output products in the form of Total Field and Analytic Signal maps

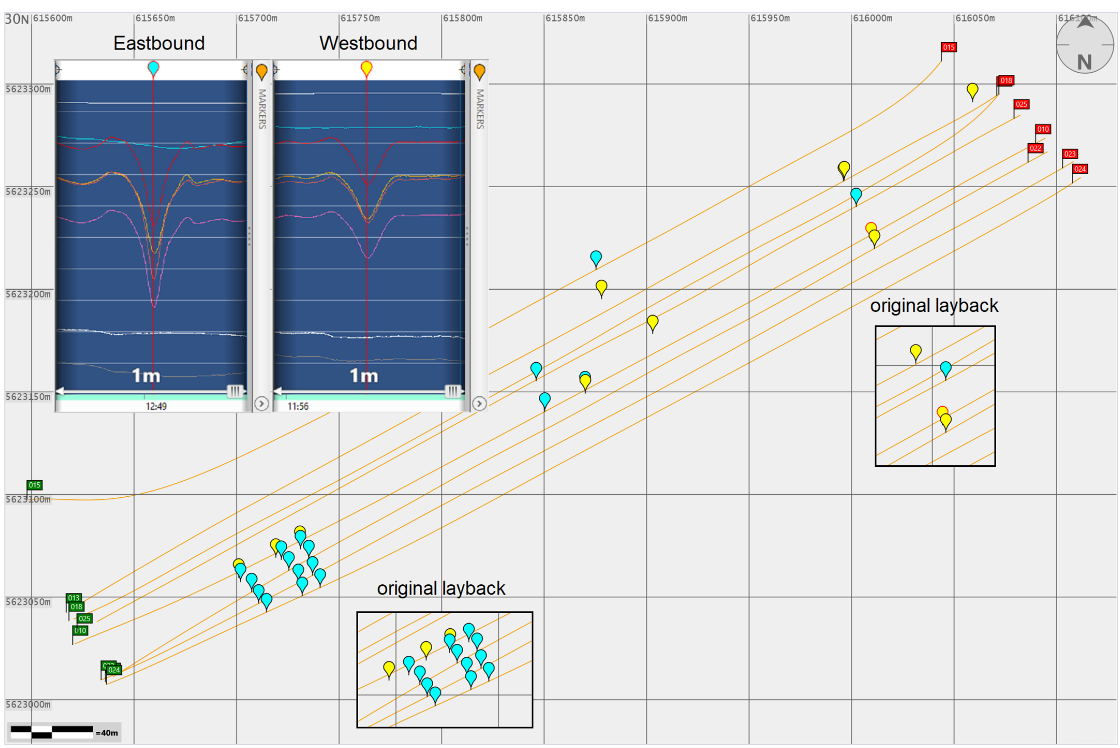
Layback Correction

The original layback, entered as 80m, corresponded to the length of the deployed soft tow cable based on the understanding that the vessel GNSS position included the necessary offsets between the GNSS receiver and the A-frame block at the stern, with which the cable length mark was aligned. BOB software then added the 6.3m offset to compensate for the Y-split adapter cable.

But no matter how precisely the initial layback offsets are measured, some error typically makes its way into the final calculations. An empirical layback measurement is essential to minimizing this source of error.

After measuring offsets between matching anomalies encountered on eastbound and westbound lines, we adjusted the layback by five meters. The improvement in anomaly peak alignment after correcting the total layback to 85m is illustrated in Figure 10, along with the colour-coded magnetic anomaly markers used to identify matching anomalies on lines with opposite headings.

Figure 10 - Layback correction involved placing colour-coded markers on matching anomalies encountered on eastbound and westbound lines, and then determining the offset between the two sets of markers. The final layback of 85m helped align marker sets.



Base Station Correction

The most dependable and precise way to correct diurnal magnetic variations is by using a local base station magnetometer near the survey location. Since the Marine Magnetics Sentinel base station wasn't available for this test, we got the diurnal correction data from a geomagnetic observatory in Hartland, Devon, UK, slightly over 200km away. This distance led to discrepancies between the local background variation and the observatory data.

Though we could only download the data two weeks after the survey, reviewing the background variation data for the six-hour survey window showed a significant change of nearly 50 nT, indicating that we needed to apply base station correction to the data before any further processing could be done (as shown in Figure 11).

Displaying the observatory background variation profile on the same graph as the towed magnetometer profile revealed a good correlation between the two (Figure 12). The survey line start and end markers are shown as green and red flags along the top of the survey profile plot. Note the pronounced difference in the average total field level between the beginning and end of survey.

Applying base station correction to the survey data helped compensate for the long-term trend visible in the towed magnetometer data and flatten the overall survey profile, eliminating most of the differences between survey lines covered at different times of the day, and also shifts within the survey lines themselves that would have been difficult to correct with traditional levelling methods.

It should be noted however that the observatory correction data did not entirely eliminate all temporal changes because of distance from the survey area and possible difference in local geology. A local base station reference magnetometer would have offered a more accurate correction.

Altitude variation between survey lines can account for the remainder of the differences in the average field levels between lines.

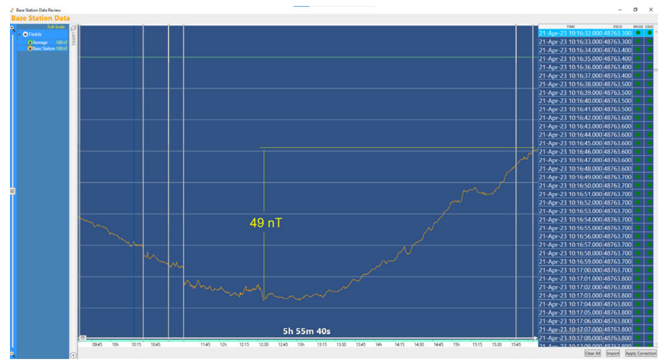


Figure 11 - Base station magnetometer data obtained from the British Geological Survey Hartland observatory located in Devon revealed a considerable change in the background total field during the 6 hour survey time window

Figure 12 - Data profile of the entire survey, before and after base station correction (Vertical scale: 100 nT). The white line in the upper plot corresponds to the background total field change and shows good correlation with the long-term trend in the towed array data.

Sensor Levelling

After marking the survey lines and applying layback and base station corrections, the survey data were exported from BOB software in CSV format for further processing in Oasis Montaj. The output data contained both raw and base-corrected magnetic field readings for each sensor, along with separate sets of coordinates for each individual magnetometer in the array, and a common set of depth, altitude and tilt (roll and pitch) values corresponding to the center of the frame.

Reviewing the data profiles for each survey line confirmed that the four magnetometers had excellent time synchronization throughout the survey but showed small constant offsets relative to each other that changed somewhat from line to line.

We applied a simple bulk shift to help bring all four sensors to the same level on each survey line without altering the shape of the profiles in any way or affecting the signal's frequency spectrum. The shift required to achieve a common level for all four sensors on the frame ranged between -1.8 nT and + 2.5 nT– substantially lower than the correction required to compensate for diurnal background variation. The difference in sensor readings between eastbound and westbound lines (i.e. heading error) was < 2 nT in all cases.

The total magnetic field map was generated using a grid cell size of 1m, and blanking distance of 15m to help fill the gaps between boat passes. The map shows good consistency across survey lines, and appears to correlate well with the features visible in the underlying MBES bathymetry data. Small undulations visible along the actual sensor paths could be attributed to frame orientation changes (pitch and roll of the frame) in the tidal current.

See the Discussion section for further details.

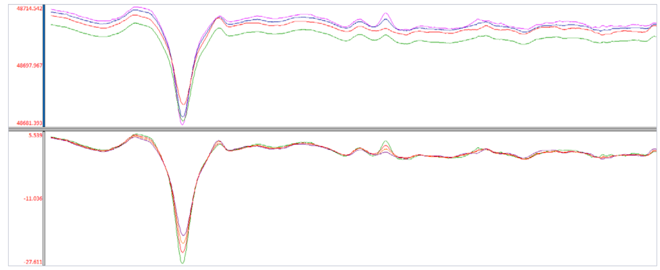


Figure 13 - Total field profiles for line #2 (westbound) showing 4 sensors on the same scale, before and after sensor levelling

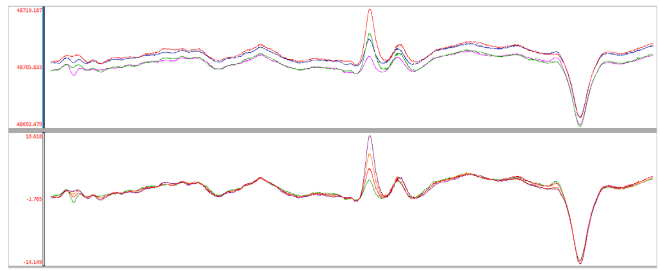


Figure 14 - Total field profiles for line #10 (eastbound) showing 4 sensors on the same scale, before and after sensor levelling.

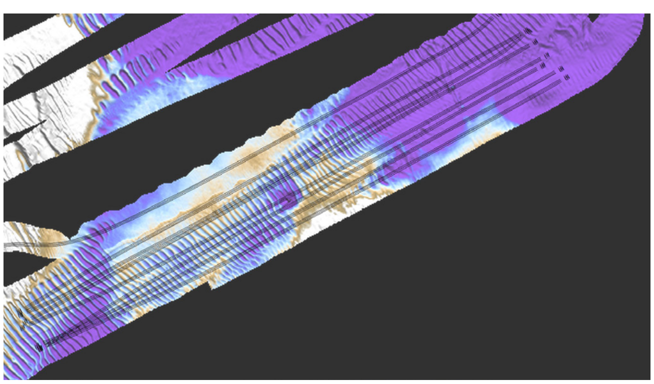


Figure 15 - MBES data captured during the survey, displaying the magnetometer array paths with individual sensors in the array.

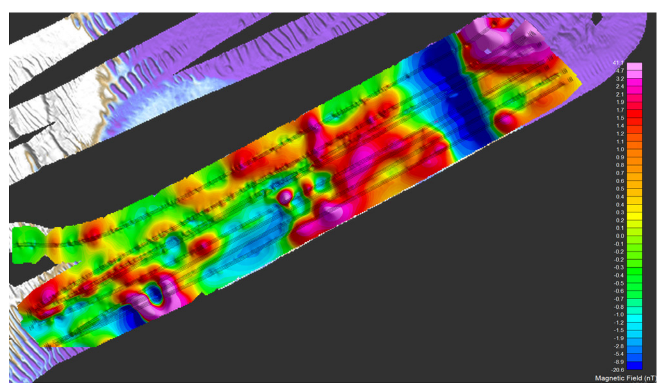


Figure 16 - Total Magnetic Field map generated using the selected survey lines

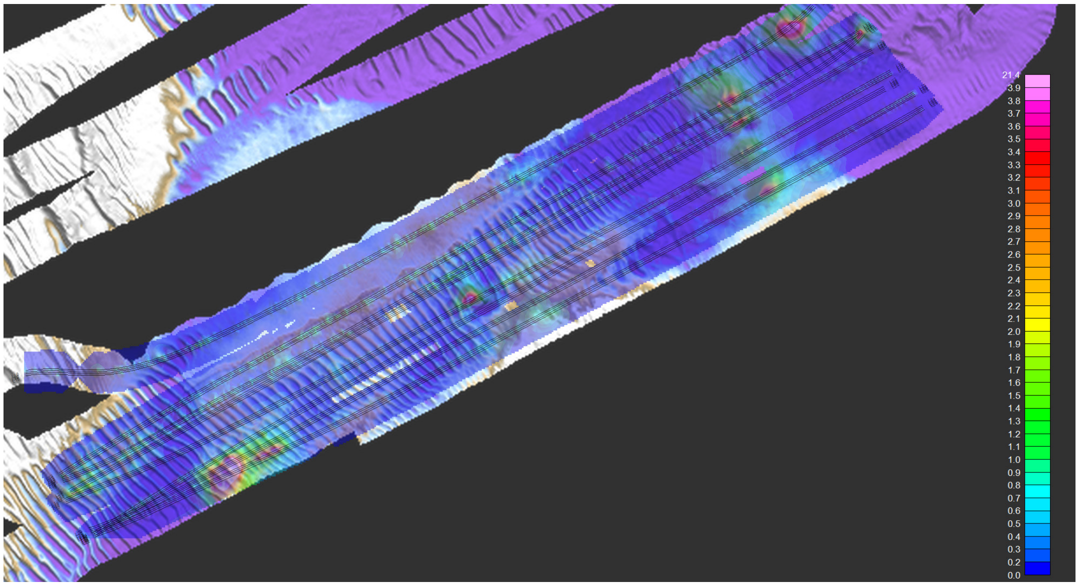


Figure 17 - Analytic Signal (Total Magnetic Gradient) displayed using linear colour scale, with transparency increased to show underlying MBES data. Two of the three prominent magnetic anomalies (center and NE corner) match features visible on the bottom and illustrate good positioning match between acoustic and magnetic data. The third magnetic anomaly (SW corner) has no corresponding surface anomaly and illustrates the magnetometer's ability to detect objects that are buried beneath the surface

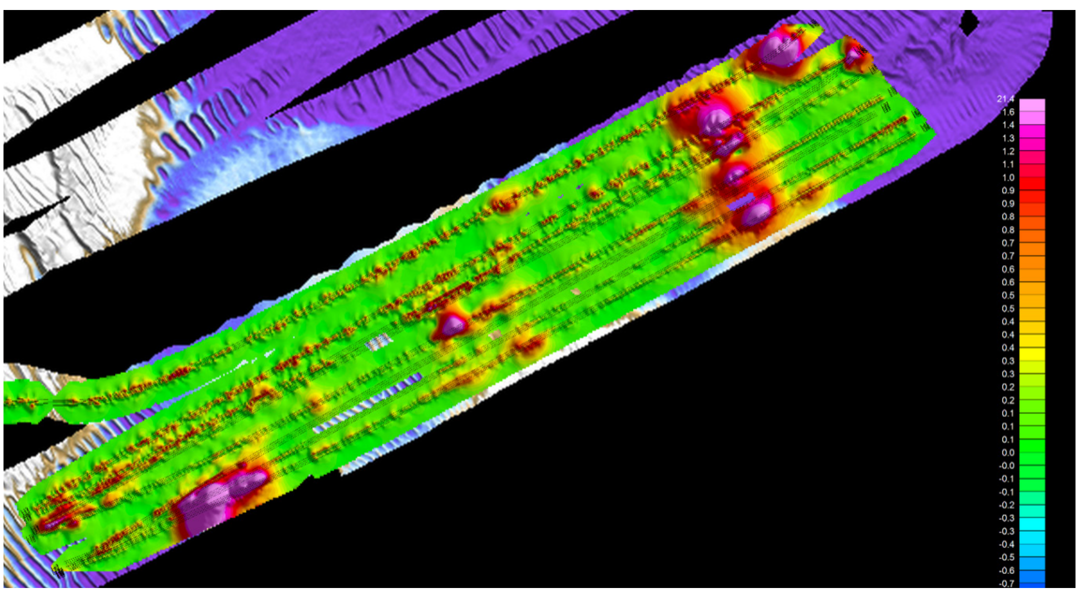


Figure 18 - Analytic Signal (Total Magnetic Gradient) displayed using an adaptive colour scale. (Negative values on the colour scale bar should be ignored). Gaps in the map along some of the lines correspond to data that was excluded due to excessive frame roll angle. Noise visible along the lines appears to correlate with the frame motion (pitch and roll variation).

The Multi-Sensor Advantage

One of the key advantages of having an array of multiple magnetometers as opposed to a single magnetometer lies in the capture of additional data points sampled in the transverse direction relative to the survey line, where data density is usually lacking. This helps the subsequent interpolation to produce results that are more accurate and better represent the complexity of the real world magnetic field.

The data profile of survey line #10 (Figure 19) illustrates a good example of the difference in anomaly sizes measured by 4 sensors mounted to a frame of only 3m width while passing over the same source object. Sensor 1 registered a 12.1 nT anomaly, while sensor 4 registered only 3.7 nT. This difference is due to the additional 3m transverse offset that sensor 4 has compared to sensor 1.

Having multiple closely-spaced 'cross-sections' of the same magnetic anomaly helps form a better understanding of its magnitude and shape, allowing more accurate calculations of horizontal position, burial depth, mass, and dipole orientation.

Figure 20 (next page) illustrates the benefit of having 4 sensors versus a single sensor to the resulting magnetic map through a comparison of data interpolated using all four sensors, versus using only 1 sensor from either end of the frame. Corresponding MBES bathymetry data captured over a notable bottom feature is also shown for reference to highlight good positional match between magnetic and acoustic data.

In cases where only a single magnetometer is used, the interpolation necessarily places the dipole minimum and maximum lobes exactly on the sensor path, due to absence of any additional data in the transverse direction.

However in the case with multiple magnetometers the interpolation has additional data points in order to generate a more accurate dipole shape. Having such additional detail on the dipole shape and orientation has additional benefits for advanced analysis (e.g. object mass or depth estimation).

The low noise performance of the magnetometer sensors is illustrated in Figure 21 and Figure 22 (next page) using examples from two of the survey lines. Features as small as 0.1 nT appear visible and distinct from the average noise.

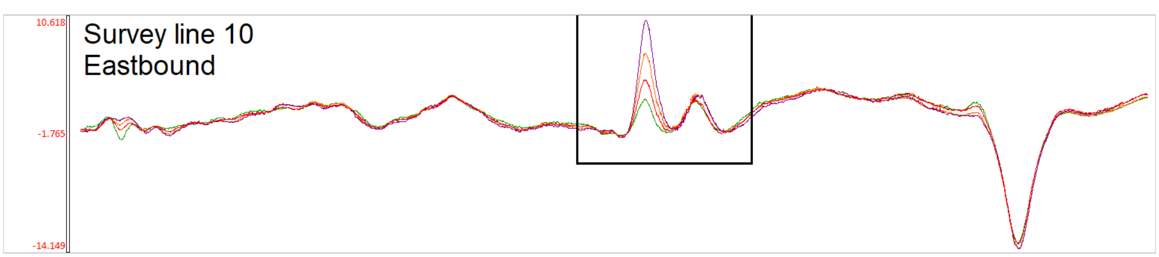


Figure 19 - Magnetic field profiles of a notable anomaly captured on line #10 over a seafloor feature visible on the MBES map

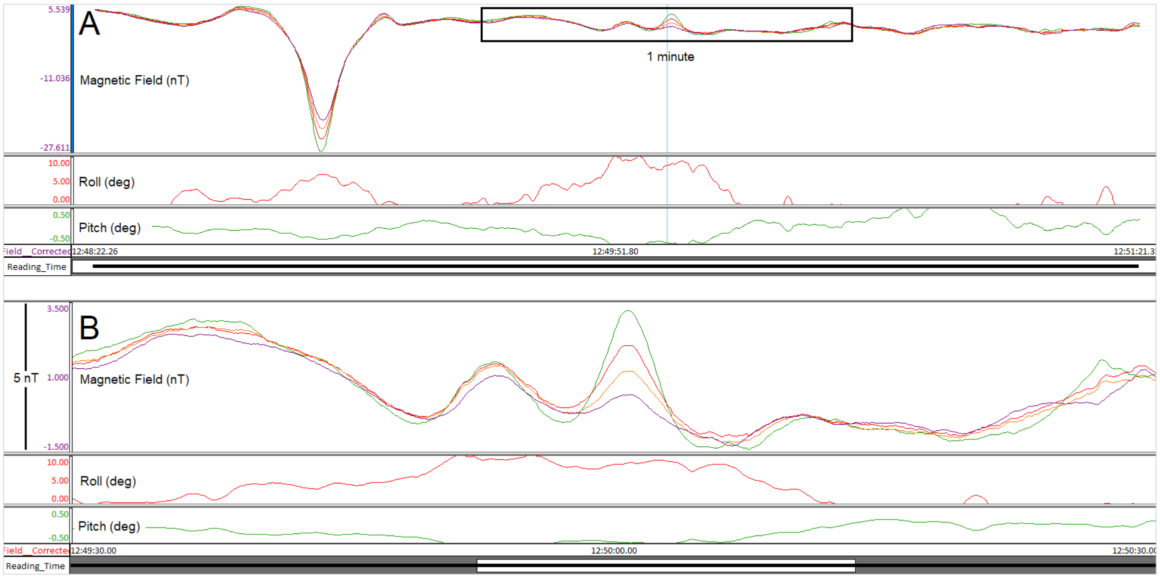


Figure 21 - Magnetometer sensor noise illustration using an example from the westbound line no. 2. — (A) shows the entire line profile. (B) shows a detailed view of a 1 min interval using a 5 nT vertical scale.

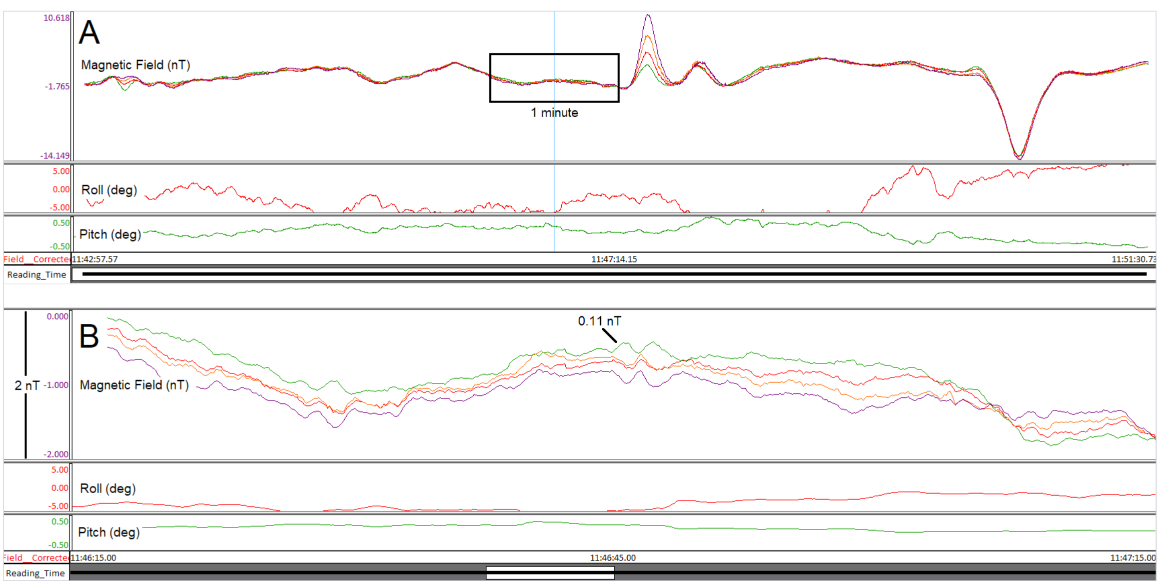
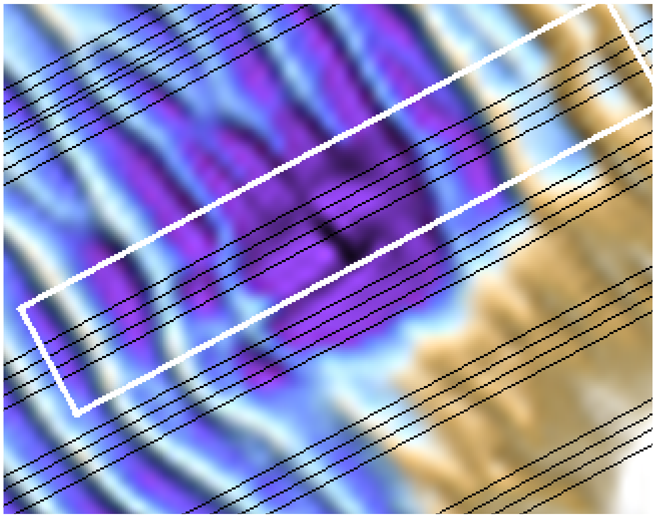
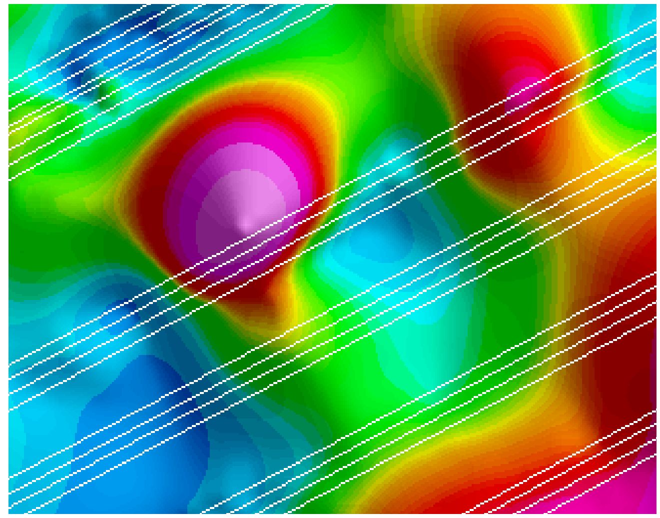


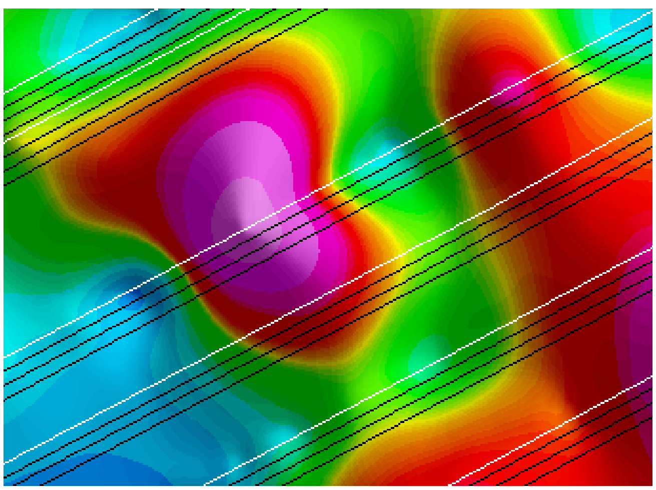
Figure 22 - Magnetometer sensor noise illustration using an example from the eastbound line no. 10. — (A) shows the entire line profile. (B) shows a detailed view of a 1 min interval using a 2 nT vertical scale.



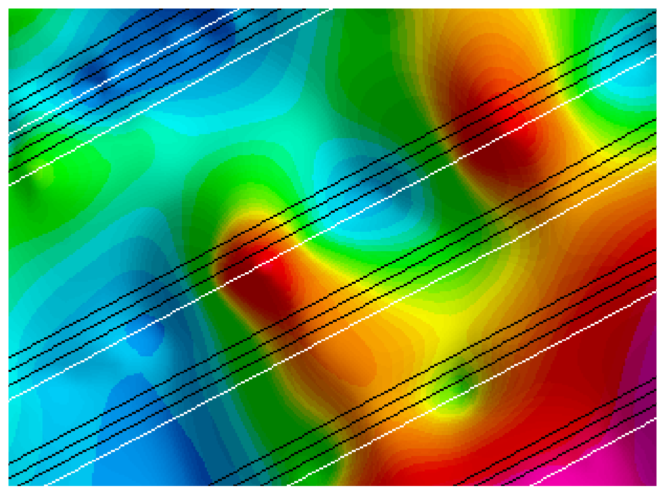
MBES data showing an anomalous feature on the seafloor, with survey line #10 highlighted displaying individual paths for all 4 magnetometer sensors in the array.



Total Magnetic Field map generated using all 4 available magnetometers in the array. Note that the dipole maximum and minimum are not centered on any specific sensor's path, but instead use all available data points.



Total Magnetic Field map generated using data from sensor 1 only (highlighted in white). Note that the dipole max and min points are placed on the path corresponding to that sensor.



Total Magnetic Field map generated using data from sensor 4 only (highlighted in white). Note that the dipole max and min points are again placed on the path corresponding to that sensor.

Figure 20 - The benefit of additional sensor data for the interpolated magnetic field map and anomaly placement

Summary

The Synapse Magnetometer Array System features small size, light weight, low power consumption, high sensitivity, and fast sampling for high data resolution.

This sea trial confirmed all of these features, and in addition highlighted fast and easy setup.

- Initial assembly of the four-sensor gradiometer and frame required minimal time (approximately 45 minutes) and allowed early transit to the survey area, maximizing data collection time.
- Finally, the array was easily deployable over the vessel side by two deckhands, meaning it was lightweight enough not to require a crane or other lifting device.

Inspection of the sensor profiles confirmed that the rubidium optically pumped magnetometer sensors exhibit low noise and show excellent time synchronization between all sensors in the array. Data processing required only the simple steps of diurnal correction and basic bulk shifting.

- No frequency-based filtering or advanced data manipulation was necessary to produce a coherent total field map.
- Two of the three notable anomalies on the magnetic maps matched the location of notable features on the MBES bathymetry data.
- The third magnetic anomaly had no corresponding surface expression in the bathymetry data and most likely originated from a buried source.

Despite the relatively small 3m width of the array frame, it's clear from both data profiles and the interpolated maps that having four sensors was beneficial to capturing additional data over the encountered anomalies, helping enhance the resolution of the final data and adding valuable directional definition in each case, as compared to a single sensor towfish.

The main challenges encountered during the sea trial can be attributed to the control and behaviour of the prototype frame and its ability to handle the current. Ongoing work will involve design improvements to stabilize the frame, to reduce roll and pitch angles to reasonable levels, less than 10 degrees.

Overall, the sea trial successfully demonstrated the capabilities of the Synapse Array and the benefits of operating multiple simultaneous total-field magnetic sensors when detecting near-surface targets and hazards.

Marine Magnetics

Marine Magnetics designs and builds highly accurate and sensitive magnetic sensors for marine environments - for oil and resource exploration, oil production, geophysical science, archaeology, and defense. Marine Magnetics products are used around the globe, on all continents, and in all the world's oceans.

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