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This document contains information on MMinE-SwEEPER's core activities. Any reference to content in this document should clearly indicate the authors, source, organisation, and publication date.

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Contents

List of Tables

List of Figures

1. Introduction

This deliverable reports on Task 6.2, which compiles current progress in studies advancing algorithms for the online processing and analysis of magnetic data from autonomous underwater vehicles (AUVs), contributing to Objective A3 on the compilation of state-of-the-art and newly generated knowledge. As with all knowledge gathered across the technological work packages (WP3–WP8), the results will support updates to the JPI Oceans Marine Munition Data Portal and will be used to develop educational materials and training datasets (WP11), thereby enabling targeted outreach and capacity-building activities under Objective D.

Marine UXO surveys are usually carried out by specialized companies using a standard repertoire of (electro-)magnetic and hydroacoustic techniques. State-of-the-art UXO detection methods in the marine environment include ship-towed magnetometer arrays, side-scan sonar (SSS), multi-beam echo sounder (MBES), sub-bottom profiler (SBP), synthetic aperture sonar (SAS), and electromagnetic induction (EMI) methods (Wigh et al., 2020, Wehner & Frey, 2022). SSS and MBES are capable of producing high-resolution images of the seabed, which makes it possible to detect surficial objects. Magnetic and SBP techniques are effective tools for detecting objects, both exposed and buried, at depths ranging from a few meters (for magnetics) to up to tens of meters (for SBP) below the seafloor. The detection depth depends on survey and sensor configurations, as well as the size or mass of the objects.

Magnetic methods are one of the main geophysical methods used to locate submerged munitions (Frey, 2020). The majority of munitions contain ferromagnetic materials, such as steel casings, which distort the Earth's ambient magnetic field. Magnetometry measures these disturbances, known as magnetic anomalies, enabling buried or partially buried objects to be detected even when they are not visible on the seafloor. The magnitude and spatial pattern of the anomaly depend on factors such as the object's size, orientation, burial depth, and magnetic properties. Total-field and vector magnetometers are both employed in unexploded ordnance (UXO) surveys, often in gradiometer arrangements to enhance sensitivity and suppress regional background variations. Magnetic methods are particularly advantageous because they are passive and robust, and can detect objects beneath sediment layers where optical or acoustic techniques may fail. Yet, magnetic methods are restricted to the detection of ferromagnetic materials since they passively measure fluctuations of the local Earth's magnetic field generated by ferrous materials.

Over the last decade, autonomous underwater vehicles (AUVs) have emerged as effective tools for conducting high-resolution marine geophysical surveys (Oehler et al., 2024; Qiao et al, 2026). Unlike towed systems, AUVs operate untethered and can maintain stable, low-altitude trajectories close to the seabed (while the mother vessel can concentrate on other duties). Their ability to follow precise survey lines at consistent velocities allows for dense spatial sampling of magnetic fields and possible anomalies, which is crucial for identifying small or deeply buried unexploded ordnance (UXO). AUVs can operate in challenging environments, including shallow waters and areas with complex bathymetry, in narrow areas like harbours, rivers, channels or lakes, in which traditional survey vessels may be limited. Furthermore, integrating magnetometers with other sensors, such as side-scan sonar, multibeam echosounders and inertial navigation systems, provides complementary datasets that support more reliable target identification.

The effectiveness of AUV-based magnetic surveys relies on advanced and robust data processing techniques. Raw magnetic data can be heavily affected by vehicle motion, heading effects, sensor offsets, platform-induced and environmental noise. Processing workflows typically involve synchronising with navigation data, compensating for platform-induced noise, removing background magnetic trends, filtering and gridding spatial data.

AUV-based magnetometry and advanced data processing form a comprehensive framework for addressing the growing challenge of submerged munitions detection. Continued improvements in sensor sensitivity, vehicle navigation accuracy, and computational methods are enhancing detection reliability, reducing operational risk, and supporting safer and more sustainable use of marine environments.

2. The Magnetic Method

Since most UXO contain significant amounts of ferrous materials, magnetometry is one of the primary tools for detecting them. The local distortion of the Earth's magnetic field caused by these materials can be detected by magnetometers. The underlying physical principle of this is illustrated in Figure 1. The ambient Earth's magnetic field, assumed to be constant and homogeneous on small scales of time and space, induces a local magnetization into any magnetizable object. The resulting magnetic field is a superposition of the background field and the local field, i.e. a 3D distorted magnetic field which can be detected as a magnetic anomaly. If the UXO possesses any additional remanent magnetization, this will also account for the resulting field. It must be noted that permanent magnetizations are independent of external fields and can point it any direction. Therefore, the resulting magnetization of different objects with identical appearance can vary significantly.

If you move a magnetometer across a ferromagnetic object (like a UXO), the sensor will collect magnetic data in the form of a 2D profile (orange curve at the bottom of Figure 1). The closer the trajectory of the sensor is to an object (i.e. the lower the flight altitude), the smaller is the wave length of the anomaly and the greater is its magnitude.

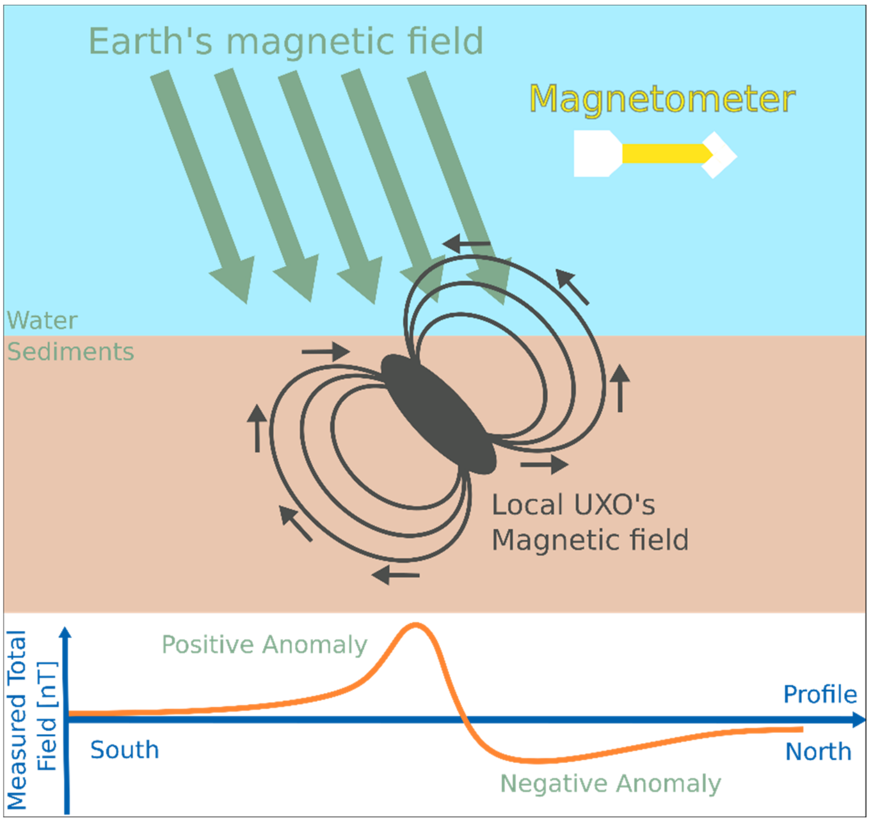

Figure 1. The basic principle of the magnetic method for detecting submerged UXO. A magnetometer is moving above the seafloor on a south-to-north (left-to-right) profile. The measured total magnetic field (orange) is a superposition of the Earth's magnetic background field (green) and the local induced (and possibly remanent) local magnetic field of the UXO (black). Copyright Marc Seidel, GEOMAR.

Yet, whether or not a possible UXO is detectable by a passing magnetometer depends on additional factors. Most importantly, the ferromagnetic mass (i.e. the material's magnetic susceptibility) of an object and the distance between the sensor and the object. Since the induced local magnetic field of a UXO is, to a first approximation, that of a magnetic point dipole field, the field strength declines as r^{-3} (r = radial distance between the dipole centre and the measurement). Therefore, doubling the distance between the sensor and the UXO reduces the detectable amplitude of the anomaly by a factor of eight. Other factors determining an object's magnetic detectability include its shape, orientation and the geographic latitude of the survey area, as this denotes the strength, inclination and declination of the ambient Earth's magnetic field.

Magnetometers are widely used for UXO detection, both onshore and offshore. When searching for UXO in underwater regimes, ship-towed systems using a frame with several magnetometers are usually used on the open sea. When the survey area is narrow or shallow, sensor systems fixed on a small vessel or mounted on a diving platform like an autonomous underwater vehicle (AUV) or remotely operated vehicle (ROV) gain importance (Seidel et al., 2023).

Although total magnetic intensity (TMI) data are successful at detecting magnetic anomalies, they struggle to discriminate between dangerous munitions and non-hazardous metallic debris. A reliable classification or identification of a specific type of UXO purely based on magnetic measurements is in general believed to be not reliable. In the field of UXO, the only reliable inference of a detected magnetic anomaly

In the field of UXO, the only reliable inference of a detected magnetic anomaly is the corresponding magnetic dipole moment in [Am^2] that explains a measured anomaly. Via forward or inverse modelling, the magnetic dipole moment can be derived and from that, a ferromagnetic mass can roughly be estimated. There is no predictable or universal relation between ferrous mass of a UXO and its magnetic dipole moment. The report by Winkelmann (2009) contains compiled information on this topic and approximated relations between different UXO sizes and their expected magnetic moments.

Additional challenges arise when multiple magnetizable objects are located closely together (or on top of each other) and their local anomaly fields are superimposing mutually. This is for example the case in munition dumpsites where huge amounts of UXO have been dumped after the Second World War (Kampmeier et al., 2019). Consequently, a reliable differentiation between distinct objects becomes challenging or even impossible.

3. AUVs

3.1 General Remarks

AUVs (autonomous underwater vehicles) are self-propelled robots that operate independently, usually conducting pre-programmed missions without the need for piloting personnel. They offer a fast and precise method of conducting surveys and are independent of the vessel that is carrying it, enabling the vessel to perform other tasks during AUV missions.

The vast majority of AUVs are torpedo-shaped, with a thruster at the rear for controlling speed and four fins for controlling heading, pitch and roll. This shape minimises water resistance, making these AUVs highly energy efficient. They can operate at relatively high speeds of up to five knots. As AUVs are constructed to be slightly positively buoyant, they must navigate at a minimum velocity to maintain a specified depth or altitude.

To address this issue, there are also non-torpedo-shaped AUVs, which typically have several thrusters and no fins. These configurations enable them to control additional degrees of freedom (e.g. heave), and they do not have a minimum speed requirement. They are therefore also referred to as hover-capable AUVs. Such AUVs are preferable in situations involving the acquisition of dense data in an area, the use of sensors that rely on low velocities to produce high-quality data, such as cameras, and deployment in narrow environments where sharp turns are required, such as harbours or near subsurface infrastructure.

AUVs are available with different depth ratings, ranging from 100 to 6,000 m. Most AUVs have classical sensors integrated for navigation, including a Global Positioning System (GPS) for surface navigation, a Doppler Velocity Log (DVL) for precise relative navigation above the seafloor, a pressure sensor for depth calculation, and an Inertial Navigation System (INS) or Inertial Measurement Unit (IMU) for inertial navigation and navigation information fusion. Scientific sensors that are often used on AUVs include conductivity, temperature and depth (CTD) sensors, camera systems, MBES, SSS and SAS, as well as towed or integrated magnetometers. The integration of scientific sensors is generally limited only by the available space in the payload section of the respective AUV, and for AUVs with proprietary software, by the availability of a suitable, manufacturer-supported interface.

Power supply is extremely significant for AUVs because it determines how long, how deep, and how effectively the vehicle can operate underwater. Since AUVs function independently without physical connections to a ship during missions, they rely entirely on onboard energy systems, typically high-capacity batteries. This means the available power directly controls mission duration. The addition of technical devices or scientific sensors to the host platform results in increased energy consumption.

3.2 AUV-Based Magnetics

There are numerous advantages to using magnetic sensors on an AUV compared to the common approach of ship-towed systems. First, towed systems can only be operated at comparatively high altitudes above the seafloor. A guideline on EOD (Explosives Ordnance Disposal) suggests a maximum height above the seafloor of 3 m for magnetic sensors (Frey, 2020). The AUV can obtain measurements closer to the ground at altitudes between 1 and 3 m, which is useful when smaller anomalies need to be detected or information on overlapping anomalies is required. Second, the AUV's INS enables very precise relative positioning of adjacent survey lines. Third, there is a minimum speed at which any vessel can navigate a towed system properly in a straight line. When operating a hover-capable AUV, it excels in areas where a very high resolution is required, as it has essentially no lower boundary for motion speed. And lastly, AUV-based measurements may be preferred inside narrow survey areas or in shallow water depths. Deep-diving AUVs are generally not necessary here since the majority of underwater UXO are lying in shallow waters (Boettcher, 2011).

Nevertheless, an AUV in operation mode is expected to be a significant source of electro-magnetic (EM) noise. Therefore, integrating sensitive instruments such as magnetometers into an AUV, which contains electric propulsion systems and other devices producing EM noise, requires careful considerations. Further insights on this topic can be found in (Seidel et al., 2023), who integrated a set of fluxgate magnetometers into a hover-capable Girona 500 AUV.

3.3 AUV-Related Magnetic Noise

When integrating magnetometers into an AUV, different sources of magnetic noise that need to be addressed: Heading-induced, motion-induced and platform-induced noise (excluding exterior sources of noise like temporal or spatial drifts or other site-specific or time-specific, like diurnal, influences).

Heading-induced noise

Heading-induced noise is generated changes of the vehicle heading. Magnetizable materials on-board the AUV distort the ambient 3D Earth magnetic field inhomogeneously, which leads to a dependency of the measured magnetic field intensities on the relative sensor positions in relation to the platform's heading.

Figure 2 exemplarily shows the heading deviation of an AUV/Magnetometer system by Seidel et al. (2023) during a circular calibration mission in the middle of the water column at a constant depth. The diameter of the mission circle was 60 m. The induced error due to the heading of the AUV is in the order of 25 nT.

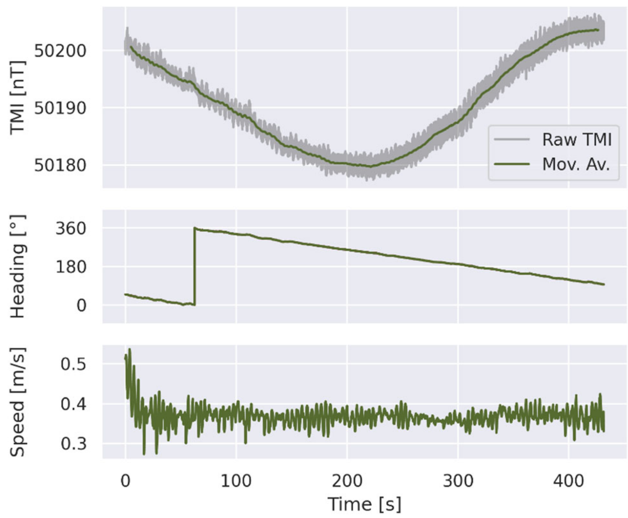

Figure 2. Total magnetic field intensity (TMI, top), AUV heading in degrees (centre) and velocity (bottom) during a circular magnetic calibration mission using a Girona 500 AUV (Image from Seidel et al., 2023)

Motion-induced noise

Motion-induced noise is generated by changes in vehicle attitude, i.e. yaw (heading), pitch and roll angles, and heave. Water currents (lateral forces, perpendicular to the AUV track), surface waves (heave) and irregular bathymetries (heave) can cause vehicle motion, and thus motion-induced noise. Motion-induced noise is lowest when the AUV is travelling at a constant velocity into a constant direction at a constant altitude and depth. Or, for hover-capable AUVS, when the vehicle is maintaining a fixed position. This is particularly true when the AUV is oriented parallel to the direction of the ambient water current, as lateral water currents perpendicular to the planned AUV track create forces that cause the AUV to laterally deviate from its planned path and/or facing direction.

Platform-induced noise

The level of platform noise is primarily determined by thruster activity during operation. Secondary sources include all other electronic devices on board. A simple way to reduce thruster noise is to increase the distance between the magnetometers and the carrying platform using an arm made of non-magnetisable material. However, increasing this distance generally decreases the vehicle's overall manoeuvrability. This, in turn, leads to increased thruster activity and undesirable vehicle motion, thereby generating additional noise.

Choosing magnetic sensors with comparably high sampling rates (> 10 Hz) allows for the application of low-pass or moving average filter techniques on the acquired data to mitigate noise that is related to thruster activity.

3.4 Integration Examples

3.4.1 Girona 500 AUV with Fluxgate Magnetometers

Within the framework of the project BASTA (Boost Applied Munition Detection through Smart Data Integration and AI Workflows), fluxgate magnetometers were integrated into the Girona 500 AUV “Luise” (Figure 3). The magnetometer system employed in this study consists of 3-axis submersible fluxgate magnetometers manufactured by SENSYS GmbH. These sensors enable high-resolution vector measurements of the ambient magnetic field, which are essential for detecting and characterizing potential UXO targets. Detailed information regarding the technical integration of the sensors into the AUV platform, as well as a comprehensive description of the vehicle system, is provided in Seidel et al. (2023).

To minimize magnetic interference originating from the vehicle itself, particularly (electro-)magnetic noise generated by onboard electronical components, the magnetometers were mounted at a horizontal offset of 1.5 m from the nose of the AUV. This configuration proved to be effective in reducing platform-induced noise to an acceptable level, thereby ensuring reliable magnetic measurements without significantly compromising vehicle manoeuvrability or stability.

For validation and ground-truthing of detected anomalies, and to enable final confirmation or rejection of suspected UXO targets under conditions of sufficient underwater visibility, the AUV is additionally equipped with a high-resolution optical camera system. This complementary sensing capability supports visual inspection and enhances confidence in the interpretation of magnetic data.

A key advantage of the Girona 500 AUV is its hovering capability, which allows for controlled operations at low velocities ranging from 0 to 1 ms^{-1} and at flight altitudes of 1 m or less above the seafloor. These navigational an positional characteristics of this system facilitate precise relative underwater navigation and enable accurate localization of detected targets, typically within a positional uncertainty of only a few decimetres.

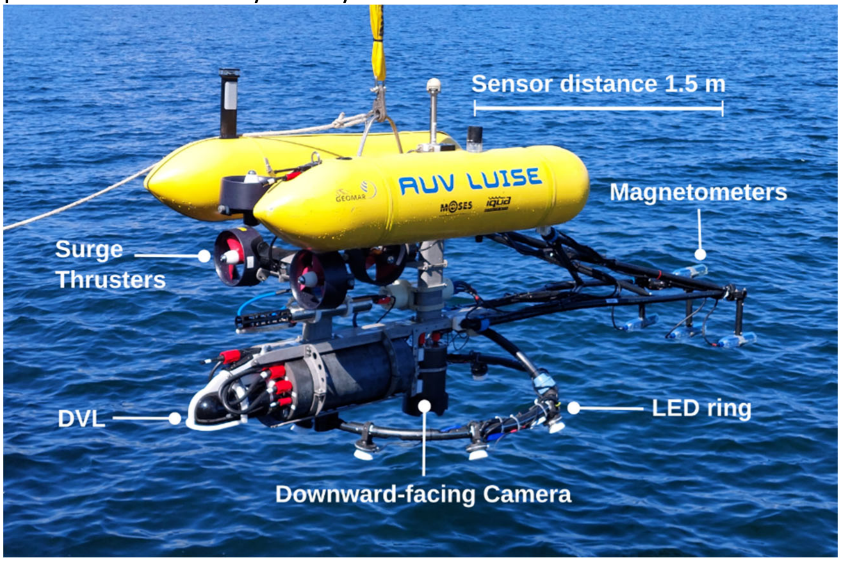

Figure 3. GEOMAR's Girona 500 AUV "Luise" equipped with four submersible fluxgate magnetometers and a camera system including illumination (DVL - Doppler Velocity Log).

3.4.2 NemoSens AUV with one Fluxgate Magnetometer

Oehler et al. (2024) deployed a micro-sized AUV called NemoSens (manufactured by RTSys), which measures about 1.5 m in length and weighs less than 10 kg. For the magnetic survey experiment, the vehicle was equipped with a 3-axis vector fluxgate magnetometer (Applied Physics Systems 1540) mounted at the front of the AUV on a rigid pole. The magnetometer was encapsulated in a watertight hull and positioned as far forward as practical on the vehicle to maximize the distance from onboard sources of magnetic noise, such as thrusters, batteries, or other electronic components, thereby improving the quality of the measured magnetic recordings.

Figure 4. NemoSens Mini-AUV with an APS1540 fluxgate magnetometer attached to the nose of the vehicle (Image from Oehler et al., 2024).

3.4.3 Iver2 AUV with an Overhauser Magnetometer

The Explorer v.AUV developed by Marine Magnetics is a neutrally buoyant, towed magnetometer system designed specifically for integration into AUVs. Unlike rigidly mounted magnetic sensors, this system is engineered to maintain neutral buoyancy in the water column, allowing it to trail a few meters behind an AUV with minimal hydrodynamic drag while preserving a stable survey altitude. This configuration reduces magnetic noise from the vehicle itself and enhances the quality of the collected magnetic data.

The magnetometer, based on Overhauser magnetometer technology, was attached to an OceanServer Iver2 AUV. In a towed configuration, the magnetometer is physically separated from the AUV's onboard navigational sensors. Though the vehicle position may be known with relatively high accuracy, the exact position of the towed sensor head is not directly measured. Instead, it must be estimated based on tow cable length, vehicle heading, speed, and hydrodynamic assumptions. This spatial offset introduces uncertainty in the horizontal position of detected magnetic anomalies, particularly during turns or acceleration phases. Even small positional deviations may yield positional errors of several meters.

Figure 5. Iver2 AUV with Explorer Magnetometer from MarineMagnetics (Copyright-MarineMagnetics, Canada)

3.4.4 ROV-Based Electromagnetics

The French company ELWAVE is a deep-tech company patented an electromagnetic technology known as CEDAR® (*Controlled Electric Detection And Ranging*), which mimics the natural 'electric sense' used by certain fish to generate and interpret distortions in an electric field for real-time environmental perception. This approach enables detection and characterization of objects regardless of visual or acoustic visibility conditions, making it particularly suitable for challenging underwater environments where sonar and optical systems may be limited.

In the context of ROV (Remotely Operated Vehicle)-based operations, ELWAVE's CEDAR-enabled sensors can be integrated directly into the skid or payload bay of observation-class ROVs and mini-ROVs (Figure 6). Once mounted, these sensors actively emit a low-frequency electric field into the surrounding water and sediment, and they measure how this field is modulated by nearby objects with differing electrical impedance, including metallic and non-metallic items like UXO, pipelines, cables, and other seabed infrastructure.

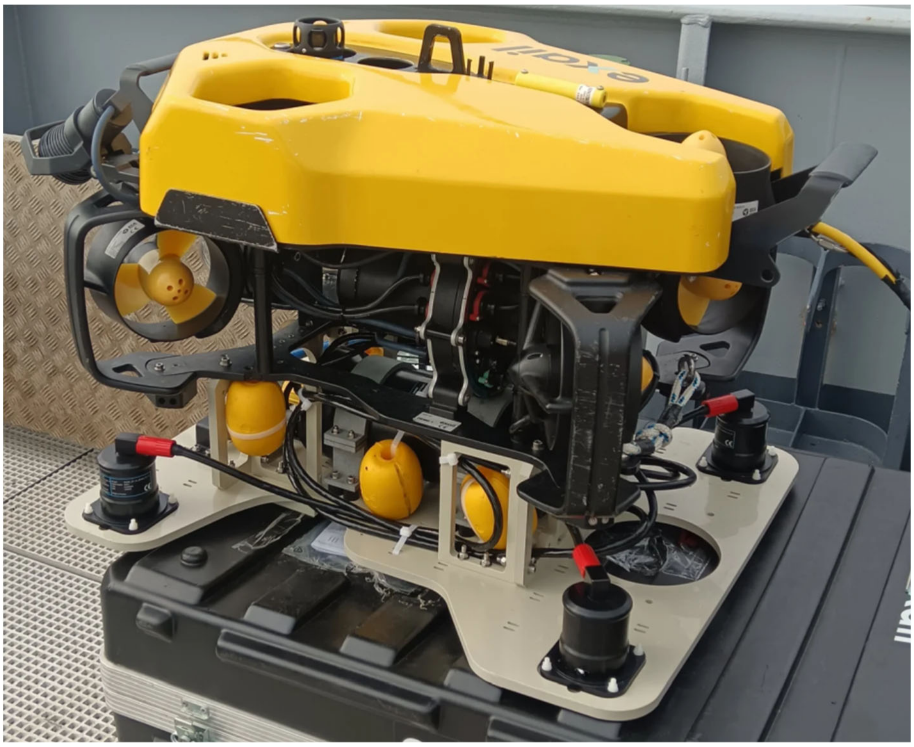

Figure 6. Inspection-Class ROV with ELWAVE's tetrapulse sensor (Copyright: ELWAVE, France).

4. Data Processing

The processing of magnetic data acquired using autonomous vehicles like AUVs presents several challenges. These challenges are based on the wide variety of AUV platforms, different types of magnetometers and different geometrical sensor configurations. AUVs, ranging from lightweight shallow-water survey vehicles to large deep-sea systems, vary significantly in size, propulsion mechanisms, payload capacity, navigation accuracy, and onboard electronics. Similarly, magnetic measurements may be collected using different (total-field or vectorial) magnetometers like fluxgate magnetometers, optically pumped magnetometers, or gradiometer systems, each with different sensitivities, noise characteristics, calibration requirements, and output data formats. This diversity makes standardization difficult and requires system-specific processing strategies. The eventual outcome of magnetic UXO surveys relies not only on best-available sensor and platform technology, but also on advanced and robust data processing.

Compared to onshore surveys, offshore environments introduce additional complexities, due to several marine-specific factors. Increased sensor–target separation arises from the combined effects of water depth and tow altitude, which reduce anomaly amplitude and broaden anomaly signatures. Platform motion, including heave, pitch, and roll, introduces dynamic changes in sensor position and orientation, leading to distortions in the recorded magnetic field. Variable sensor altitude caused by seafloor topography further complicates interpretation because anomaly amplitude depends strongly on distance to the target. Magnetic noise generated by vessels or sensor platforms, can affect magnetic signals. In addition, regional geological or geogenic magnetic variations introduce background anomalies that may mask UXO signatures. Collectively, these factors influence anomaly amplitude, spatial shape, and localization accuracy.

Accurate positioning through high-precision GNSS (global navigation satellite system) systems and subsea positioning techniques like USBL (Ultra Short Baseline) is critical for reliable anomaly localization. Motion sensors such as inertial measurement units provide additional information necessary for correcting attitude-related distortions. The raw dataset typically consists of time-stamped magnetic field measurements accompanied by 3D positions and, where available, orientation data.

4.1 General Magnetic Processing

The processing of magnetic data for UXO detection generally follows these steps:

1. **Data quality control** (QC): The acquired data and the chosen survey parameters must be checked against a set of given data quality factors, see for example Wehner & Frey (2022).

2. **Time synchronization**: All data streams (magnetometer, GNSS, motion sensors, etc) must be synchronised with a common time reference. Even small temporal offsets can result in spatial misplacement of detected anomalies. Interpolation to a uniform sampling rate throughout all data streams is commonly applied.

3. **Diurnal correction**: Temporal variations of the Earth's Magnetic Field (diurnal variations) can reach tens of nanotesla and may mask small UXO anomalies. This is typically done using (onshore) base station measurements or reference observatory data when available. In the absence of external references, high-pass filtering is usually sufficient to suppress long-period variations. For the purpose of diurnal correction, the International Geomagnetic Reference Field (IGRF) can be used to provide reference values of the Earth’s main magnetic field. The IGRF is a globally accepted mathematical model describing the large-scale internal (core-generated) geomagnetic field and its secular variation

4. **Heading and platform noise correction**: Platform-related magnetic noise represents another critical pre-processing challenge. Vessel magnetization generate heading-dependent magnetic offsets that must be compensated, for example by sailing a figure-8, a circular or a rectangular calibration mission prior to the main survey. If applicable, platform-dependent (e.g. ROVs and AUVs) noise generated by a variety of electronic onboard devices generate magnetic noise that must be compensated (Oehler et al., 2024).

5. **Offset correction**: Calculate the precise 3D coordinates of all data points (all sensor positions and all times), depending on their position in relation to the position of the GNSS sensor.

6. **Filtering**: Filtering aims to enhance UXO-related anomalies while suppressing noise and large-scale geological trends. Low-pass filters are used to remove high-frequency instrumental noise, whereas high-pass or band-pass filters help isolate anomalies within expected wavelength ranges associated with typical UXO dimensions and burial depths. In line-based UXO surveys, filtering is often performed along survey lines (1D) before cross-line processing is applied after gridding (2D). In areas with geological background variations, regional magnetic fields may be removed using polynomial surface fitting or large-window smoothing techniques. Trend elimination (detrending) may be applied to remove regional or long-wavelength components of the magnetic field associated with deep sources or geological structures in order to emphasize local or short-wavelength anomalies.

7. **Transformations**: A set of transformation techniques can be applied to enhance the interpretability of magnetic anomalies. *Field continuation* (upward or downward continuation) mathematically transforms the measured field to a different observation level. Upward continuation transforms magnetic anomalies measured at one elevation to those that would be observed at a higher level, farther from the sources. This process attenuates short-wavelength signals from near-surface bodies and enhances the relative contribution of deeper, long-wavelength sources, thereby providing additional geometric information about deeper subsurface structures. Downward continuation enhances high-frequency components but may amplify noise. *Reduction to the pole* (RTP) is another transformation that transforms the magnetic anomaly as it would appear if measured on top of one of Earth's magnetic poles, where the inducing field is vertical. It therefore removes the effect of the direction of Earth's magnetic field at the measurement site.

8. **Gridding and Interpolation**: After pre-processing and filtering, magnetic data are interpolated onto a regular grid to enable spatial analysis and visualization. Grid resolution must be selected carefully, both, along track and across track, to preserve anomaly integrity without introducing interpolation artifacts.

9. **Target detection**: Identifying local magnetic anomalies that exceed background variability and noise. Simple detection approaches rely on amplitude thresholds determined from noise statistics. Automated detection algorithms use local maxima searches, matched filtering using theoretical dipole responses, or wavelet-based methods that identify characteristic anomaly signatures across multiple scales. The selection of detection criteria directly influences both detection probability and false alarm rate. Typical signal-to-noise ratios for a reliable identification are >= 3.

10. **Dipole Modelling and Parameter Estimation:** For isolated anomalies, dipole modelling or inversion can be used to estimate the position, depth and magnetic moment of the target. The inversion process involves minimising the misfit between the observed magnetic data and

the forward-modelled dipole response. Depth estimation is particularly sensitive to altitude uncertainty because the amplitude of an anomaly decays as the cube of the distance from the source. The recovered magnetic moment can be used as an indicator of object size or ferrous mass, which supports subsequent classification and risk assessment.

4.2 Magnetic Processing on a Girona 500 AUV

The following example illustrates the data processing routines involved in integrating four 3-axis fluxgate magnetometers into a Girona 500 AUV manufactured by Iquarobotics in Spain (see Figure 3). The Girona 500 AUV's basic properties are displayed in Table 1. The AUV is equipped with a conductivity, temperature and depth sensor, as well as navigational sensors such as an inertial navigation system (INS), a Doppler velocity log (DVL), an attitude and heading reference system, an ultra-short baseline (USBL) and a global positioning system (GPS). Unlike most torpedo-shaped AUVs, the Girona 500s can hover or move very slowly at velocities below 1 m/s. Thanks to their modular design and open-source, ROS-based software architecture, Girona 500 AUVs can be fitted with extra sensors and software for specific tasks.

Table 1. Basic characteristics of GEOMAR's Girona 500 AUVs.

AUV Property	**Value**
Dimensions	1 x 1 x 1.5 m^3 (+1.5 m with magnetometers)
Maximum depth rating	500 m
Propulsion system	5 thrusters (customizable)
Endurance without camera and magnetometers	Up to 8 h
Maximum velocity	1 m/s
Underlying Software Architecture	Based on ROS (open-source)

The magnetic sensors used are FGM3D/100 UW II 3-axis fluxgate magnetometers from SENSYS GmbH. Each magnetometer samples three spatial components at a rate of 200 Hz, yielding a data point spacing of 2.5 mm in the direction of travel at a velocity of 0.5 m/s. The basic modular system consists of aluminium poles and submersible magnetometers, and can be attached to AUVs 1.5 m to the side of the front of the AUV (see Figure 3).
This layout enables all three spatial magnetic gradients to be measured. Combining these gradients enables the calculation of the 3D analytic signal, a derived value exhibiting maxima over magnetisation contrasts that determines the outlines of magnetic sources.
The Girona 500 AUV's power source is a Li-ion battery pack with a capacity of 2.2 kWh. With powered magnetometers and all the aforementioned sensors and an active camera taking images every second, the AUV can operate independently for approximately 5–6 hours.
Following acquisition, magnetic data are subject to several automated post-processing steps. Only data recorded during stable, straight flight is considered. Data recorded during turning manoeuvres are usually discarded.

1. A ROS node (magnetometer driver) running on the AUV hardware connects to the Sensys data logger via an Ethernet port using either TCP or UDP. It then receives and publishes the data on a ROS topic.

2. All topics are saved in a ROS log file called a 'ROS bag' inside the AUV hardware in the order they are published on the network.
3. Once the mission has been completed and the AUV has been recovered, all of the mission data, including the bag file, is downloaded to an external computer.
4. The GEOMAR AUV team has developed a Python-based export tool that extracts all sensor and navigation data from the ROS bag file. As the timestamps of the navigation and sensor data do not coincide, the navigation data is resampled and interpolated to align with the timestamps of the sensor data. Typically, the magnetometer data is downsampled to 20 Hz, as this frequency is sufficient to capture all relevant measurements while minimizing data volume.
5. To gain an initial understanding of the mission and perform a quick plausibility check, several plots of navigation and magnetic data are created and saved as PNG files.
6. Compute magnetic 3D gradients derived from the provided sensor geometry and corresponding dataset.
7. Determine and compute the precise sensor position by integrating the known sensor geometry with the AUV's position and orientation data, ensuring accurate spatial alignment and transformation within the reference frame
8. Apply an appropriate low-pass filtering technique to the dataset in order to attenuate high-frequency noise components.
9. Automatic line extraction: Implement an automated procedure that selectively identifies and processes only data acquired along straight-line trajectories, ensuring that measurements collected during turning manoeuvres or other non-linear movements are systematically excluded from interpretation and further analysis.
10. Eliminate any extracted lines that fall below a specified minimum length threshold.
11. Optional: Omit leading and trailing lines, where the AUV is traveling to or from the ship, or transitioning between mission phases, ensuring that only operationally relevant data is considered for analysis.
12. Apply a magnetic offset to the extracted lines based on the vehicle's heading. This heading information must be acquired during calibration missions beforehand.
13. Compute the levelled gradient from the pre-processed gradient data by subtracting the trimmed mean.
14. Calculate the analytic signal from the 3D magnetic gradients.
15. Generate visual plots (GeoTIFF and/or PNG files) ensuring clear and accessible representations of the data for further analysis or presentation (see Figure XXX).
16. Compile the sensor and navigation data, along with the associated navigation uncertainty, and export them into a CSV file for easy access, storage, and further analysis.

Figure 7 shows a 73 x 31 m² section of an AUV mission at Kolberger Heide, a munitions dumping site sear Kiel (Kampmeier et al, 2020). The underlying bathymetry shown in Figure 7 were acquired during a previous MBES survey. The acoustic data indicated dozens of potential UXO targets of different shapes and sizes on the seabed. All these objects generated anomaly signals in the magnetometers and are therefore very likely UXO.

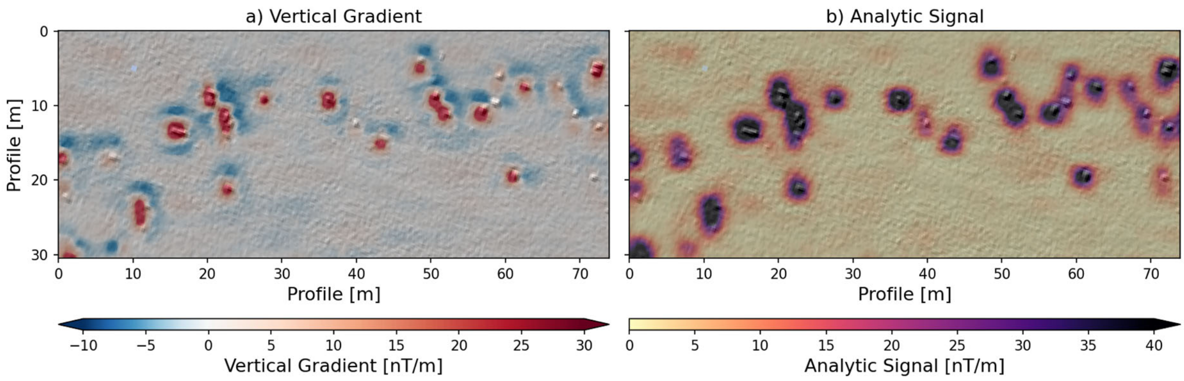

Figure 7. Exemplary magnetic data of an AUV mission from the munitions dumping site Kolberger Heide near Kiel, Germany. a) Vertical magnetic gradient and b) analytic signal of a 73 x 31 m² area. The bathymetric data shown underneath the magnetic data were acquired during a previous MBES survey.

5. Smart AUVs

Smart AUVs are increasingly being used and several fields and also to detect and map unexploded ordnance in offshore environments, where traditional survey methods can be slow, costly and risky. These vehicles may be equipped with advanced sensors like magnetometers, and intelligent navigation systems, enabling them to autonomously scan large seabed areas of interest while maintaining high-resolution data quality.

In the context of offshore UXO detection, smart AUVs facilitate the more efficient identification of potential hazards through adaptive mission planning and real-time data analysis. The integration of technologies such as machine learning, multi-sensor fusion and precise localisation improves the reliability of detection and reduces the need for repeated surveys, thereby supporting safer offshore construction, energy development and environmental management.

Project SAM[1] (Smart AUV-based Magnetics) focused on the development of a fully autonomous system for the detection of ferromagnetic objects, such as unexploded ordnance, using autonomous underwater vehicles. The project aims to enable AUVs to react directly to in-situ magnetic measurements, allowing them to autonomously generate new waypoints or entire mission plans without human intervention.

A key innovation of the project is the integration of smart navigation routines and onboard decision-making capabilities, enabling the AUV to identify magnetic anomalies, adapt its survey trajectory and produce detailed reports including object location, estimated mass and optional optical imagery. This approach significantly reduces the need for pre-programmed missions and enables more efficient, targeted UXO surveys.

The project also demonstrates how intelligent AUV systems can cluster nearby anomalies and investigate them within optimised missions, reducing survey time while maintaining high-resolution mapping of potential hazards on the seafloor. Beyond UXO detection, the developed methods can also be adapted in the future to support the monitoring of subsea infrastructure, like pipelines, cables, harbours and sea lanes.

Overall, SAM is a significant step towards fully autonomous offshore survey systems, enhancing the efficiency, safety and scalability of underwater munitions detection and seabed monitoring.

[1] https://sam-project.eu

6. Conclusions

AUV-based surveys using magnetics have significantly improved the detection of submerged unexploded ordnance (UXO) in marine environments in recent years. The integration of magnetometers, as well as side-scan sonar and other sensors on AUVs enables the collection of high-resolution data, particularly in shallow, narrow or complex areas where traditional towed systems are limited. AUVs can operate at low altitudes and slow speeds, increasing their sensitivity to small or buried UXO while providing precise navigation for dense spatial sampling and accurate target localization. This autonomy reduces risk to human personnel and enables survey vessels to carry out other tasks simultaneously.

Robust data processing workflows have been developed to handle magnetic data acquired by AUVs, including noise compensation, filtering techniques, etc. These advancements improve anomaly detection and characterization, while automated and semi-automated algorithms enable efficient data analysis, reducing the need for manual intervention and producing survey results more quickly. Integrating smart routines, as demonstrated in project SAM, enables AUVs to adapt survey trajectories autonomously, cluster anomalies, and generate detailed reports, thereby significantly enhancing efficiency and scalability.

However, challenges remain, particularly in mitigating (electro-)magnetic noise from AUV thrusters and electronics, which can interfere with magnetometer measurements. Standardized calibration procedures and data quality control are essential due to the diversity of AUV platforms and sensor configurations. Although magnetic methods can effectively detect ferromagnetic UXO, they cannot reliably classify objects, making the integration of optical, acoustic, and electromagnetic sensors necessary for comprehensive target identification and classification as well as and risk assessment. Methods must be developed to distinguish between hazardous UXO and harmless scrap metal using magnetometers on AUVs. The limited duration of missions also highlights the need for more efficient batteries or power systems. Additional challenges arise when magnetizable objects are grouped together in such a way that their local magnetic fields interfere with each other. In such cases, it is often impossible to distinguish between these objects reliably.

Overall, although AUV-based UXO detection has made significant progress, ongoing efforts are needed to further standardize processes, improve energy efficiency and enhance multi-sensor fusion, in order to enhance automated offshore UXO detection methods and to realize a reliable object classification for potential UXO in the future.

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