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Platform-corrected analyses of near-bottom magnetic data acquired by autonomous underwater vehicles

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SUMMARY

Autonomous underwater vehicles (AUVs) provide high-resolution magnetic measurements essential for investigating crustal accretion, tectonic segmentation and hydrothermal processes at mid-ocean ridges. However, raw magnetometer measurements are strongly influenced by platform-induced magnetic fields, attitude-dependent biases and navigation uncertainties that must be corrected to recover geophysically meaningful anomaly fields. We apply a procedure to measurements from AUVs, which includes platform independent scalar calibration, transformation into geographic reference frames, spin-based removal of permanent and induced vehicle magnetization and computation of magnetic anomalies relative to the International Geomagnetic Reference Field. The framework also incorporates a 2-D spectral upward continuation to reconcile altitude variations, thereby recovering anomalies at a uniform reference level. Application of this system to AUV data sets from the East Pacific Rise and Mid-Atlantic Ridge demonstrates effective suppression of platform biases, improved crossover consistency and the generation of internally coherent geomagnetic anomaly fields suitable for subsequent analysis and mapping.

Key words: Magnetic anomalies: modelling and interpretation; Marine magnetics and palaeomagnetism; Fourier analysis.

1 INTRODUCTION

Marine magnetic surveys are essential tools for studying the evolution of ocean basins and the processes governing seafloor formation at mid-ocean ridges. Sea-surface magnetic profiles, collected several kilometres above the seafloor, provide the first-order record of seafloor spreading, crustal accretion, plate tectonic history and the geomagnetic polarity timescale (F.J. Vine & D.H. Matthews 1963; W.C. Pitman & J.R. Heirtzler 1966). At these large sensor-seafloor offsets, the measured anomalies are dominated by long-wavelength variations that reflect geomagnetic polarity reversals, but cannot resolve subtle crustal features because short-wavelength signals are strongly attenuated (e.g. S.P. Miller 1977; M.A. Tivey & H.P. Johnson 1993). As a result, metre-scale magnetic footprints such as fault zones, individual lava-flows and narrow hydrothermal alteration zones remain unresolvable with sea surface observations. Autonomous underwater vehicles (AUVs) help to overcome these limitations by providing a platform to acquire higher resolution near-bottom data, though with reduced areal coverage.

Near-bottom magnetic surveys have contributed to our understanding of a variety of processes operating at mid-ocean ridges. For example, magnetic anomalies have been used to map and estimate the thickness of an individual lava flow (M.A. Tivey *et al.* 1998) or to image fluid pathways and alteration zones beneath hydrothermal vents (e.g. M.A. Tivey & H.P. Johnson 2002; F.C. Tontini *et al.* 2012; C. Honscho *et al.* 2013; M.A. Tivey *et al.* 2014; F. Sztikar & B.J. Murton 2018). Magnetic anomaly variations near the axis also should be sensitive to the pattern of lava accumulation and may therefore help to constrain the lava emplacement history (e.g. H. Schouten *et al.* 1999; J.S. Gee *et al.* 2000; C.M. Williams *et al.* 2008; N. Berrios-Rivera *et al.* 2023). Similarly, near-axis magnetic anomalies may potentially provide information on deeper magnetic sources. A short wavelength axial magnetic anomaly low observed at some ridges has been interpreted as reflecting the presence of shallow, weakly magnetized dikes (e.g. A.K. Shah *et al.* 2001; F. Sztikar *et al.* 2016). Finally, near-bottom anomaly data may provide insights into past geomagnetic intensity fluctuations that also modulate anomaly amplitudes (e.g. J.S. Gee *et al.* 2000; N.E. Bowers *et al.* 2001). When combined with paleointensity estimates from surface samples that may provide age information (e.g. J. Carlot & D.V. Kent 2000; J. Bowles *et al.* 2006), near-axis anomaly fluctuations may yield additional constraints on the timing and extent of eruptions.

Despite their scientific potential, AUV-based magnetic data require careful processing before interpretation. The metallic hull and onboard electronics of the vehicle generate complex permanent and induced magnetic fields that can distort true geomagnetic signals

(e.g. J. Korenaga 1995; M. Munsch *et al.* 2007). These platform effects vary with vehicle orientation and operational configuration, producing time-dependent magnetic interference (e.g. M.A. Tivey & H.P. Johnson 1993; N. Olsen *et al.* 2003; B. Armstrong *et al.* 2009). Furthermore, changes in the vehicle's attitude (i.e. roll, pitch and yaw), and navigation over variable bathymetry result in irregular sampling surfaces, complicating direct comparison of data between different tracklines and hampering detailed interpretation (R.J. Blakely 1995; M. Pilkington & O. Boulanger 2017). Without accurate correction, uncompensated vehicle signals can obscure the anomalies of interest. Existing approaches typically treat these corrections individually, lack reproducible open-source implementation and rarely integrate crossover analysis and upward continuation into a single unified workflow.

Recent advances underscore the importance of a detailed approach to correcting these signals. For example, data collected using the AUV *URASHIMA* demonstrated that accurate removal of pitch-dependent magnetic biases is essential for obtaining reliable anomaly fields from low-altitude surveys (T. Kasaya *et al.* 2023). Complementary developments such as ellipsoidal disturbance modelling, evolutionary optimization and neural-network-based compensation highlight the growing need for robust, transparent and reproducible magnetic interference mitigation methods tailored to AUV platforms (H. Wen *et al.* 2025).

To address the need for a unified workflow for processing near-bottom magnetic data collected by AUVs, we present a new open-source framework that converts raw three-component fluxgate magnetometer measurements into calibrated, corrected and reference-level-normalized magnetic anomaly grids. The framework is organized into five self-contained processing modules. It includes an optional platform-independent scalar calibration of the three-component fluxgate magnetometer; rotation of magnetic vectors from the vehicle into a geographic reference frame; spin-maneuver-based estimation and correction of permanent and induced vehicle magnetization; a tool to apply crossover levelling among intersecting tracks; and 2-D upward continuation to enable comparison of data collected at variable altitudes. The architecture allows individual steps to be used independently or integrated into other workflows, enabling flexibility. We demonstrate its performance on AUV *Sentry* magnetic surveys acquired along the East Pacific Rise and Mid-Atlantic Ridge, illustrating substantial improvements in internal consistency and the retrieval of spatially coherent magnetic anomalies.

2 DATA

This study uses near-bottom magnetic measurements acquired during three AUV *Sentry* surveys conducted at three geologically distinct mid-ocean ridge environments. First, the ultrafast-spreading East Pacific Rise (EPR) at 19°S; second, the fast-spreading EPR at 9°50'N; and third, the slow-spreading Mid-Atlantic Ridge (MAR) at 14°N. In all surveys, *Sentry* was equipped with a three-axis fluxgate magnetometer mounted in a fixed position on the vehicle. Surveys were conducted at altitudes 60–100 m above the seafloor, enabling high-resolution mapping of crustal magnetic anomalies. Alongside magnetic measurements, *Sentry* recorded navigation and vehicle attitude parameters, including heading, pitch and roll using an inertial navigation system. Environmental data including temperature and depth were simultaneously measured with a Sea-Bird SBE49 CTD sensor. All data and calibration files are publicly available with the code repository to ensure reproducibility.

3 METHODOLOGY

Near-bottom magnetic data were processed using a workflow designed to convert raw three-axis fluxgate magnetometer measurements collected by AUV *Sentry* into internally consistent and geophysically interpretable magnetic anomaly fields (Fig. 1).

3.1 Platform independent scalar calibration

For a three component fluxgate magnetometer, small differences in the sensor offsets, scale factors and the mutual orthogonality of the sensing axes can affect the measured total field and its components. The nine calibration coefficients (three for each sensor axis) may be determined by positioning the magnetometer in a variety of orientations in a constant magnetic field, independent of the survey platform (N. Olsen *et al.* 2003). These calibration parameters are typically temperature-dependent and for each sensor the temperature-dependent bias $b(T)$, scale $S(T)$ and small-axis rotation $P(T)$ can be modelled as quadratic functions of the measured sensor temperature. When sensor-specific calibration data are available, this calibration can be applied. The raw magnetic field vector $B_{\text{raw}} = [X, Y, Z]^T$ is first corrected for bias, then adjusted for differences in axis sensitivity (scale correction) and for small misalignment of the sensor axes (rotation correction) by

$$B_{\text{cal}} = P^{-1} \cdot S^{-1} \cdot (B_{\text{raw}} - b(T)) \quad (1)$$

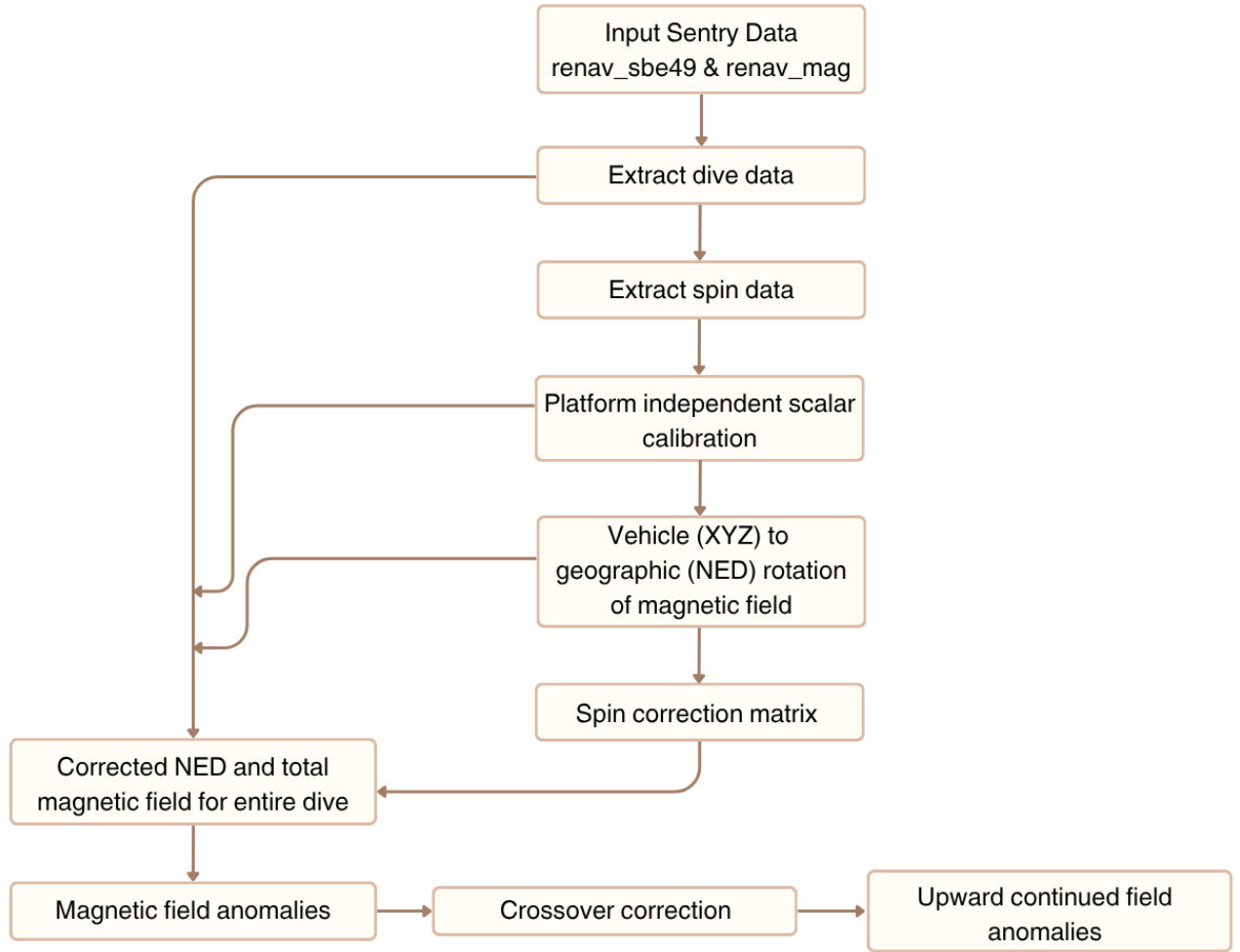


Figure 1. Workflow of AUV magnetic data processing.

where $S(T)$ is a 3×3 diagonal scale matrix, and $P(T)$ is a 3×3 rotation matrix that restores orthogonality of the sensor axes. The scale matrix is written as

$$\mathbf{S}(T) = \begin{pmatrix} S_1(T) & 0 & 0 \\ 0 & S_2(T) & 0 \\ 0 & 0 & S_3(T) \end{pmatrix}. \quad (2)$$

The non-orthogonality matrix follows the formulation of N. Olsen *et al.* (2003):

$$\mathbf{P}(T) = \begin{pmatrix} 1 & 0 & 0 \\ -\sin u_1(T) & \cos u_1(T) & 0 \\ \sin u_2(T) & \sin u_3(T) & \sqrt{1 - \sin^2 u_2(T) - \sin^2 u_3(T)} \end{pmatrix}, \quad (3)$$

where u_1 , u_2 and u_3 are small non-orthogonality angles. In this parametrization, the first sensor axis is taken as projection invariant, the second axis is allowed to rotate within the 1–2 plane and the third axis has two degrees of freedom relative to the ideal orthogonal coordinate system.

3.2 Coordinate rotation

Platform-independent, scalar-calibrated magnetic measurements in the vehicle reference frame (XYZ) are rotated into the geographic north, east and down (NED) frame (N. Olsen *et al.* 2003). Sensor axes are adjusted according to the mounting orientation (e.g. top, port, starboard) to account for polarity changes in XYZ components. The transformation uses an Euler rotation matrix $R(\alpha, \beta, \gamma)$

constructed from the measured heading (α), pitch (β) and roll (γ), so NED components are given by

$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = R(\alpha, \beta, \gamma)^T \begin{bmatrix} X \\ Y \\ Z \end{bmatrix},$$

where the R matrix as a function of heading (α), pitch (β) and roll (γ) is given by

$$R(\alpha, \beta, \gamma) = \begin{bmatrix} \cos \alpha \cos \beta & \sin \alpha \cos \beta & -\sin \beta \\ \cos \alpha \sin \beta \sin \gamma - \sin \alpha \cos \gamma & \sin \alpha \sin \beta \sin \gamma + \cos \alpha \cos \gamma & \cos \beta \sin \gamma \\ \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \cos \beta \cos \gamma \end{bmatrix}.$$

3.3 Spin calibration

The measured magnetic field can be expressed as the sum of the true geomagnetic field and the vehicle's permanent and induced magnetic fields. A more general three-component compensation function can be written following the shipboard three component magnetometer formulation of N. Isezaki (1986) as

$$\mathbf{H}_{\text{obs}} = (\mathbf{I} + \mathbf{A})\mathbf{R}(\alpha, \beta, \gamma)\mathbf{F}_{\text{earth}} + \mathbf{H}_p, \quad (4)$$

where $\mathbf{H}_{\text{obs}}$ is the observed field, $\mathbf{F}_{\text{earth}}$ is the ambient geomagnetic field, $\mathbf{A}$ represents induced magnetization effects, $\mathbf{H}_p$ is the permanent magnetic field of the vehicle and $\mathbf{R}(\alpha, \beta, \gamma)$ rotates the ambient field into the vehicle frame using roll α , pitch β and heading γ . This full attitude-dependent formulation is appropriate when the calibration maneuver independently samples heading, pitch and roll over a broad range. During the spin maneuvers executed by AUVs like *Sentry*, heading spans nearly the full 0° – 360° range, whereas pitch and roll vary over much narrower ranges, generally within about $\pm 4^\circ$ – 5° (Fig. S1, Supplementary Material). These pitch variations are substantially smaller than the $\pm 15^\circ$ – 20° pitch variations considered by T. Kasaya *et al.* (2023). Therefore, the *Sentry* spin data appropriately constrain heading-dependent magnetic offsets but provide only weak independent constraints on pitch- or roll-dependent permanent and induced magnetization terms. A full shipboard three component magnetometer inversion would therefore be poorly conditioned for these calibration data.

For this reason, we use a first-order empirical spin correction that represents the dominant repeatable vehicle magnetic signal as a function of heading. To quantify and remove these platform effects (permanent and induced fields), controlled in-place 360° spin maneuvers are performed near the seafloor at the start of each AUV mission. We assume that the vehicle maintains an approximately fixed position relative to the seafloor during the spin maneuver, such that heading varies while the local geomagnetic field remains constant over the duration of the rotation. Spin segments are easily identified by their rapidly changing character in heading time-series data, and candidate spin intervals are inspected using the distribution of heading, position and altitude. Start and end times of each spin maneuver are selected interactively by an analyst. For a selected interval, the NED components are detrended and initially fit with a robust sinusoidal model of the form

$$B(\alpha) = a \cdot \sin(b + \alpha) + c \cdot \sin(d + 2\alpha) + e, \quad (5)$$

where B is field component, α is heading, a and c are amplitude of the permanent and induced magnetic field, respectively. b and d are the respective phases and e is a constant offset. A robust least squares fitting method, with bisquare weights is used to reduce the influence of outliers. This fitting allows compensation for permanent and induced components from the signal and yields a magnetic field that closely approximates the geomagnetic field. This correction should be interpreted as a stable first-order heading-dependent compensation, not as a replacement for full three-component attitude-dependent calibration.

3.4 Magnetic anomaly computation

Corrected NED components are compared with the theoretical geomagnetic field predicted by the International Geomagnetic Reference Field (IGRF-13; P. Alken *et al.* 2021). The reference field is evaluated at the position, depth and acquisition time of each measurement. For surveys acquired between 2020.0 and 2025.0, the 2020.0 IGRF coefficients and the predictive 2020–2025 variation coefficients are used. The three-component (NED) anomaly, ΔB , can be written as

$$\Delta B = B_{\text{obs}} - B_{\text{IGRF}}, \quad (6)$$

where B_{obs} is the corrected field component and B_{IGRF} is the modelled geomagnetic field at the corresponding latitude, longitude, depth and time. The total field anomaly, ΔM , is obtained using

$$\Delta M = \Delta N \cos(\theta_D) \cos(\theta_I) + \Delta E \sin(\theta_D) \cos(\theta_I) + \Delta D \sin(\theta_I), \quad (7)$$

where ΔN , ΔE and ΔD are the north, east and down anomaly components; and θ_I and θ_D are the geomagnetic inclination and declination, respectively. This IGRF correction highlights localized magnetic anomalies that may be associated with particular features. This

quantity represents the projected, or linearized, total-field anomaly commonly used in magnetic interpretation and is distinct from the exact scalar total-field anomaly,

$$\Delta M_s = |\mathbf{B}_{\text{obs}}| - |\mathbf{B}_{\text{IGRF}}|. \quad (8)$$

3.5 Crossover analysis

Residual offsets may arise from instrumental drift, navigation uncertainties or variations in vehicle altitude, where AUV track lines intersect. A crossover adjustment ensures internal consistency across all survey lines using a least-squares approach (R.A. Prince & D.W. Forsyth 1984). Dives are divided into straight segments based on vehicle heading. Crossover differences are computed at the exact crossover location using linearly interpolated magnetic data along each segment where segments intersect. This approach assumes that vehicle altitude differences at the crossover points are minimal (e.g. typical RMS difference for the Sentry surveys analysed here is ~ 8 m) and we discuss this further in the following section. The optimal set of corrections minimizes the sum of the squared residual crossover errors, preserving the relative anomaly variations along each segment while improving agreement across the survey. Line-specific bias terms are optimized to minimize the sum of squared residual crossover errors. At each valid crossover, the field difference Δ_{ij} between the intersecting lines was computed as

$$\Delta_{ij} = B_i - B_j, \quad (9)$$

where B_i and B_j are the field values of lines i and j at the crossover location. The complete set of crossover differences was then formulated as a network adjustment problem, given by

$$\Delta_{ij} = b_i - b_j, \quad (10)$$

where b_i and b_j are unknown bias terms for each line. These terms were determined by minimizing the least-squares objective function, Φ , written as

$$\Phi = \sum_{i,j} [\Delta_{ij} - (b_i - b_j)]^2. \quad (11)$$

Applying these corrections reduces the global root mean square (RMS) crossover misfit by more than 80 per cent, similar in magnitude to the improvements reported by R.A. Prince & D.W. Forsyth (1984) for marine gravity surveys. The levelled magnetic field provides an internally consistent data set suitable for further processing. In the present workflow, we use the unweighted least-squares solution as a baseline correction, in which all valid crossover differences contribute equally to the objective function. Although heading, pitch, roll, altitude and line (navigation) information are available for all dives, converting these quantities into statistically meaningful crossover weights requires an additional uncertainty model. The relative importance of attitude variability, heading-dependent residuals, altitude mismatch, navigation uncertainty and local magnetic gradient can vary between surveys and sensors. We therefore use these parameters as diagnostic tools to assess the segment corrections, while treating directional or uncertainty-weighted crossover adjustment as a future extension of the workflow.

3.6 Upward continuation of anomalies

Irregular AUV altitude can distort anomaly amplitude and wavelength. To standardize the observation level, the frequency-domain upward continuation method of Guspí (F. Guspí 1987) can be applied. This method suppresses short-wavelength noise associated with vehicle altitude, while preserving the longer-wavelength anomaly signal (M. Pilkington & O. Boulanger 2017). Near-bottom AUV surveys are typically designed to acquire complete, high-resolution bathymetric coverage, such that the accompanying magnetic data sample a 2-D area rather than isolated profiles, after interpolation on a uniform grid.

For gridded survey data, we apply the 2-D Guspí method to account for spatial variability in both horizontal directions (x and y). While upward continuation can also be performed by treating along-track magnetic data as a 1-D time-series, such an approach compromises the spectral content of an inherently 2-D magnetization source. We therefore generate a 2-D gridded magnetic data set on the observation surface and, when needed, apply 2-D upward continuation to obtain a common-level anomaly field. This approach is useful for visualization, line-to-line comparison and modelling approaches that require data on a horizontal surface, but it may also attenuate short-wavelength components and is therefore treated as an optional step.

The input grid is symmetrically padded by 10 per cent to minimize spectral boundary artifacts and then resampled at a uniform 10 m node spacing. The resampled grid field is reduced iteratively to a chosen reference level z_{ref} , which can be the minimum, maximum, mean or median of the resampled depth along the track or a user-specified depth, and represents a surface-to-level reduction. At each grid point, the local height perturbation $h(x) = \text{depth}(x) - z_{\text{ref}}$ is removed using an iterative Guspí reduction in the spectral domain using discrete 2-D Fourier transform. A truncated Taylor series is applied to the Fourier-transformed field, with terms weighted by $(-h)^n/n!$, where n is the order of the Taylor series expansion. The iteration proceeds until convergence, yielding $m_{\text{ref}}(x, y)$, the field

reduced to a consistent reference level. For convergence, a band-limited spectral filter is applied, which uses a tapered cosine (Tukey) transition between the pass and stop bands, producing smooth roll-on and roll-off that reduces ringing in the spatial domain. In our implementation, we choose the mean depth as z_{ref} , which provides a reference level that minimizes sensitivity to outliers and reduces the extreme downward continuation, to improve numerical stability. The short-wavelength cut-off w_s is fixed to three times the vertical range of the observation surface expressed in units of the horizontal grid spacing,

$$w_s = 3 \frac{\Delta z}{\Delta x},$$

where Δz is the vertical range of the AUV observation surface and Δx is the mean horizontal grid spacing. The long-wavelength cut-off (w_l) corresponds to the dominant anomaly wavelength identified from the field's spectrum. After convergence of the Guspí iteration, $m_{\text{ref}}(x, y)$ is upward continued to depth z_2 using

$$F(k_{x,y}, z_2) = F(k_{x,y}, m_{\text{ref}}(x, y)) \cdot e^{-K \cdot (z_2 - z_{\text{ref}})}, \quad (12)$$

where k_x and k_y are wavenumbers in the x and y directions, respectively, and $K = \sqrt{(k_x^2 + k_y^2)}$. This second step is a standard level-to-level continuation in the frequency domain. The upward-continued profile is recovered by inverse Fourier transform (F. Guspí 1987).

The exponential factor shows that upward continuation preferentially attenuates high-wavenumber, short-wavelength components. Therefore, upward continuation should be interpreted as a low-pass transformation rather than as an intrinsic improvement of the geological signal. If the continuation distance is large, or if short-wavelength anomalies are important for the geological interpretation, both the corrected draped anomaly field and the upward-continued common-level field are retained. These draped data can be used for quantitative modelling or inversion methods that explicitly account for bathymetry, variable observation altitude and source geometry, such as near-seafloor vector magnetic inversions. In contrast, the upward-continued product is useful for visualization, line-to-line comparison, map compilation, crossover assessment, spectral analysis and simpler modelling approaches that require data on a horizontal or common reference surface.

To quantify the effect of upward continuation, we compared the spectral content of the measured and upward-continued fields. Before computing the spectra, both grids were demeaned, detrended in the x and y directions, and multiplied by a 2-D Hanning window to reduce edge effects. We then calculated 2-D Fourier amplitude spectra for the measured and upward-continued fields. The comparison is expressed using the normalized amplitude difference. Positive values indicate spectral bands in which the measured field has larger amplitude than the upward-continued field. Radially averaged spectra show that upward continuation preserves the dominant low-wavenumber anomaly structure while attenuating relatively higher-wavenumber components.

3.7 Benchmarking using synthetic forward models

To evaluate the numerical implementation of the upward continuation module, we performed synthetic forward modelling following the formulation and test case described by Pilkington and Boulanger (M. Pilkington & O. Boulanger 2017). The purpose of this experiment is not to reproduce all complexities of real AUV magnetic surveys, but to test whether the implemented Guspí continuation algorithm recovers a known reference field under controlled conditions. Synthetic bathymetry was generated on a 128×128 cell grid, with easting and northing from -63.5 to $+63.5$ units. This configuration emulates AUV survey paths with realistic undulations and spatial coverage comparable to deep-sea magnetic surveys (M. Pilkington & O. Boulanger 2017). The surface elevation was defined as:

$$z(i, j) = z_0 + f_0 \sin \left(\frac{4\pi x(i)y(j)}{x_M y_M} \right) \exp \left[-a \frac{x(i)^2 + y(j)^2}{x_M y_M} \right], \quad (13)$$

where $z_0 = 0$ units is the mean reference altitude, $f_0 = 10$ units controls the amplitude of the surface undulations, $a = 0.2$ governs the lateral decay towards the grid boundaries and $x_M, y_M = 63.5$ units represent the maximum grid extents in the x and y directions, respectively. The grid spacing was $\Delta x = \Delta y = 1$ unit. Model depth variations span approximately ± 3.8 units (Fig. 2a), chosen to represent a deep ocean setting. These surfaces produced maximum slopes of 38 per cent, covering a range from gentle to steep draped terrains. The magnetic anomaly was calculated on this non-planar observation surface for a simple 3-D rectangular prismatic source. The prism was centred beneath the grid at $x = 0$ and $y = 0$, with horizontal limits $x = [-20, +20]$ and $y = [-20, +20]$ units. Vertically, the prism extends from $z = -20$ to $z = -10$ units, so that its top lies 10 units below the mean observation level and its base lies 20 units below the mean observation level. The prism was assigned a uniform magnetization intensity of 5 A m^{-1} in the inducing-field direction used for the total-field anomaly calculation. This simple source geometry follows the controlled benchmark configuration of M. Pilkington & O. Boulanger (2017), while allowing the expected field at a target reference level to be calculated independently.

The resulting synthetic anomaly ranges from approximately -350 to 820 nT on the draped observation surface (Fig. 2b). The field was then upward continued to a horizontal reference plane located 4 units above the mean observation level. In this test, we use $w_l = 128$ units and $w_s = 24$ units, based on the dominant anomaly wavelength and the relief of the observation surface, as described in the previous section. The upward continued field F_{cont} was compared against the analytically derived theoretical field F_{theory} at the same elevation (Figs 2c and d), so the residual field, ΔF_{res} , is given by

$$\Delta F_{\text{res}} = F_{\text{cont}} - F_{\text{theory}}. \quad (14)$$

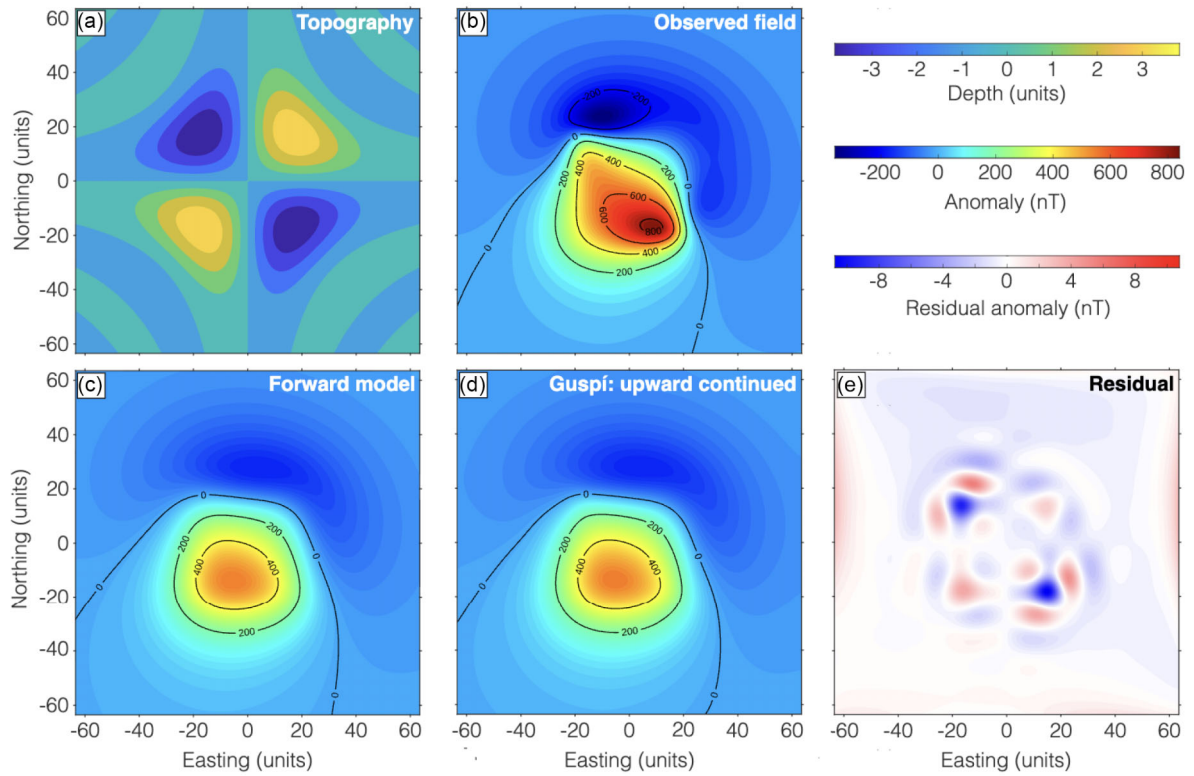


Figure 2. (a) Synthetic topography with two highs and two lows and maximum slope of 38 per cent. (b) Magnetic field anomaly observed on synthetic surface. (c) Forward model at $z = 4$ units. (d) Upward continued field at $z = 4$ units using Guspí's (F. Guspí 1987) method. (e) Difference between forward model and upward continued field anomalies.

The residual anomalies are generally within approximately ± 10 nT for this controlled example (Fig. 2e). This result indicates that the implementation reproduces the expected continued field for the specified synthetic geometry. However, this benchmark should be interpreted as a numerical implementation test rather than a complete validation for realistic AUV magnetic surveys. Real near-bottom data sets commonly include irregular line spacing, data gaps, navigation uncertainty, variable altitude, heading-dependent residual vehicle noise, gridding artifacts and more complex magnetization than represented by the single-prism model used here. Therefore, the synthetic test is used to verify the behaviour of the optional Guspí continuation module under known conditions.

4 CODE STRUCTURE AND USAGE

The processing framework is implemented in both MATLAB (R2024a) and Python (version 3.13.11), providing a reproducible and flexible environment for handling AUV magnetic data sets. The repository is organized into three principal components: a core processing module, an upward continuation module and a set of auxiliary utilities. Each component consists of self-contained functions with defined inputs and outputs, enabling users to modify or extend individual steps without altering the overall workflow.

At the top level, a single driver script `main_processing.m` coordinates data loading, processing and output generation through user prompts. The core module includes routines for data initialization, component rotation, spin calibration, file input-output and plotting. Each function operates on structured MATLAB data, ensuring consistency across processing stages and reducing manual data handling. After vehicle correction, users can choose to process either selected track segments to cross-check if the calibration is performed well or not. Based on this choice, the user can save entire processed dive data, with or without spin sections, for further calculations. Following this, the data files without spin section times are crossover corrected. Then the upward continuation method is implemented for the 2-D Guspí approach, which contains all pre-processing, path setup and frequency-domain operations required to perform continuation from arbitrary survey levels to a chosen reference level. Utilities supporting the main workflow provide general-purpose functions for navigation handling, distance calculations, figure saving, IGRF coefficient calculations and user interaction. All outputs are stored in structured `.mat` files and ASCII formats (`.txt`), with detailed headers that capture metadata such as time, location, orientation, raw and corrected magnetic data and anomaly values. This consistent output format ensures compatibility with downstream gridding, mapping and modelling tools.

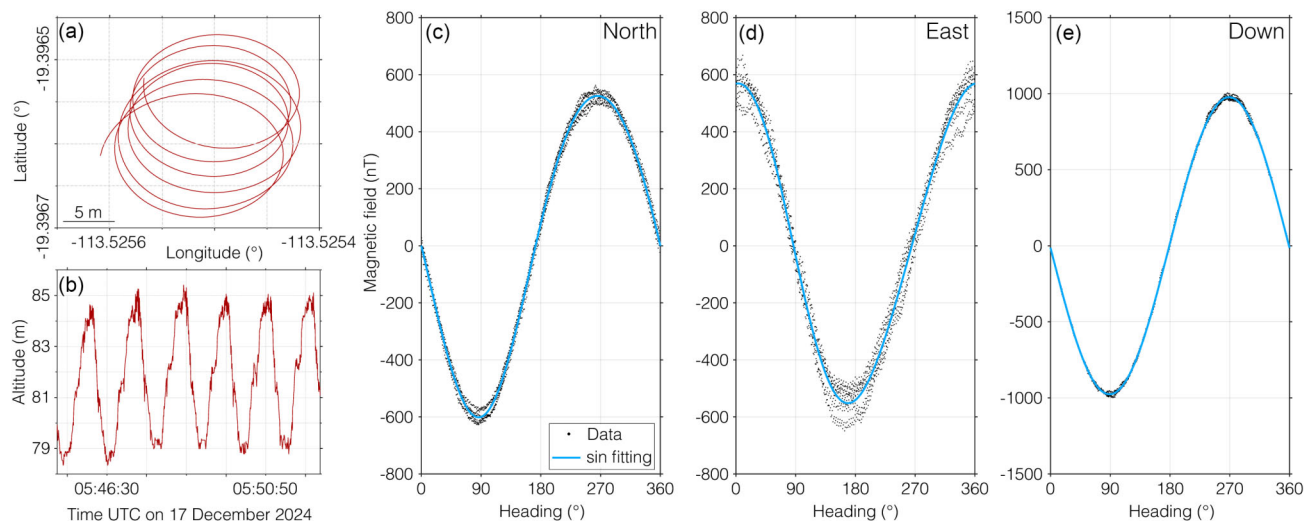


Figure 3. Spin calibration of AUV *Sentry* dive 750 magnetic data along 19°S segment of East Pacific Rise. (a, b) Position (grid lines are at 5 m intervals) and altitude of *Sentry* during spin maneuver, respectively. (c–e) Dots are magnetic field components as function of heading; lines are sinusoidal fits to compensate permanent and induced magnetic fields for (c) North, (d) East and (e) Down components.

5 RESULTS

5.1 Case study 1: AUV *Sentry* survey at 19°S, EPR

Magnetic data were acquired during AUV *Sentry* dive 750 along the 19°S EPR segment during R/V *Atlantis* cruise AT50-31 in December 2024. Three Applied Physics Systems Model 1520 triaxial fluxgate magnetometers were mounted on the vehicle (top: SN0690; port: SN0689 and starboard: SN0687). Strong magnetic fluctuations, reaching several thousand nT, were observed in the lower-mounted port and starboard sensors due to their proximity to other vehicle subsystems. To avoid contamination from these platform-related disturbances, only the data from the top sensor were used.

Although the top magnetometer provides the cleanest record in this example, the sensors at athwartships (port and starboard) still generated useful data. The athwartships sensors recovered the same broad magnetic-field behaviour as the top sensor, although they contain stronger offsets, short-period noise and heading-related jumps during the vehicle turn (Figs S2 and S3, Supplementary Material). The port sensor shows a clear disturbance during heading changes, whereas the starboard sensor shows a larger step-like response, indicating that these sensors are affected differently by vehicle geometry and nearby electrical or magnetic sources. For this reason, we use the top magnetometer as the primary record in the main workflow because it gives the most stable component behaviour before and after heading correction. The port and starboard records are included as supplementary examples to show that the athwartships sensors can still preserve useful magnetic information under favourable conditions. A full multisensor treatment, including relative offset calibration, timing checks, sensor-specific heading correction and possible port–starboard gradient analysis, could be addressed in future work.

Sensor temperature measured within the AUV was recorded during the dive, and enabled removal of thermally induced biases by sensor offset, scale factor and non-orthogonality of axes in each magnetometer component using pre-determined shore-based calibration parameters (Fig. S4, Supplementary Material). Over a representative segment, the temperature-dependent scalar calibration results in changes of approximately 120 nT (X), 100 nT (Y) and 240 nT (Z) (Fig. S5, Supplementary Material). The correction produces systematic component-dependent shifts while preserving the short-period magnetic variations. The effect is most evident in the X and Z components.

Magnetic distortions due to permanent and induced fields of the AUV were then characterized using controlled spin maneuvers performed near the start of the dive. Spin segments were identified from rapid heading changes during stationary rotations when the vehicle was near bottom (Fig. 3). For each NED component, robust sinusoidal models were fit to estimate heading-dependent offsets and amplitudes for both permanent and induced components. These corrections were then subtracted from the entire data set. The larger heading-dependent amplitude in the Down component may reflect the projection of vehicle-generated permanent and induced magnetic fields into the geographic Down direction. Such projection can arise from a vertically oriented platform-field contribution, sensor mounting geometry or asymmetric magnetization of the vehicle. A segment of data spanning three distinct headings illustrates the efficacy of the corrections (Fig. 4). Although the corrected NED components exhibit high-frequency fluctuations in the immediate vicinity of turns, there is little remaining offset between the component values on the straight segments prior to and after each turn.

Despite removal of the dominant heading-dependent distortions, the corrected components still contain high-frequency fluctuations (Fig. 4). To attenuate these fluctuations, we apply an optional iterative reweighted least-squares smoothing filter independently to

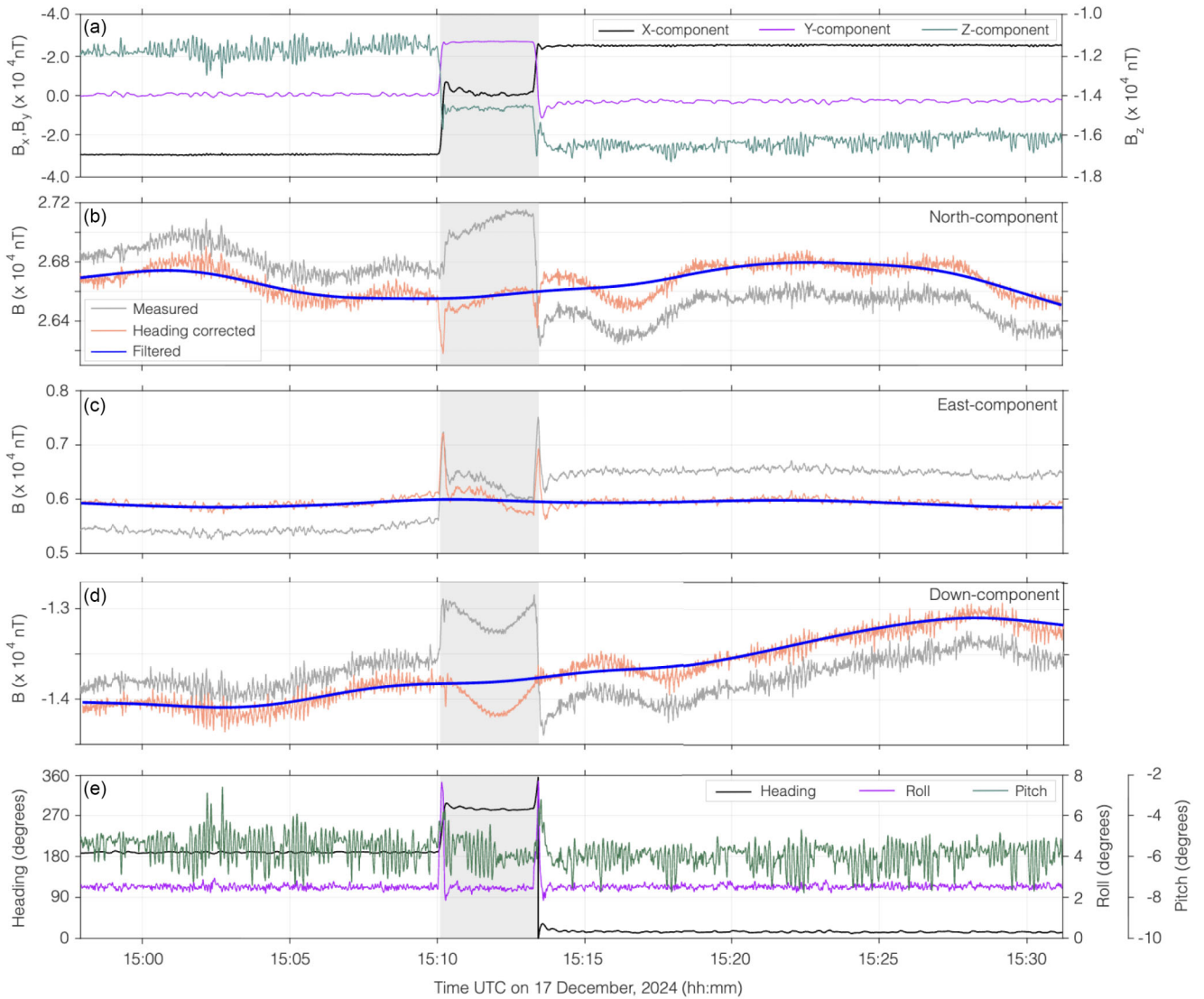


Figure 4. Portion of time-series data (2000 s) collected through a turn during AUV *Sentry* dive 750. (a) Magnetic field in vehicle (XYZ component) reference frame. (b)–(d) Measured, heading corrected and filtered magnetic data in geographic (NED component) reference frame. (e) Vehicle attitude: heading, pitch and roll. Grey shaded area shows turn along survey line.

each corrected magnetic component, written as $B_i^s = \text{IRLSSmooth}(B_i, \tau, 2)$ (Jim 2026). Here B_i is the corrected magnetic component, B_i^s is the smoothed component, τ is the smoothing parameter and the final argument specifies a second-order derivative penalty. The parameter τ controls the trade-off between fidelity to corrected data and smoothness of the output. The filter minimizes the misfit to the magnetic component while penalizing second-order curvature in the time-series, thereby suppressing rapid point-to-point oscillations while preserving broader magnetic variations. The algorithm first computes a uniformly weighted least-squares solution and then iteratively updates the data weights based on the residuals between the input and smoothed series. In our implementation, the maximum number of iterations is 25, the convergence tolerance is a relative output change of 10^{-6} , the Gaussian error breakpoint is 1.5 standard deviations and the loop gain is 1.3. Because this smoothing acts as a low-pass operation, it is treated as an optional post-processing step rather than a mandatory correction. If the smoothing parameter is too large, real short-wavelength geological anomalies may be attenuated.

Residual anomaly offsets between intersecting dive tracks were then quantified and minimized using a crossover adjustment. A total of 16 segments longer than 300 m yielded crossover points. The initial RMS misfit of the total field anomaly was 136.9 nT, with 170.3, 73.9 and 99.2 nT for the N , E and D components, respectively. Following a least-squares adjustment, the RMS misfit was reduced to 16.4 nT for the total field anomaly (9.9, 14.3 and 30.5 nT for the N , E and D components). This reduction reflects a more than 80 per cent improvement in internal consistency. The intersecting segments differed in altitude by only a few metres, which is smaller than the local bathymetric relief, and well within the scale at which significant anomaly variations are expected.

To correct for altitude variations along the survey, the total-field and component anomalies were upward continued to a depth of 2650 m. Prior to upward continuation, the anomaly data were interpolated onto a uniform $10 \text{ m} \times 10 \text{ m}$ grid using an adjustable

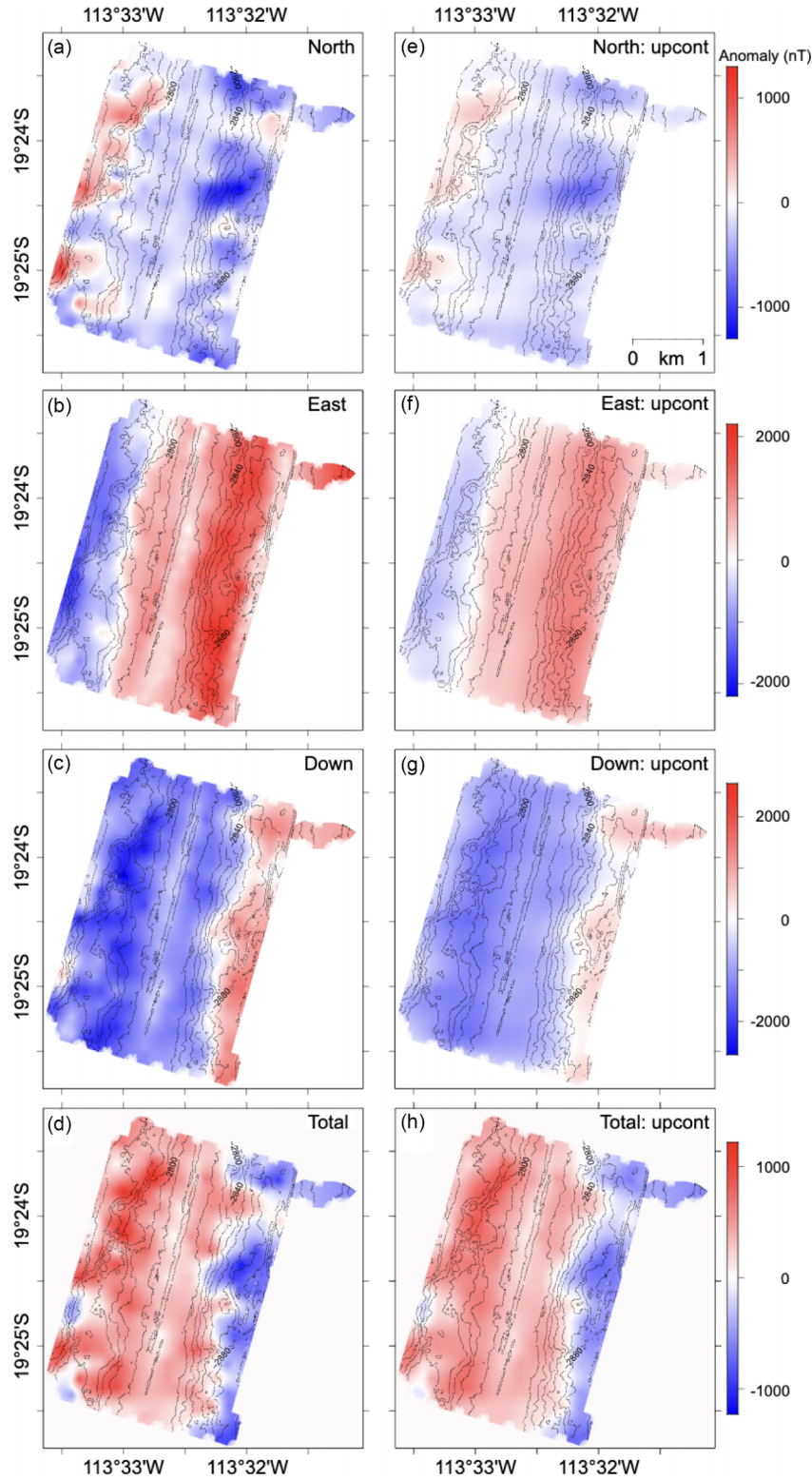


Figure 5. Magnetic anomaly data from AUV *Sentry* dive 750, at 19°S, EPR, before and after upward continuation, overlaid by bathymetry contours. (a)–(d) Observed north, east, down and total magnetic anomalies, respectively, prior to upward continuation. (e)–(h) Upward continued north, east, down and total magnetic anomalies, respectively.

tension continuous curvature splines method, implemented via the *surface* algorithm in the Generic Mapping Tools (P. Wessel *et al.* 2019) to ensure consistent spatial sampling. A spectral bandpass filter between wavelengths of 0.5 and 4 km was applied to suppress unwanted high-frequencies while preserving longer-wavelength signals associated with crustal magnetization (Fig. 5).

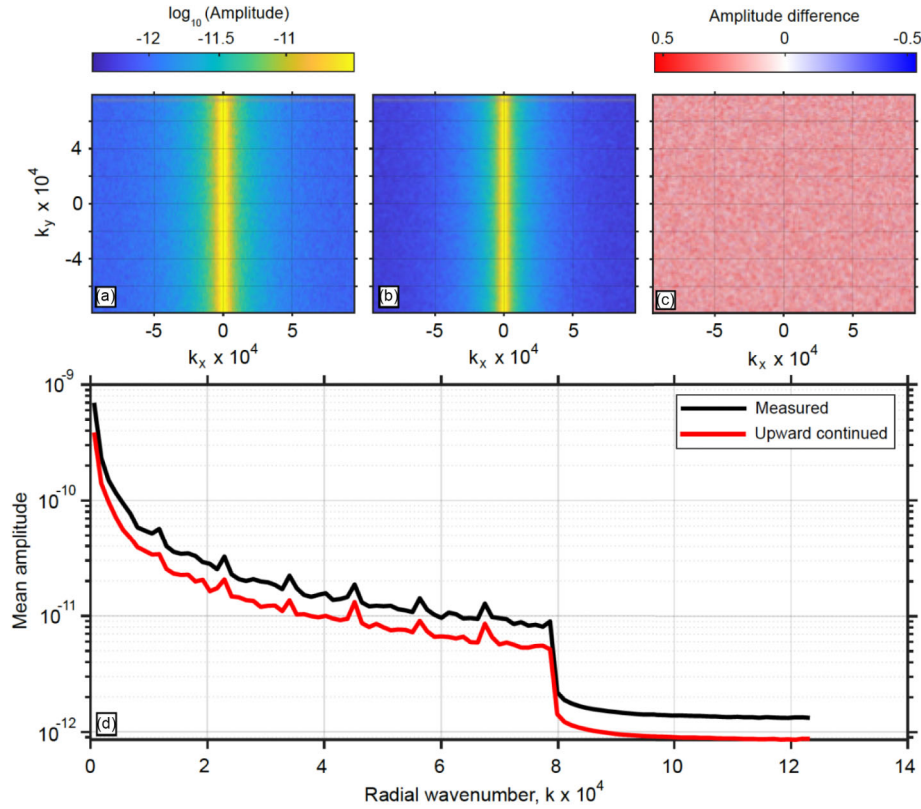


Figure 6. Amplitude spectra from *Sentry* dive 750. (a, b) 2-D amplitude spectra for measured and upward-continued fields, respectively. (c) Normalized difference between measured and upward-continued field spectra. (d) Radially averaged amplitude spectra for measured and upward-continued fields.

The upward-continued anomaly grids exhibit smoother spatial variations across the survey region because continuation to a common level attenuates short-wavelength components. The main longer-wavelength anomaly patterns are retained, whereas track-scale and high-wavenumber variations are reduced. Because upward continuation is a low-pass operation, we treat this step as an optional common-level transformation rather than as a required correction or an intrinsic improvement of the geological signal. The corrected draped anomaly data are also retained by the workflow and can be exported for modelling or inversion approaches that account directly for variable observation altitude.

The 2-D log-amplitude spectra of the measured and upward-continued fields for *Sentry* dive 750 show similar dominant low-wavenumber structure (Fig. 6), indicating that the broad anomaly pattern is retained after continuation. However, the upward-continued spectrum has systematically lower amplitudes than the measured-field spectrum, particularly towards higher radial wavenumbers. This behaviour is expected because upward continuation applies an exponential attenuation factor to the Fourier spectrum, with stronger attenuation at shorter wavelengths. The normalized amplitude-difference map is mostly positive, showing that the measured field contains larger spectral amplitudes than the upward-continued field over most of the wavenumber domain. The radially averaged spectra show that both spectra decrease with increasing radial wavenumber, but the upward-continued field remains consistently lower than the measured field. The radially averaged normalized amplitude difference is positive across the analysed wavenumber range, confirming that upward continuation reduces spectral power rather than introducing new high-wavenumber content. This spectral behaviour supports the interpretation of upward continuation as a smoothing or low-pass transformation. The comparison therefore provides a quantitative basis for the smoother appearance of the upward-continued maps, while also emphasizing that this step attenuates short-wavelength signal.

5.2 Case study 2: AUV *Sentry* survey at $9^{\circ}50'N$, EPR

To evaluate the performance of our processing workflow, we compared it against the calibration approach of J.-F. Oehler *et al.* (2024) for *Sentry* 582 data acquired during cruise RR2102 at the $9^{\circ}50'N$ segment of EPR (R. Parnell-Turner *et al.* 2021). In the method of J.-F. Oehler *et al.* (2024), calibration is performed in the vehicle's sensor reference frame (XYZ), hence the data are not rotated into the navigation-aligned frame (NED). They used it as a figure-of-merit calibration to estimate and remove static magnetic effects from the AUV. As a result, heading-dependent platform-induced distortions are not treated in a coordinate system where they manifest most clearly. Moreover, their workflow appears to calibrate the spin data to the IGRF, effectively assuming that local crustal anomalies are

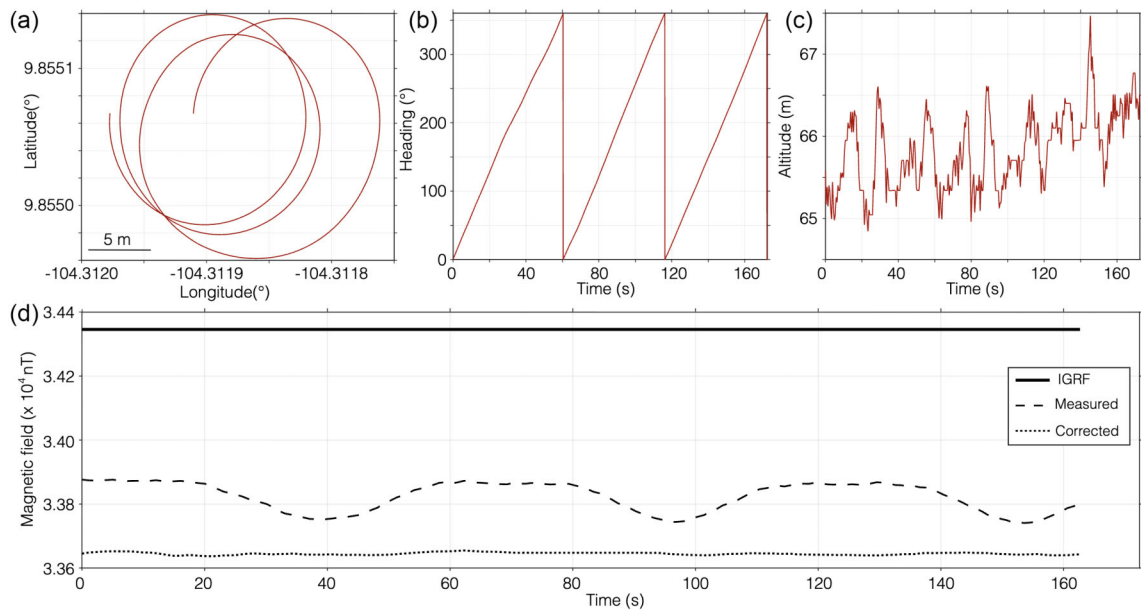


Figure 7. Spin calibration for magnetic data collected during AUV *Sentry* dive 582, near 9° 50'N, EPR. (a) Trackline position, with gridlines at 5 m intervals. (b, c) Time-series of heading and altitude, respectively. (d) Dashed and dotted lines are temperature and spin corrected magnetic field time-series, respectively; solid line is modelled IGRF total field.

Table 1. Comparison of residual statistics from near-bottom spin maneuver during *Sentry* dive 582. Values from Oehler et al. (2024) are compared with residual statistics obtained using the present workflow. Residuals are calculated relative to the IGRF during the selected spin interval.

Workflow/study	Residual definition	STD before	STD after	Peak-to-peak before	Peak-to-peak after
Oehler <i>et al.</i> (2024)	Total field—IGRF	97.30 nT	5.80 nT	348.20 nT	41.00 nT
This study	Corrected field—IGRF	45.32 nT	4.15 nT	133.75 nT	17.75 nT

negligible (fig. 10 in their study). Applying this method to the data from *Sentry* dive 582, with a near-bottom spin maneuver at 2583 m water depth, the standard deviation between measured and IGRF total fields was reduced from 97.3 to 5.8 nT, and the peak-to-peak amplitude from 348.2 to 41.0 nT (J.-F. Oehler *et al.* 2024).

In contrast, the modular workflow developed here only applies heading corrections after transformation from vehicle to geographic reference frame. By rotating the coordinate frames, the heading correction becomes more stable and less sensitive to vehicle attitude. Importantly, our approach calibrates the fluxgate independently of the platform and does not assume that the anomalous field is zero, allowing the method to preserve the local crustal signal. Fig. 7 shows the *Sentry* 582 spin interval processed using our workflow, which includes vehicle track, heading, altitude and the magnetic field before and after spin correction, compared with the IGRF field evaluated at the vehicle position and time. For this data with exact time interval of spin maneuvers, we achieved a reduction in the standard deviation between measured and IGRF fields from 45.32 to 4.15 nT, with peak-to-peak amplitude decreasing from 133.75 to 17.75 nT (Fig. 7 and Table 1). Both the raw and corrected residuals are lower than those obtained through the calibration method of J.-F. Oehler *et al.* (2024). This suggests that the rotation into NED and spin corrections based on sinusoidal fitting better isolates directional biases.

In the approach followed by J.-F. Oehler *et al.* (2024), the spin calibration is evaluated relative to the IGRF, implicitly assuming that any local crustal anomaly is negligible or constant during the spin. This assumption may be restrictive for near-bottom data. In our workflow, the IGRF is used only as a long-wavelength reference to assess the spin correction, and the corrected survey data are not forced to match the IGRF. Therefore, the residuals should be interpreted as a measure of reduced platform based heading-dependent variation.

5.3 Case study 3: AUV *Sentry* survey at 14°N, MAR

We also applied this workflow to AUV *Sentry* dive 378, carried out along the 14°N segment of the MAR during R/V *Atlantis* cruise AT33-03 in March 2016 (M. Kurz *et al.* 2016). After temperature correction, coordinate rotation and spin calibration, residual anomaly offsets between intersecting dive tracks were quantified and minimized using a crossover adjustment. A total of 13 segments longer than 300 m yielded crossover points. The initial RMS misfit of the total field anomaly was 205.1 nT, with 197.8, 115.2 and 86.4 nT for

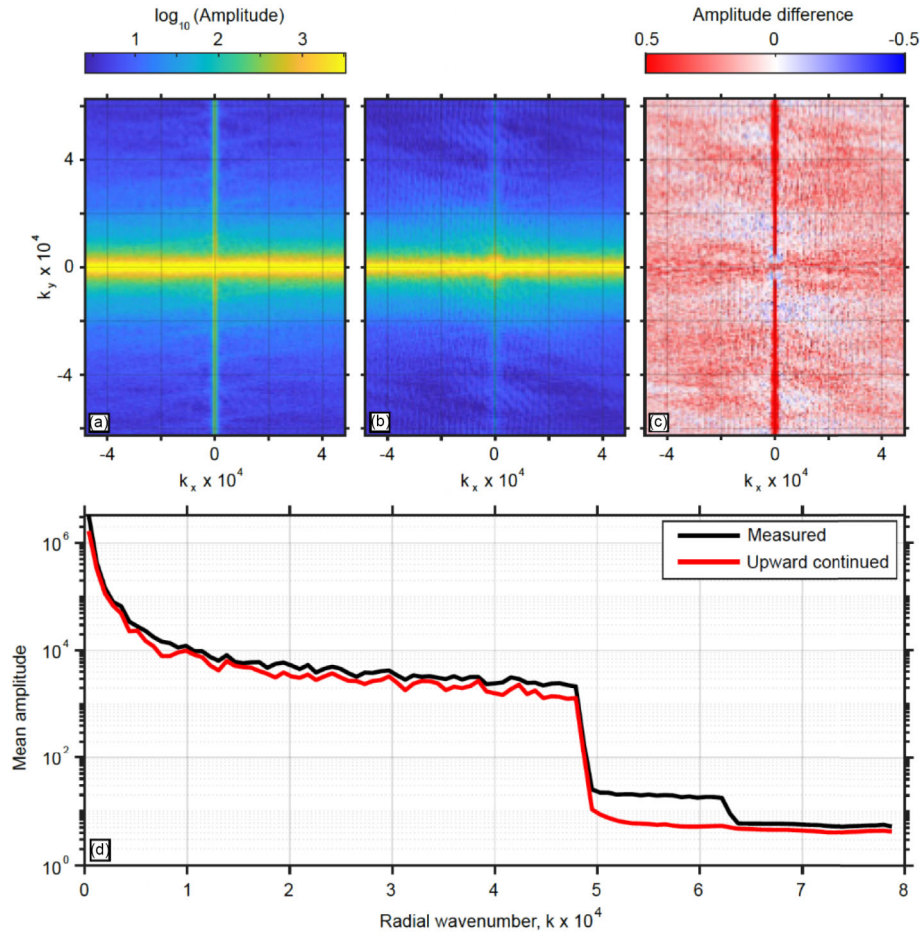


Figure 8. 2-D amplitude spectrum of (a) measured and (b) upward-continued fields for *Sentry 378*. (c) Normalized amplitude difference. (d) Radially averaged amplitude spectra for measured and upward-continued fields. (e) Radially averaged normalized amplitude difference.

the N , E and D components, respectively. Following crossover correction, the RMS misfit was reduced to 24.1 nT for the total field anomaly, and 19.5, 22.3 and 28.1 nT for the N , E and D components, respectively. Following these steps, the total-field and component anomalies were resampled, gridded and upward continued to a constant level of 2650 m, and a spectral bandpass filter between 0.5 and 5 km was applied. After upward continuation, the levelled anomaly data were gridded at 10 m node spacing (Fig. S6, Supplementary Material).

The comparison between the measured, upward-continued and residual anomaly fields shows that continuation to a constant elevation produces a smoother and more coherent spatial structure while preserving the overall anomaly geometry (Fig. S6, Supplementary Material). The NED components show only modest amplitude reduction after continuation, indicating that the dominant long-wavelength magnetization patterns are retained. Residual maps reveal short-wavelength differences concentrated in areas of steep bathymetry reflecting localized sensitivity to vehicle altitude and navigation variability. For the total-field, upward continuation reduces fine-scale, track-parallel fluctuations while maintaining the broader distribution of positive and negative anomalies.

The measured and upward-continued spectra show similar dominant low-wavenumber structure, indicating that the broad anomaly pattern is retained after continuation (Fig. 8). However, the upward-continued spectrum has systematically lower amplitudes, especially at higher radial wavenumbers, consistent with the expected low-pass behaviour of upward continuation. The normalized amplitude difference is mostly positive, indicating that the measured field contains larger spectral amplitudes than the upward-continued field over most of the wavenumber domain. The radially averaged amplitude spectra show that both spectra decrease strongly with increasing radial wavenumber, and the upward-continued field remains consistently lower than the measured field.

6 DISCUSSION

6.1 Demonstration of workflow efficiency

The modular architecture of the workflow enables efficient processing of near-bottom magnetic data sets. Once spin intervals are identified, the complete sequence, from raw navigation and sensor streams to levelled and upward-continued anomaly fields, executes

with minimal user intervention. All computations were performed on two platforms: (1) a MacBook Pro equipped with an Apple M1 processor (8 cores: 4 performance and 4 efficiency) and 16 GB of RAM, and (2) a Linux workstation running Ubuntu 20.04 LTS with an Intel Core i9-14900K processor and 32 GB of RAM. On both systems, a typical dive required approximately 2 min of processing time, demonstrating the computational efficiency and platform independence of the approach. The quick generation of diagnostic plots for vector rotation, spin calibration and upward continuation provides rapid visual assessment of data quality at each stage. This level of efficiency is advantageous for modern AUV campaigns that acquire tens of dives per expedition, and facilitates consistent, reproducible processing across surveys. The combination of speed and modularity positions this workflow for eventual integration into near-real-time processing frameworks.

6.2 Performance and limitations of the two-dimensional upward continuation

The 2-D Guspi method used for upward continuation demonstrates robust numerical stability by iteratively correcting local height perturbations in the spectral domain. Synthetic forward modelling confirms that the method reproduces theoretical anomaly fields with residuals typically below 1 per cent. For example, residual errors were of order 10 nT for the anomalies in the range ~ 1200 nT (Fig. 2). Such accuracy is within the range necessary for crustal-scale geological interpretations and is particularly suitable for identifying intermediate-wavelength anomalies while minimizing the amplification of high-frequency noise caused by local topographic variations. This method, however, assumes relatively smooth variations in the observation surface; therefore, extremely steep topography or sparse spatial sampling can introduce edge effects or spectral ringing. These limitations underscore the importance of careful survey design and consistent vehicle altitude control to maximize the fidelity of upward-continued fields (R.J. Blakely 1995).

As illustrated in Fig. 2, determining optimal short- and long-wavelength cut-off parameters is essential for balancing noise suppression with anomaly preservation. The residual amplitude between synthetic forward model and upward continued field at a given level defines the stability criterion of this method (Fig. S7, Supplementary Material). Low misfit corresponds to stable filter combinations, whereas high misfit indicates that either noise is being amplified (short-wavelength cut-off too high) or long-wavelength energy is being overly suppressed (long-wavelength cut-off too low). We observe that solutions diverge when energy from short wavelengths is overly retained ($< \sim 20$ units), causing amplification of high-frequency noise associated with steep local slopes in the draped survey geometry (Fig. S7, Supplementary Material). Conversely, when long and short wavelengths are almost equal, it leads to unstable solutions with unfavourably high residuals. The domain of minimum residual misfit forms a coherent low-amplitude trough centred around short-wavelength cut-offs of 20–24 units and long-wavelength cut-offs of 90–128 units. These values correspond to the onset of noise amplification at high wavenumbers and the wavelength of the dominant magnetic anomaly peak produced by the forward model, respectively. Therefore, automatic selection of short-wavelength cut-off of 24 units and long-wavelength cut-off of 128 units in Fig. 2 falls within the stable region and minimizes spectral ringing while preserving true anomaly signal. The same approach to select wavelength filters has been applied for *Sentry* data at 19°S segment along EPR and 14°N along MAR.

6.3 Crossover analysis and role of vehicle depth variability

In our workflow, crossover differences are assessed after heading correction and resampling the magnetic field onto uniform temporal and spatial grids. For small altitude differences, the residual mismatch at a crossover point primarily reflects true line-to-line biases, such as navigation uncertainty, long-period instrumental drift or small-scale platform effects. This approach is conceptually aligned with the least-squares segment correction methodology described by Prince and Forsyth (R.A. Prince & D.W. Forsyth 1984), in which systematic errors along long straight-line survey segments are treated as approximately constant and corrected to minimize crossover discrepancies. In the context of the AUV surveys examined in this study, each track segment can be considered to have a locally constant additive bias. These biases are estimated from crossover differences and corrected segment-wise, preserving the relative amplitude of the underlying anomalies. When survey segments cannot be approximated as having a locally constant additive bias, for example, when track lines vary nonlinearly or the magnetic source changes over short distances, crossover levelling may partially suppress the true anomaly signal and should be interpreted cautiously.

6.4 Applications to seafloor exploration and survey design

Accurately processed AUV magnetic data provide essential constraints for seafloor characterization and geological structural analysis. The computational efficiency of this workflow makes it suitable for near-real-time data evaluation during AUV missions. Such rapid feedback can support adaptive survey strategies in which vehicle trajectories are adjusted in response to preliminary anomaly patterns or navigational uncertainties. The framework's compatibility with terrain-draped surveys is particularly important as AUV missions increasingly employ terrain-following autonomy to maintain optimal sensor geometry. By improving anomaly fidelity under variable-altitude conditions, this workflow enhances the reliability of magnetic interpretations across diverse seafloor settings.

6.5 Broader relevance beyond mid-ocean ridge environments

Although this workflow is demonstrated using AUV surveys along mid-ocean ridges, the methodology is broadly applicable across terrestrial, marine and airborne magnetic investigations. This framework can be readily adapted to a variety of platforms, including remotely operated vehicles (ROVs), towed magnetometers, gliders and autonomous surface vehicles, as well as airborne and terrestrial systems such as helicopter-borne magnetometers, fixed-wing aircraft surveys and ground-based magnetic cart surveys. Beyond marine studies, the workflow can be effectively applied to mineral exploration, tectonic mapping, volcanic monitoring, environmental and archaeological geophysics and infrastructure assessment.

6.6 Applicability to other near-bottom platforms

Although the workflow is demonstrated here using magnetic data acquired by AUV *Sentry*, several core modules are platform independent. These include temperature correction, coordinate transformation, reference-field removal, crossover adjustment, filtering, gridding and optional upward continuation. Platform-specific steps of the workflow are the magnetic compensation strategy and the availability, geometry and synchronization of magnetic, navigation and attitude sensors. Extension to human occupied vehicle (HOV) and ROV magnetic data sets is likely to be feasible, but poses new challenges. For example, a preliminary application to an HOV *Alvin* data set shows that the magnetic response may not always follow a simple first- and second-harmonic dependence on heading alone. The magnetic response shows substantial scatter around the fitted curve, and systematic residuals remain after correction. This result indicates that the platform magnetic signal may depend not only on heading, but also on factors such as electrical state and thruster activity. Nonetheless, application of these methods to HOV and ROV data sets could be an important future extension of the workflow presented here.

7 CONCLUSIONS

This study presents a modular, open-source workflow for the calibration and correction of near-bottom magnetic data collected by AUVs. By sequentially addressing platform and environment related effects, including coordinate frame rotation, heading correction, spin compensation, altitude normalization, spectral filtering and crossover levelling, the framework produces internally consistent, high-fidelity magnetic anomaly maps that preserve the physical amplitude and spatial distribution of geophysical signals. The integrated workflow reduces heading-dependent bias by 70–90 per cent, crossover RMS by 80–90 per cent and achieves upward-continuation errors ≤ 1 per cent in synthetic tests. Its modular design allows individual components to be used independently or adapted to different acquisition strategies, accommodating ROVs, towed systems, autonomous surface vehicles and other platforms capable of vector magnetic and navigation measurements. Application to multiple mid-ocean ridge data sets, including the East Pacific Rise and Mid-Atlantic Ridge, demonstrates the workflow's robustness across diverse tectonic environments, survey geometries and vehicle operational conditions. These case studies illustrate the technical performance of the workflow and do not constitute geological interpretation of the measured anomalies.

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SUPPORTING INFORMATION

Supplementary data are available at [GJIRAS](https://doi.org/10.1093/gji/ggab279) online.

Figure S1. Heading, roll, pitch during *Sentry* 750 spin maneuvers.

Figure S2. NED components of port-side magnetometer of *Sentry* 750 dive.

Figure S3. NED components of starboard-side magnetometer of *Sentry* 750 dive.

Figure S4. Temperature calibration parameters for sensor SN0690.

Figure S5. Temperature corrected XYZ components of magnetic field *Sentry* 750 dive.

Figure S6. 2-D magnetic anomaly maps of *Sentry* 378 dive along 14°N segment of Mid-Atlantic Ridge.

Figure S7. Synthetic residual magnetic anomaly amplitude.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The computational workflows implemented in MATLAB and Python for this study are available at Zenodo (V.V. Ingale 2026a) and (V.V. Ingale 2026b), respectively. AUV *Sentry* data acquired at 9°50'N on the EPR are archived at Zenodo via R. Parnell-Turner *et al.* (2021). Data from 14°N on the MAR are available at M. Kurz *et al.* (2016). Figures are made with the Generic Mapping Tools (P. Wessel *et al.* 2019) and with MATLAB 2024a.

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