

Article

Magnetic Interference Compensation Method for a Deep-Sea Human-Occupied Vehicle Based on Dynamic Excitation

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Abstract

Human-occupied vehicles (HOVs) provide an ideal platform for high-resolution near-bottom magnetic anomaly detection. However, complex platform-generated magnetic interference severely limits the reliable extraction of weak magnetic signals. The conventional Tolles–Lawson (T–L) model relies on large-amplitude attitude maneuvers to estimate interference coefficients, but such maneuvers are infeasible for HOVs because of their large inertia, hydrodynamic coupling, and deep-sea safety constraints. To address this limitation, we propose a dynamic-excitation magnetic interference compensation method that exploits the inherent dynamic characteristics of the platform. By commanding the HOV to execute acceleration–deceleration cycles and horizontal S-shaped turns, the method indirectly excites pitch and roll variations through coupled vehicle dynamics and provides the attitude-dependent information required by the complete 18-term T–L model. The 18-term basis set is constructed from measured direction cosines and their time derivatives, with coefficient identifiability determined by the excitation data. Helicopter-based analog experiments showed that the proposed maneuver yielded improvement ratios of 6.6 and 12.1 on two test lines, comparable to the values of 6.3 and 12.5 obtained using conventional airborne calibration maneuvers. In an in situ trial with the Shenhai Yongshi (“Deep-Sea Warrior”) HOV, the method reduced the magnetic-field standard deviation from 0.8870 nT to 0.4157 nT, corresponding to an improvement ratio of 2.13. The compensated record exhibited a residual dynamic-field variation of 0.4157 nT under the tested maneuvering conditions. The helicopter experiment evaluated the shared excitation sequence and signal-processing workflow on a controllable airborne platform. These results demonstrate a practical engineering approach to suppressing dynamic magnetic-field variations below 1 nT in the tested HOV conditions.



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1. Introduction

Deep-sea magnetic anomaly detection has important scientific and defense applications in seafloor mineral-resource exploration (e.g., polymetallic nodules and hydrothermal sulfides), interpretation of seafloor geological structures, underwater archaeology, and

target detection [1–3]. Compared with sea-surface towed systems and autonomous underwater vehicles (AUVs), a human-occupied vehicle (HOV) offers unique advantages in human–machine collaboration and station keeping, enabling close-range, high-resolution near-bottom detection of small magnetic-anomaly sources [4–6]. Relative to AUVs and remotely operated vehicles (ROVs), HOVs provide direct human decision-making, precise control when following seafloor microtopography, and adaptability to complex geological environments, making them effective platforms for high-precision near-bottom magnetic surveys [7,8].

In addition to the target-induced magnetic field, a high-precision magnetometer mounted on an HOV inevitably measures the field generated by the platform, the local geomagnetic field, and other interference sources during a survey [9]. An HOV is a large, highly integrated electromechanical platform whose thruster motors, high-power battery packs, servo-hydraulic mechanisms, and titanium-alloy pressure hull create a complex electromagnetic environment [10]. The field generated by the platform can significantly distort underwater magnetic measurements [11]. It consists mainly of permanent, induced, and eddy-current magnetic fields. Unless these components are accurately characterized and removed, platform noise can mask the target signal measured by the magnetometer [12]. Magnetic interference compensation is therefore essential for high-precision deep-sea magnetic detection.

Conventional magnetic interference suppression on moving platforms is based primarily on the Tolles–Lawson (T–L) model [13]. For more than half a century, this model has been applied successfully in fixed-wing aeromagnetic surveys by representing platform interference through an 18-coefficient regression equation based on body-frame geomagnetic direction cosines [14]. Stable least-squares (LS) estimation depends on the rank and conditioning of the corresponding basis-function matrix. Aircraft therefore execute deliberately rich calibration maneuvers, including independent, large-amplitude pitch, roll, and yaw oscillations along multiple headings, to excite the T–L basis functions [15].

Studies specifically addressing magnetic interference mitigation on HOVs remain limited, although related work has established several useful approaches for underwater platforms. Li et al. proposed a platform-interference compensation method for an underwater vector magnetic measurement system and validated it through simulations and land-based and marine experiments [11]. For autonomous underwater vehicles (AUVs), Cracchiolo et al. examined sensor placement, vehicle self-noise, and denoising on a REMUS 100, showing that increased sensor–platform separation and low-pass filtering can improve magnetic isolation [16]. Yan et al. investigated magnetometer calibration for AUV navigation using multiconstraint optimization [17]. These studies address sensor isolation, calibration, or interference mitigation, but they do not resolve the maneuver-design problem encountered when a large HOV must estimate a full dynamic compensation model without independently exciting its attitude axes. Accordingly, this study links an HOV-executable trajectory to the direction-cosine and derivative variations used in the T–L regression.

Unlike an aircraft, which can achieve rapid and largely independent attitude control through aerodynamic control surfaces, a deep-sea HOV exhibits strongly nonlinear, coupled hydrodynamics and is controlled indirectly by a thruster array distributed around the hull [18]. Moreover, the HOV control system suppresses attitude oscillations to satisfy stringent deep-sea safety and stability requirements. For a deep-diving vehicle weighing more than ten metric tons and maneuvering at low speed, independent periodic pitch and roll maneuvers with amplitudes commonly used in airborne calibration, such as pitching by $\pm 5^\circ$ or rolling by $\pm 10^\circ$, are difficult to realize because the hydrodynamic and control responses are coupled and the safety controller suppresses rapid attitude excursions.

sions [19]. Vehicle-specific attitude-rate and control-bandwidth limits were not measured in this deployment, so the analysis below focuses on the measured vehicle response. This constrained and coupled maneuvering behavior makes it difficult to generate the diverse attitude excitation required for stable estimation of all T–L compensation coefficients.

To overcome the calibration limitations imposed by HOV hydrodynamic and safety-control constraints, this study proposes a coordinated magnetic interference compensation method based on composite dynamic-excitation maneuvers. Longitudinal acceleration–deceleration cycles induce pitch variation, whereas horizontal S-shaped turns induce coupled roll and yaw variations. These maneuvers are embedded in a four-heading square track to generate the direction-cosine and angular-rate variations required by the complete 18-term T–L model. Near-bottom in situ measurements were conducted in the South China Sea using the “Deep-Sea Warrior” HOV. Compensation reduced the standard deviation of the magnetic-field record from 0.8870 nT to 0.4157 nT, corresponding to an improvement ratio of approximately 2.13.

Figure 1 presents the overall system and method framework. A cesium optically pumped magnetometer (Cs OPM) acquires the scalar total-field signal, which contains the geomagnetic background, target anomalies, and platform interference. A three-axis fluxgate magnetometer provides the vector reference and is synchronized with the attitude and navigation data used to construct the T–L basis functions. The compensation coefficients are estimated from the calibration data using LS and deployed on a Zynq field-programmable gate array (FPGA)/ARM processing unit for real-time interference subtraction, online display, and storage.

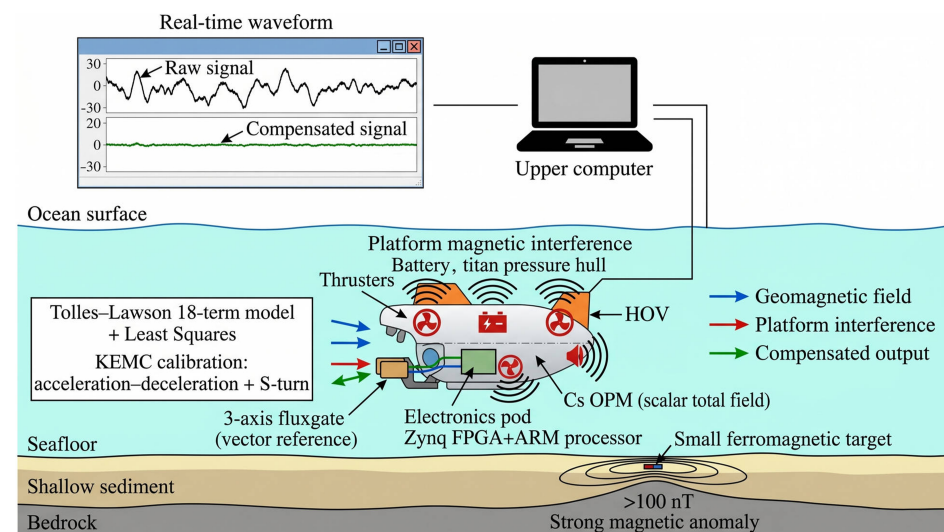


Figure 1. Method and system framework for real-time magnetic interference compensation on an HOV.

The main contributions of this study are as follows:

1. A dynamic-excitation magnetic interference compensation method is proposed for an HOV platform on which conventional large-amplitude independent attitude maneuvers are infeasible. Longitudinal cycles of acceleration and deceleration induce pitch variation, and horizontal S-shaped turns induce roll and yaw variations. The composite sequence is designed to excite all 18 T–L basis functions while remaining compatible with HOV operating constraints.
2. A helicopter-based analog experiment was conducted using an Airbus H125. The proposed maneuver produced improvement ratios of 6.6 and 12.1 on two test lines, comparable to the values of 6.3 and 12.5 obtained using conventional three-axis

airborne calibration maneuvers. These results demonstrate consistent compensation performance under opposite flight headings.

3. An integrated magnetic interference compensation trial was conducted in the South China Sea using the “Deep-Sea Warrior” HOV. After dynamic-excitation calibration at a safe altitude of approximately 50 m above the seafloor, compensation reduced the standard deviation under dynamic maneuvering from 0.8870 nT to 0.4157 nT, corresponding to an improvement ratio of approximately 2.13. This in situ result demonstrates sub-nanotesla dynamic magnetic interference compensation on an HOV platform.

The remainder of this paper is organized as follows. Section 2 introduces the theoretical basis of the T–L magnetic interference model, analyzes HOV maneuvering characteristics, and presents the dynamic-excitation compensation maneuver. Section 3 describes the system hardware, helicopter-based analog experiment, and HOV sea trial. Section 4 summarizes the work and outlines directions for future research.

2. Analysis of the Deep-Sea Magnetic Interference Compensation Model

2.1. Theoretical Basis of the Tolles–Lawson Magnetic Interference Model

The T–L model represents the scalar interference measured by a total-field magnetometer as the projection of the platform-induced magnetic field onto the direction of the ambient geomagnetic field [20–22]. Let $\vec{B}_e$ denote the ambient geomagnetic-field vector and $\vec{B}_{\text{int}}$ the platform-induced interference-field vector. Over the calibration interval considered here, the magnitude of $\vec{B}_{\text{int}}$ is assumed to be much smaller than that of $\vec{B}_e$:

$$|\vec{B}_{\text{int}}| \ll |\vec{B}_e| \quad (1)$$

By the superposition principle, the total magnetic flux-density vector at any point, $\vec{B}_{\text{total}}$, is the vector sum of the geomagnetic field $\vec{B}_e$ and the platform-induced interference field $\vec{B}_{\text{int}}$:

$$\vec{B}_{\text{total}} = \vec{B}_e + \vec{B}_{\text{int}} \quad (2)$$

A total-field magnetometer measures the magnitude of the total magnetic field vector:

$$T = |\vec{B}_{\text{total}}| = |\vec{B}_e + \vec{B}_{\text{int}}| \quad (3)$$

Under the small-interference assumption, a first-order Taylor expansion gives the interference projected onto the total-field measurement, denoted by H_T :

$$H_T = T - T_e \approx \frac{\vec{B}_e \cdot \vec{B}_{\text{int}}}{T_e} = \hat{u}_e \cdot \vec{B}_{\text{int}}, \quad |\vec{B}_{\text{int}}| \ll |\vec{B}_e| \quad (4)$$

Here, $T_e = |\vec{B}_e|$ is the ambient total-field intensity, and $\hat{u}_e = \vec{B}_e / T_e$ is the unit vector in the ambient geomagnetic-field direction. This expression is the linearization used in the T–L model.

2.2. Modeling of Magnetic Interference Sources

To relate H_T to platform attitude, each interference-field component is expressed in the body-fixed coordinate frame [23]. Let α , β , and γ denote the angles between $\hat{u}_e$ and the body-frame x , y , and z axes, respectively; $(\cos \alpha, \cos \beta, \cos \gamma)$ are the corresponding

direction cosines. The permanent-field vector $\vec{B}_p$ is fixed in the body frame [24]. For $\vec{B}_p = (p_x, p_y, p_z)$, its projection onto the measurement direction is

$$H_p = \hat{u}_e \cdot \vec{B}_p = p_x \cos \alpha + p_y \cos \beta + p_z \cos \gamma \quad (5)$$

This expression introduces three coefficients to be estimated. The induced magnetic field results from the magnetization of soft-magnetic materials by the external geomagnetic field. The induced-field vector $\vec{B}_i$ is related to $\vec{B}_e$ through a 3×3 magnetic-susceptibility tensor $\mathbf{M}$:

$$\begin{bmatrix} B_{ix} \\ B_{iy} \\ B_{iz} \end{bmatrix} = T_e \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} \\ m_{yx} & m_{yy} & m_{yz} \\ m_{zx} & m_{zy} & m_{zz} \end{bmatrix} \begin{bmatrix} \cos \alpha \\ \cos \beta \\ \cos \gamma \end{bmatrix} \quad (6)$$

The projection of the induced field onto the ambient-field direction is therefore

$$H_i = \hat{u}_e \cdot \vec{B}_i \quad (7)$$

For passive, quasi-static magnetic materials, the susceptibility tensor is commonly taken as symmetric, so this expression can be expanded and rearranged in terms of six independent coefficients. In an integrated HOV, active sources such as thruster currents and battery cables can introduce non-reciprocal or frequency-dependent effects. Their contributions are represented in the scalar model through the permanent and eddy-current terms according to their projection onto the measured field. Frequency-dependent source behavior would require additional source characterization. In the standard 18-coefficient T-L model, it is written as

$$\begin{aligned} \frac{H_i}{T_e} &= c_4 \cos^2 \alpha + c_5 \cos^2 \beta + c_6 \cos^2 \gamma \\ &+ c_7 \cos \alpha \cos \beta + c_8 \cos \beta \cos \gamma \\ &+ c_9 \cos \gamma \cos \alpha \end{aligned} \quad (8)$$

The eddy-current magnetic field originates from currents induced as conductive structures move through the geomagnetic field. Its magnitude is proportional to the rate of change of magnetic flux through conductive loops and is therefore linearly related to $\dot{\cos} \alpha$, $\dot{\cos} \beta$, and $\dot{\cos} \gamma$. Its projection onto the ambient-field direction is

$$\begin{aligned} \frac{H_e}{T_e} &= c_{10} \cos \alpha \dot{\cos} \alpha + c_{11} \cos \alpha \dot{\cos} \beta \\ &+ c_{12} \cos \alpha \dot{\cos} \gamma + c_{13} \cos \beta \dot{\cos} \alpha \\ &+ c_{14} \cos \beta \dot{\cos} \beta + c_{15} \cos \beta \dot{\cos} \gamma \\ &+ c_{16} \cos \gamma \dot{\cos} \alpha + c_{17} \cos \gamma \dot{\cos} \beta \\ &+ c_{18} \cos \gamma \dot{\cos} \gamma \end{aligned} \quad (9)$$

The permanent, induced, and eddy-current contributions are retained in their physical forms above and combined in the compact 18-coefficient T-L model used for estimation:

$$H_T(t) = \sum_{k=1}^{18} c_k f_k(t) \quad (10)$$

Here, H_p , H_i , and H_e are the scalar permanent, induced, and eddy-current interference components, respectively; c_k are the 18 coefficients to be estimated; and $f_k(t)$ are the basis functions constructed from the direction cosines and their time derivatives.

2.3. Estimation of Compensation Coefficients and the Role of Calibration Maneuvers

For N samples ($N > 18$), the following overdetermined linear system can be constructed:

$$Y = FC \quad (11)$$

Here, Y is the $N \times 1$ scalar-interference vector, $F = [f_1, \dots, f_{18}]$ is the $N \times 18$ design (basis-function) matrix, and C is the 18×1 coefficient vector. The matrix F contains the complete set of 18 standard T-L basis functions. When F has full column rank, the LS estimate is

$$\hat{C} = (F^T F)^{-1} F^T Y \quad (12)$$

In this study all 18 columns were retained; no basis-function selection or dimensionality reduction was applied. The phrase “complete model” therefore refers to model order, not to a guarantee that every coefficient is independently identifiable for every data segment.

The rank and conditioning of F depend directly on the diversity and independence of the platform’s attitude variations. For the present data set, rank, conditioning, and coefficient-confidence diagnostics are left for a repeated-track study. Conventional airborne calibration schemes therefore use pitch, roll, and yaw maneuvers along four headings—east, west, south, and north [25]. Their design rationale is as follows:

- The four headings change the projection of the geomagnetic field in the body-fixed frame, which can help separate permanent and induced contributions.
- Pitch maneuvers vary the pitch angle and the basis functions associated with $\cos \beta$ and its derivative.
- Roll maneuvers vary the roll angle and the basis functions associated with $\cos \gamma$ and its derivative.
- Yaw maneuvers vary the yaw angle and the basis functions associated with $\cos \alpha$ and its derivative.

2.4. Analysis of HOV Maneuvering Characteristics

Using the Jiaolong HOV as an example, the kinematic model describes the transformation between the inertial and body-fixed coordinate frames [26]. The origin of the body-fixed frame is located at the center of mass; the x axis is longitudinal, the y axis is lateral, and the z axis is vertical and perpendicular to the xy plane. The transformation between the two frames is

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \mathbf{T} & \mathbf{0} \\ \mathbf{0} & \mathbf{W} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} \quad (13)$$

Here, $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ are the HOV velocity components along the inertial-frame X , Y , and Z axes, respectively; $\dot{\phi}$, $\dot{\theta}$, and $\dot{\psi}$ are the corresponding Euler-angle rates. The variables u , v , and w denote velocities along the body-fixed axes, whereas p , q , and r denote angular velocities about those axes. The matrices $\mathbf{T}$ and $\mathbf{W}$ contain trigonometric functions of the Euler angles.

Based on six-degree-of-freedom (6-DOF) rigid-body motion and the principles of linear and angular momentum, the HOV dynamics can be expressed as follows [27]:

$$\sum_i F_{x_i} = m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] \quad (14)$$

$$\sum_i F_{y_i} = m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})] \quad (15)$$

$$\sum_i F_{z_i} = m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})] \quad (16)$$

$$\sum_i F_{k_i} = I_x \dot{p} + (I_z - I_y)qr + m[y_G(\dot{w} + pv - qu) - z_G(\dot{v} + ru - pw) - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy}] \quad (17)$$

$$\sum_i F_{M_i} = I_y \dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} + qw - rv) - x_G(\dot{w} + pv - qu) - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{xz} + (pq - \dot{r})I_{yz}] \quad (18)$$

$$\sum_i F_{N_i} = I_z \dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} + ru - pw) - y_G(\dot{u} + qw - rv) - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{xz}] \quad (19)$$

In these equations, u , v , and w are the body-frame translational velocities; p , q , and r are the body-frame angular velocities; ϕ , θ , and ψ are roll, pitch, and yaw angles; I_x , I_y , and I_z are the principal moments of inertia; I_{xy} , I_{xz} , and I_{yz} are products of inertia; and (x_G, y_G, z_G) are the coordinates of the center of gravity in the body frame. The resultant external loads and moments include thruster, hydrodynamic, gravity, buoyancy, and added-mass contributions. The six-degree-of-freedom equations are retained here because they identify the load pathways that motivate the reduced pitch and roll relations used in the maneuver design.

The acceleration–deceleration maneuver produces pitch excitation through moments generated by thrust and buoyancy about the center of gravity. Let $\vec{r}_T$, $\vec{r}_B$, and $\vec{r}_G$ denote the position vectors of the thrust application point, center of buoyancy, and center of gravity, respectively. For predominantly axial thrust, a vertical offset between the thrust line and the center of gravity produces the thrust-dependent pitch moment

$$M_y^{(T)} = [(\vec{r}_T - \vec{r}_G) \times \vec{T}]_y \quad (20)$$

Thus, changes in main-thruster output during acceleration and deceleration generate alternating pitch moments according to Equation (20). The resulting pitch response is moderated by buoyancy-induced restoring moments, damping, added mass, and the vehicle-specific control law.

The S-shaped maneuver produces roll excitation through alternating lateral accelerations and hydrodynamic roll moments. For a turn with forward speed U , instantaneous yaw rate r , and effective turning radius R , the lateral acceleration is

$$a_y = \frac{U^2}{R} = Ur \quad (21)$$

At the mechanism level, the roll response can be represented as

$$I_x \dot{p} = K_\phi \phi + K_p p + K_r r + K_v v + M_x^{(\text{hyd})} + M_x^{(T)} \quad (22)$$

where the hydrodynamic derivatives and control contributions are vehicle specific. Reversing the turn reverses the signs of r and the dominant roll moment, thereby producing alternating variations in roll angle and roll rate. Equations (21) and (22) define the physical mapping used to design the composite maneuver; the synchronized attitude measurements then provide the actual pitch, roll, yaw, and angular-rate responses used to construct the T–L basis functions.

Because of its complex hull geometry, an HOV exhibits strongly nonlinear, coupled dynamics. The vehicle generates control moments indirectly by adjusting a distributed thruster array; consequently, its attitude response is relatively slow. In addition, the control system is designed to suppress attitude disturbances and maintain stable navigation. Aggressive periodic attitude maneuvers are therefore generally unsuitable under deep-sea operating constraints.

This analysis indicates that, unlike an aircraft, an HOV cannot independently and accurately execute periodic pitch or roll maneuvers while maintaining an essentially constant heading and speed. Conventional airborne calibration maneuvers therefore cannot be transferred directly to an HOV.

2.5. Design of a Dynamic-Excitation Calibration Maneuver for an HOV

The proposed method uses translational acceleration–deceleration and alternating turns that an HOV can execute safely. The resulting coupled pitch, roll, yaw, and angular-rate response is measured directly and inserted into the 18-column regression. The core concept is to exploit translational maneuvers that an HOV can execute safely—acceleration, deceleration, and turning—to induce the pitch and roll variations required for magnetic interference compensation. The overall maneuver follows a large square track to cover four principal headings. Acceleration–deceleration cycles are embedded in each straight leg to excite pitch-related terms, and alternating S-shaped turns are used to excite roll-, yaw-, and angular-rate-related terms.

To excite the pitch-related T–L basis functions, a cyclic acceleration–deceleration maneuver was designed in the longitudinal plane. When the thrust line is vertically offset from the center of gravity (CG), changes in thrust generate an additional pitch moment and induce a passive pitch response.

Along each long straight leg, the HOV executes three consecutive acceleration–deceleration cycles: it accelerates from a steady cruising speed to its maximum maneuvering speed and then decelerates to the cruising speed. The nominal cruising speed and maximum maneuvering speed are 1.5 and 2.5 kn, respectively, and each acceleration and deceleration phase lasts 10–20 s. These settings were selected to remain within the low-speed control envelope, avoid abrupt load changes, and produce repeatable attitude responses visible above the sensor noise. They were based on vehicle handling limits and preliminary sea-trial practice. The regression uses the measured attitude record, which avoids prescribing a pitch amplitude.

Because the main thruster is installed at the stern, an acceleration command increases thrust and produces a pitch moment when the thrust line is vertically offset from the CG. Deceleration produces an opposing change in the pitch moment. Repeated acceleration–deceleration cycles therefore vary the pitch angle and pitch rate and provide the observations required to estimate the associated T–L coefficients. The maneuver uses basic forward-motion control and remains compatible with the operational safety requirements of an occupied vehicle.

To excite the roll-related basis functions, a continuous S-shaped maneuver was designed in the horizontal plane. Alternating the turn direction reverses the lateral acceleration, yaw rate, and associated hydrodynamic roll moment.

Along each straight leg, the HOV executes three consecutive left–right turns. From straight-ahead motion, it performs a 45° left turn immediately followed by a 90° right turn and then returns to straight-ahead motion. At each corner, it changes to the next square-track heading before entering the following leg.

During a turn, lateral thrusters or control surfaces generate the force required to change heading. The associated lateral acceleration is given by Equation (21), and the resulting hydrodynamic forces and moments depend on vehicle speed, turning radius, hull geometry, and control allocation. A continuous left–right–left sequence produces alternating roll-angle and roll-rate variations. In this study, the yaw rate during turns was set to 3–5°/s, and the turn angle was set to 45°–90°. The detailed nominal maneuver settings used in this study are summarized in Table 1.

Table 1. Nominal maneuver settings used in the HOV trial and helicopter analog experiment.

Parameter	HOV Trial	Helicopter Analog
Cruise/maximum speed	1.5/2.5 kn	30/25–35 m/s
Acceleration/deceleration	10–20 s	5/8 s
Cycles per leg	3	3
Turn angle	45–90°	45–90°
Yaw rate	3–5°/s	not reported
Turn duration	vehicle dependent	20–30 s per turn
Turning radius	platform dependent	approximately 600 m
Heading sequence	0, 90, 180, 270°	E, N, W, S
Altitude / depth	approximately 50 m above seafloor	3000 m altitude

2.6. Applicability of the Proposed Maneuver to the T–L Model

The proposed maneuver was designed according to the mathematical structure of the T–L basis set, with each executable motion assigned a specific excitation role.

The square track changes the HOV heading among the four principal directions of 0°, 90°, 180°, and 270°. These changes alter the body-frame projection of the geomagnetic field and can help separate permanent and induced contributions. The S-shaped turns also vary the yaw rate, thereby contributing to the derivative-related basis functions.

The acceleration–deceleration cycles generate pitch variation. This changes the projection of the geomagnetic field onto the body-frame y axis and hence the direction cosine $\cos \beta$. The associated pitch-rate variation also excites the derivative-related basis functions.

The alternating S-shaped turns generate roll variation. Roll changes the projection of the geomagnetic field onto the body-frame z axis and hence the direction cosine $\cos \gamma$, while roll-rate variation excites the derivative-related basis functions. Together with the four-heading track and acceleration–deceleration cycles, these motions systematically vary the complete set of 18 T–L basis functions.

Thus, although the proposed composite maneuver differs in form from conventional airborne calibration maneuvers, it provides coordinated pitch, roll, yaw, and angular-rate

excitation for the complete T–L model. The recorded attitude variations are converted into direction cosines and their time derivatives and assembled into the 18-column basis-function matrix for LS coefficient estimation. During compensation, the interference is estimated from each basis-function vector and subtracted from the scalar total field. The direction cosines are recomputed from the measured three-dimensional attitude at every sample, so heading changes and non-horizontal pitch and roll during seafloor following enter the same basis construction.

3. Experimental Procedures and Results

3.1. Overview of the Deep-Sea High-Sensitivity Magnetic Survey System

The deep-sea high-sensitivity magnetic survey system developed in this study comprises four main components: a miniaturized Cs OPM probe, a three-axis fluxgate compensation probe, a magnetic-signal processing unit, and a deep-rated nonmagnetic pressure housing. The installed fluxgate magnetometer is shown in Figure 2. The fluxgate magnetometer comprises a probe and an electronics unit. The probe contains three magnetic-field-sensitive elements aligned with the X, Y, and Z axes that convert magnetic-field signals into electrical signals. The electronics unit provides excitation, filtering, and signal extraction. Using a Co-based amorphous core and second-harmonic detection, the fluxgate magnetometer measures the geomagnetic-field vector in the HOV body-fixed frame in real time.

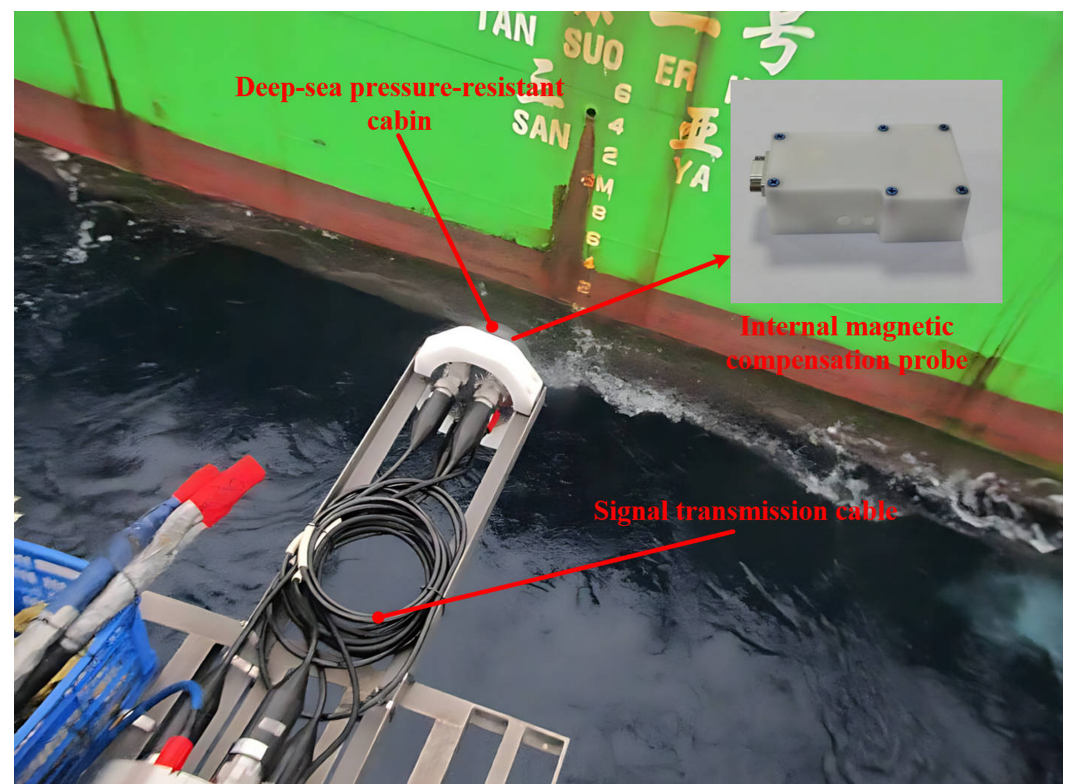


Figure 2. Installed three-axis fluxgate compensation probe.

Figure 3 shows the architecture of the electronics unit for the three-axis fluxgate compensation probe. The signal chain comprises five functional stages for high-precision vector magnetic-field measurement. First, the sensor head detects the external magnetic field $\mathbf{B} = [B_x, B_y, B_z]^T$ using three orthogonal fluxgate elements (X, Y, and Z). Here, $\mathbf{B}$ denotes the measured external magnetic-flux-density vector in the sensor frame. A drive module then generates clocked square-wave excitation signals that periodically drive the magnetic cores into saturation. Next, a synchronous demodulator (Demod) and a

low-pass filter (LPF) extract the second-harmonic component from the induced signals while suppressing high-frequency noise. Finally, the processed signals are converted into buffered voltage outputs (V_x , V_y , and V_z) that are linearly proportional to the measured magnetic-field components. The power-management bus (PWR) supplies stable power throughout the signal chain.

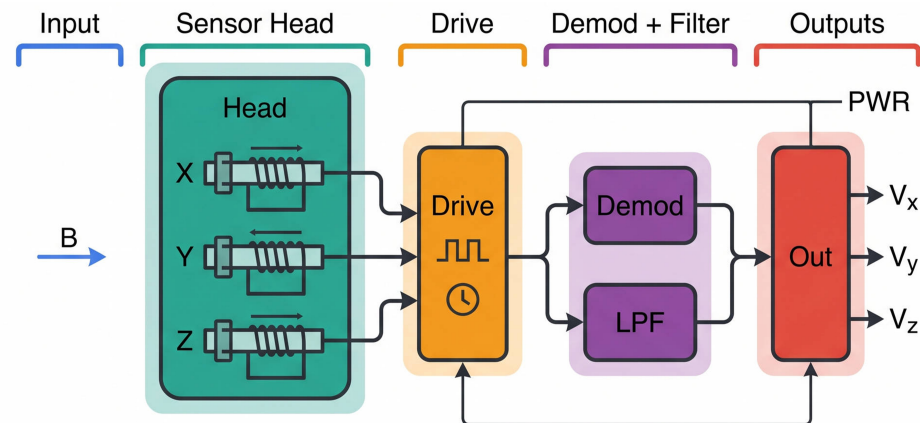


Figure 3. Electronics-unit architecture of the three-axis fluxgate compensation probe.

In the HOV trial, the Cs OPM measured the scalar total field, whereas a self-developed three-axis fluxgate magnetometer measured the body-frame magnetic-field vector. Before deployment, laboratory tests yielded noise spectral densities of 5.97, 7.67, and 5.91 pT Hz^{-1/2} along the x , y , and z axes, respectively. The fluxgate was calibrated before deployment for zero bias, scale factor, axis non-orthogonality, and temperature drift using a multi-position reference-field procedure; the acquisition rate was selected to resolve the 0–0.3 Hz maneuver band; and the Cs OPM, fluxgate, and INS/GPS streams shared a millisecond-level hardware timestamp. The reported axis noise densities are laboratory measurements for the deployed sensor. The scalar-field, vector-field, and navigation/attitude data streams were acquired synchronously. For each sample, the vector data were converted into direction cosines and their time derivatives to construct the complete 18-term T–L basis-function vector.

3.2. Helicopter-Based Analog Experiment

Before the in situ HOV trial, a helicopter-based analog experiment was conducted to reduce the cost and safety risks associated with exploratory maneuver tests on the “Deep-Sea Warrior.” The helicopter provided a controllable platform for evaluating the performance of the proposed acceleration–deceleration and S-shaped-turn calibration maneuver before deep-sea deployment.

3.2.1. Test Platform and System Configuration

An Airbus H125 helicopter (Airbus Helicopters, Marignane, France) was selected as the test platform because of its maneuverability and relatively low magnetic contamination. This experiment evaluated maneuver sequencing and the synchronized signal-processing workflow on a controllable airborne platform. The common elements are the direction-cosine and derivative variations and the calibration-to-test-line workflow; platform-specific speeds, durations, radii, and attitude amplitudes were selected independently for each vehicle. This model was formerly designated the Eurocopter AS350 B3e (Airbus Helicopters, Marignane, France). The primary sensor was a high-precision Cs OPM with a sensitivity better than 0.01 nT. It was installed at the tip of a forward-extending nose boom to increase its separation from the main airframe interference sources. A three-axis fluxgate

magnetometer rigidly attached to the primary sensor provided the vector reference in the body-fixed frame. The inertial navigation system/global positioning system (INS/GPS) provided centimeter-level positioning and attitude measurements with a precision of approximately 0.01° . A multichannel synchronous acquisition card assigned a common millisecond-level timestamp to the magnetic-field and attitude data.

3.2.2. Test Flight Plan

The flight plan followed the calibration-maneuver logic designed for the HOV, with the motion parameters adjusted to ranges suitable for helicopter flight. The test area had a relatively uniform geomagnetic background, and the flight altitude was 3000 m. The calibration track was a closed square with four approximately 10 km legs oriented east, north, west, and south. Two groups of comparative flights were conducted: one used conventional airborne calibration maneuvers with independent three-axis oscillations, and the other used the proposed HOV-inspired maneuver. On each leg, the helicopter stabilized at the predefined heading and an initial speed of 30 m/s. During the first half of the leg, it executed three acceleration–deceleration cycles between 25 and 35 m/s; each acceleration lasted approximately 5 s, and each deceleration lasted approximately 8 s, producing pitch variations of approximately $\pm 5^\circ$. During the second half, it executed three S-shaped turns, each comprising a 45° left turn followed by a 90° right turn and producing roll variations of approximately $\pm 20^\circ$. Each turn lasted approximately 20–30 s and had a radius of approximately 600 m. The maneuver was repeated along all four headings. Two straight test lines were also flown to evaluate the magnetic-field data before and after compensation. The trajectory is shown in Figure 4.

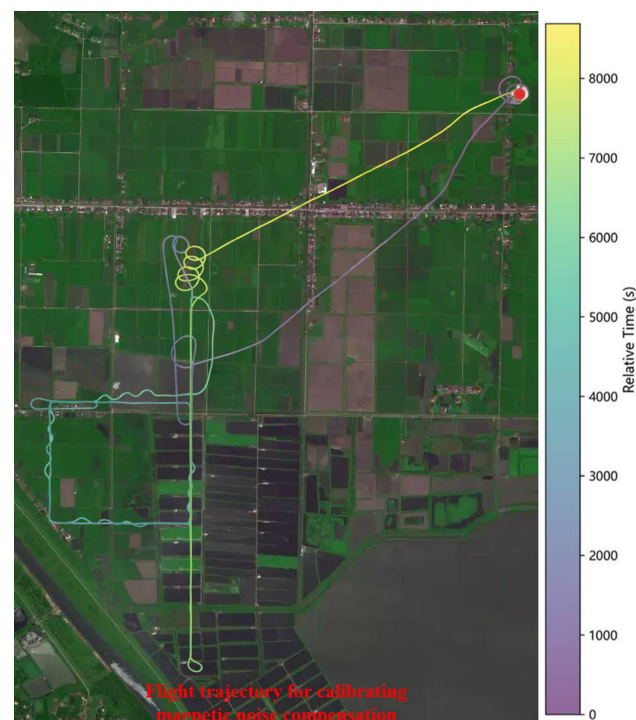


Figure 4. Flight trajectory for the helicopter-based analog experiment.

3.2.3. Evaluation Metrics and Results

The data-processing workflow comprised (i) temporal alignment of the multisensor data and outlier rejection; (ii) calculation of the 18 T–L basis-function time series from the fluxgate and INS/GPS data; (iii) extraction of the four-heading calibration-maneuver segments, construction of the overdetermined system, and LS estimation of the compen-

sation coefficients; and (iv) application of the estimated coefficients to the independent test-line data.

Performance was quantified using two metrics commonly applied in aeromagnetic compensation: the standard deviation (STD) before and after compensation and the improvement ratio (IR), defined as the ratio of the pre-compensation STD to the post-compensation STD.

Two long test lines, L1 (north to south) and L2 (south to north), were selected for detailed analysis. Their compensation results are summarized in Table 2.

Table 2. Standard deviations and improvement ratios for the conventional airborne and proposed calibration maneuvers on independent helicopter test lines.

Survey Line	Flight Direction	Scheme	STD (pT)		Improvement Ratio (IR)
			Before Compensation	After Compensation	
L1	North → South	Traditional calibration maneuver	1000.0	157.8	6.3
L1	North → South	Proposed maneuver	1000.0	151.9	6.6
L2	South → North	Traditional calibration maneuver	1020.0	81.5	12.5
L2	South → North	Proposed maneuver	1020.0	84.4	12.1

As shown in Table 1, the proposed maneuver reduced the post-compensation STD to 151.9 pT on L1, yielding an IR of 6.6, slightly higher than the value of 6.3 obtained using conventional airborne maneuvers. On L2, the post-compensation STD was 84.4 pT, and the IR reached 12.1, comparable to the value of 12.5 obtained using the conventional maneuver. For L1 (Figure 5), the raw time-domain fluctuations reached approximately ± 2 nT. Compensation suppressed these fluctuations to within approximately ± 0.2 nT, and the compensated curve closely followed that obtained using conventional calibration. The power spectral density (PSD) in the 0.1–1 Hz band decreased by approximately one to two orders of magnitude. For L2 (Figure 6), the raw peak-to-peak fluctuation exceeded 6 nT. Compensation reduced the STD from 1020 to 84.4 pT, while the dominant spectral peak near 0.3 Hz decreased by nearly 20 dB. The similar compensated spectra for the two opposite headings demonstrate the consistency and robustness of the proposed calibration maneuver under strong interference.

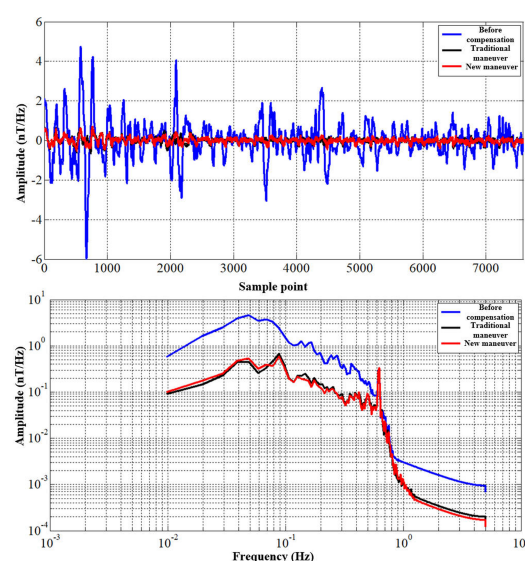


Figure 5. Comparison of magnetic-field time series and power spectral density before and after compensation for helicopter test line L1; coefficients were estimated from the proposed calibration maneuver and applied without re-estimation to L1.

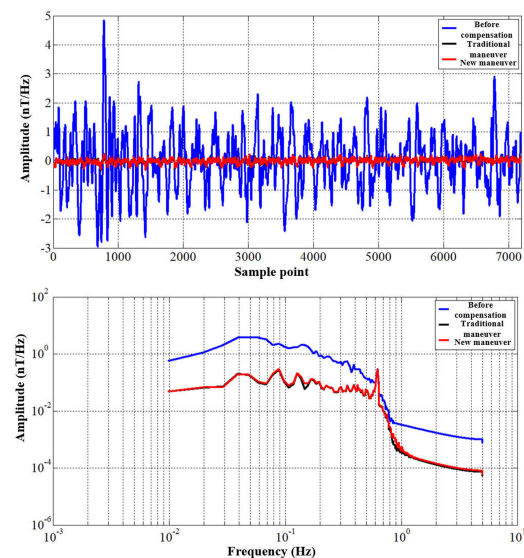


Figure 6. Comparison of magnetic-field time series and power spectral density before and after compensation for helicopter test line L2; coefficients were estimated from the proposed calibration maneuver and applied without re-estimation to L2.

3.3. Deep-Sea Experimental Validation of Magnetic Interference Compensation

To validate the proposed dynamic-excitation method in an actual deep-sea environment, an in situ trial was conducted in the South China Sea using the Shenhai Yongshi (“Deep-Sea Warrior”) HOV, shown in Figure 7. After completing its seafloor task, the HOV ascended to a safe altitude of approximately 50 m above the seafloor, maintained an approximately constant altitude, and executed the composite acceleration–deceleration and S-shaped-turn calibration maneuver. The resulting attitude excitation was used to estimate the 18 T–L compensation coefficients. The magnetometer system during seafloor operations is shown in Figure 8.

Figure 9 shows the HOV attitude during the magnetic interference compensation trial. From approximately 11:04 to 11:14, the vehicle executed pronounced pitch and roll maneuvers while maintaining an approximately constant altitude. Both attitude angles exhibit clear quasi-periodic fluctuations. This multi-axis dynamic excitation varies the direction cosines and their derivatives, thereby providing observations for estimating the permanent, induced, and eddy-current interference terms in the complete T–L model.

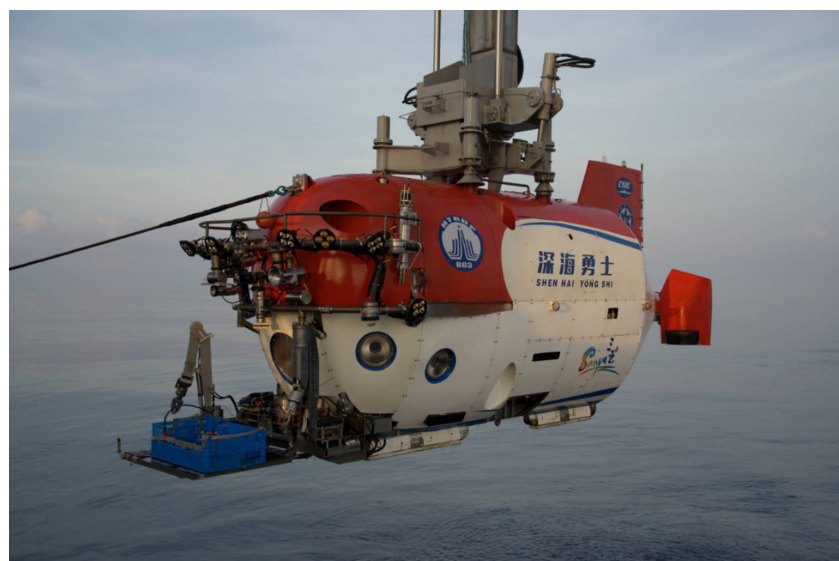


Figure 7. The “Deep-Sea Warrior” HOV at the deployment site.

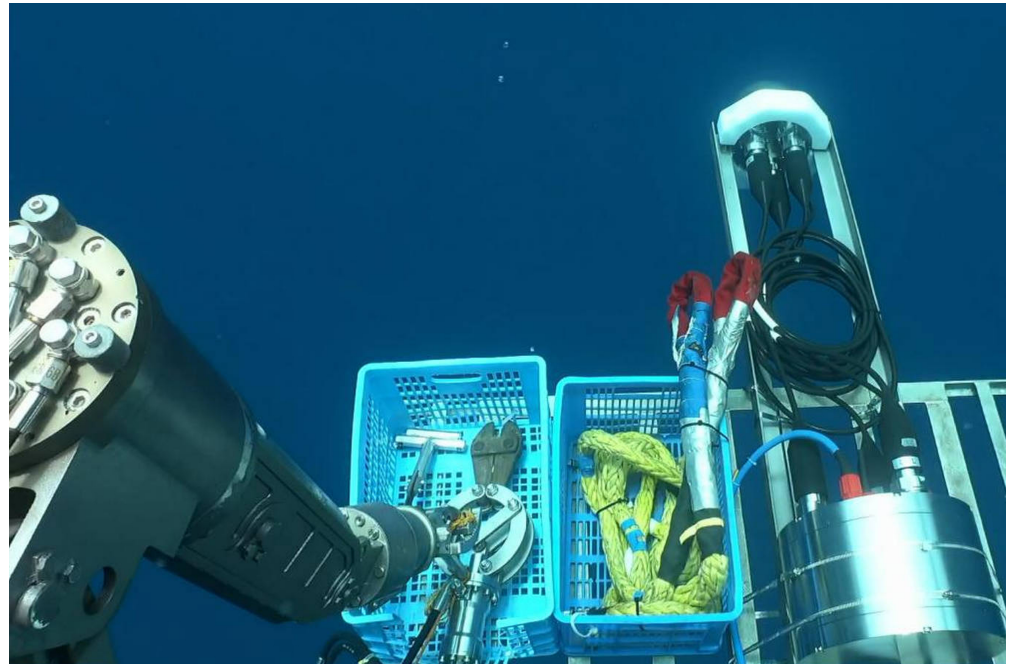


Figure 8. Magnetometer system during seafloor operations.

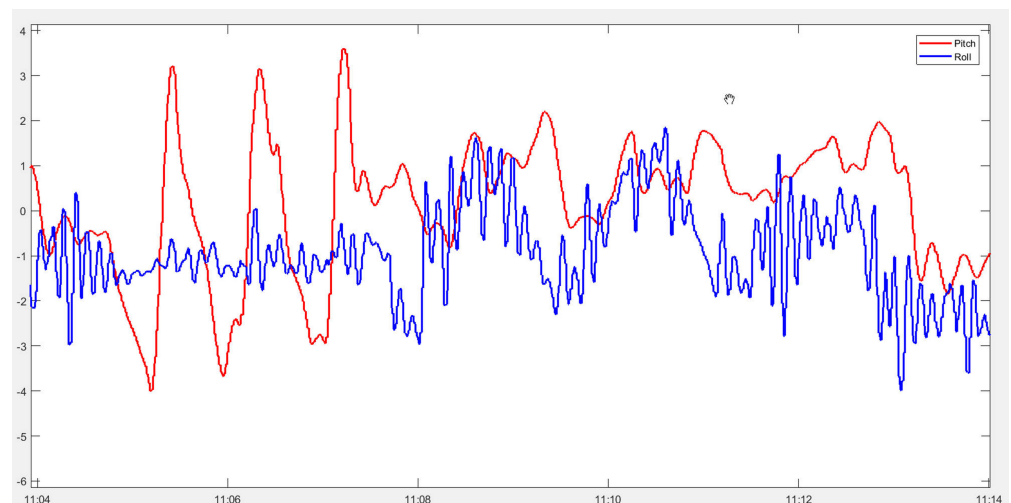


Figure 9. Pitch and roll (degrees) versus time (hours:minutes) for a representative segment (approximately 11:04–11:14) of the HOV dynamic-excitation maneuver at an altitude of approximately 50 m above the seafloor.

Corresponding to the attitude maneuvers, Figure 10 shows the synchronously recorded raw scalar total-field data. The record exhibits pronounced oscillations correlated with the attitude variations, with peak-to-trough fluctuations on the order of tens of nanoteslas. This attitude–magnetic-field coupling directly reveals the platform-induced magnetic interference and its effect on the ambient-field measurement. The record contains the geo-magnetic background, platform interference, possible spatial anomalies, and instrument noise and serves as the input for estimating the compensation coefficients. The helicopter and HOV experiments therefore provide complementary tests of the same excitation logic and processing workflow under different platform dynamics.

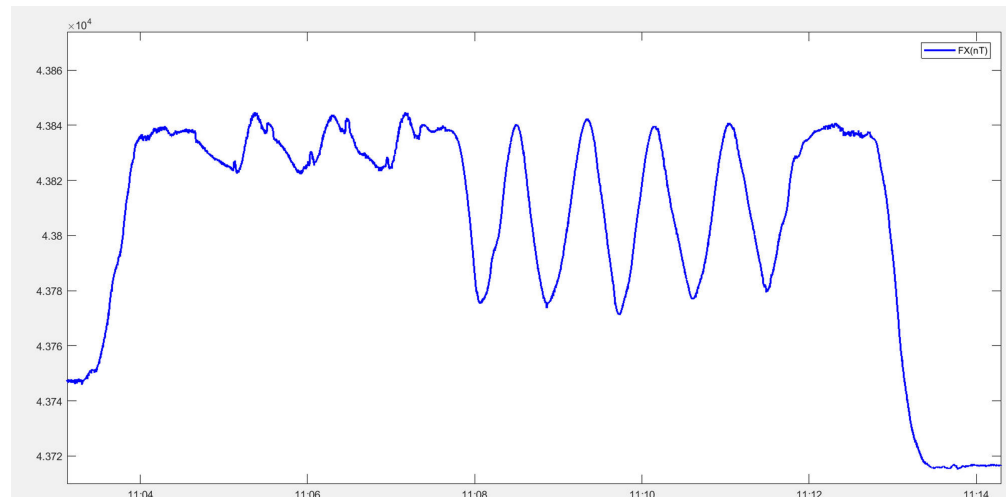


Figure 10. Raw scalar total-field record (nT) versus time (hours:minutes) acquired synchronously with the HOV calibration maneuver shown in Figure 9.

Compensation-Performance Analysis

Using the vector magnetic-field, attitude, and scalar total-field data acquired during the calibration maneuver, the complete 18-coefficient T-L model was estimated using LS. The resulting compensation coefficients were applied to the same recorded calibration interval for an in-interval assessment to estimate and remove the platform-induced interference. The STD decreased from 0.8870 nT before compensation to 0.4157 nT after compensation, corresponding to an IR of approximately 2.13. The HOV assessment uses a single calibration track and therefore reports in-interval performance; independent predictive validation remains for future repeated-track experiments.

Figure 11 compares the magnetic signals before and after compensation. The upper panel shows the high-pass-filtered dynamic components, whereas the lower panel shows the total-field records, including the slowly varying background trend. After compensation, the large oscillations at high frequencies induced by vehicle maneuvering are strongly suppressed, and the corrected record retains the slowly varying geomagnetic background. The residual STD of 0.4157 nT represents the dynamic noise level under the tested maneuvering conditions and demonstrates effective suppression of the principal HOV-induced interference components. The display filters serve only visualization; the quoted STD is calculated from the unfiltered pre- and post-compensation records and includes residual platform interference, instrument noise, and local geological variation. The HOV improvement ratio reflects the attitude excursion, the interval-specific initial interference, residual active-source fields, and contributions from instrument and geological variation. The pre-compensation value of 0.8870 nT is specific to the sensor placement, operating state, maneuver amplitude, local background, and analyzed interval; comparison across HOVs requires repeated measurements under matched conditions.

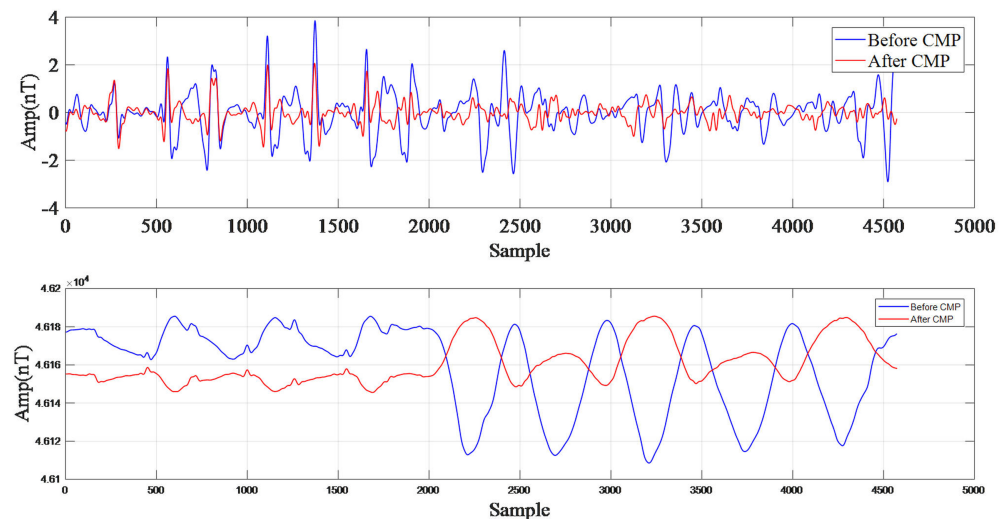


Figure 11. Raw and compensated HOV scalar total-field records over the analyzed calibration interval. The upper panel shows the 0.04 Hz high-pass-filtered signals used to visualize short-period variations. The lower panel shows the signals after low-pass filtering at 0.3 Hz using a 111th-order Hamming-window finite-impulse-response (FIR) filter; this panel retains the slowly varying component for joint target discrimination.

4. Conclusions

This paper proposes a dynamic-excitation magnetic interference compensation method for HOVs in deep-sea environments, addressing the engineering challenge that conventional airborne calibration maneuvers based on independent three-axis attitude excitation cannot be applied directly to a large occupied submersible. Analysis of the T–L model shows that stable coefficient estimation depends on sufficiently rich attitude-dependent basis functions, whereas strongly coupled HOV hydrodynamics constrain independent pitch and roll maneuvers. The proposed composite calibration maneuver therefore uses longitudinal acceleration–deceleration cycles to induce pitch variation, horizontal S-shaped turns to induce roll and yaw variations, and a four-heading square track to vary the geomagnetic-field projection in the body frame. The measured response supplies the 18-term T–L regression while remaining compatible with HOV operational constraints.

The helicopter-based analog experiment showed that coefficients estimated using the proposed maneuver yielded IR values of 6.6 and 12.1 on two test lines, comparable to the values of 6.3 and 12.5 obtained using conventional airborne calibration maneuvers. The compensated spectra were substantially flatter over the analyzed frequency range. The in situ trial in the South China Sea using the “Deep-Sea Warrior” HOV further showed that compensation reduced the magnetic-field STD under dynamic maneuvering from 0.8870 nT to 0.4157 nT. These results demonstrate sub-nanotesla residual dynamic-field variation after compensation in the tested HOV interval and support the practical feasibility of the method. The HOV value is not an absolute measurement-accuracy specification, and the present single-track experiment cannot separate platform interference from instrument noise and geological variation or establish independent predictive performance. Future work will repeat the maneuver over low-anomaly areas, use independent survey segments, report rank/conditioning and uncertainty diagnostics, and evaluate compensation against known magnetic targets. Additional validation will include RMSE, peak-to-peak residual, band-limited attenuation, coefficient confidence intervals, and spectral-energy reduction when the corresponding raw and independent records are available.

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