Analyzing the Effect of Flux Intensification Due to Propeller Shaft and Rudder Upon the 3D Induced Magnetic Signature of Marine Vessels

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ABSTRACT This study investigates and analyzes the effect of flux intensification due to the propeller shaft and rudder on the 3D mapped induced magnetic signature of marine vessels. The study was designed to extrapolate the 3D induced magnetic signature and to analyze the difference between signature components in two different cases: a vessel without propeller shaft or rudder and a vessel with the propeller shaft and rudder attached. Numerical modeling was conducted using full-scale vessel dimensions and finite-element analysis (FEA) modeling software. Measurements on a 1:100 properly scaled and designed physical scale model (PSM) were conducted in a magnetically clean area. To enrich the analysis, both signature components from the numerical evaluation and experimental measurements were 3D mapped. Both the scaling technique and scaling effect on magnetic signature were investigated. The signature measurements of the scaled vessel model were performed to verify the numerical model. Both the numerical and experimental results are both discussed and shown to be consistent. The extrapolated signature components revealed that the studied effect became prominent as the saliency of the 3D mapped signature components increased. Consequently, this effect increases the magnetic susceptibility of the vessel to detection or destruction. Finally, this study suggests solutions to reduce this effect.

INDEX TERMS Geomagnetic field, marine vessels, electromagnetic modeling, scale modeling, magnetic signatures, computational electromagnetics.

I. INTRODUCTION
Earth can be considered as a giant magnet. The geomagnetic field predominantly induces magnetization in marine vessels. As they are mainly built from ferromagnetic materials, marine vessels disturb the uniform geomagnetic field. This disturbance is characterized by uniqueness of a vessel class; and is known as a magnetic signature. The term signature is used to describe the spatial distribution of a vessel’s magnetic field.

The steel used in the construction of marine vessels has high relative permeability; consequently, the hull of a marine vessel represents a path with low reluctance for the geomagnetic field, and as a result, the latter is distorted. The geomagnetic field disturbances produced are detected when the vessel sails over a magnetic sensor aimed at vessel detection or the detonation of a sea influence mine.

Sea influence mines are triggered by the geomagnetic field disturbance created by the passage of a marine vessel, which represents a dangerous threat to marine vessel operation. Mines can be used to restrict navigation in littoral areas, against commercial shipping, or as a new tactic for international terrorism. Mines can also be used as tools for economic warfare by disrupting sea traffic and diverting supply lines. It is well known that almost 90% of global trade is carried out by sea shipping, and it is expected that the global maritime trade volume will double by 2030. Therefore, it is imperative that the magnetic signature of the vessel be reduced [1], [2], [3], [4], [5].
To render the vessel magnetically silent, compensation of the geomagnetic anomalies is performed using a set of current coils onboard the vessel, known as a degaussing system. Accurate signature evaluation is key to properly designing magnetic silencing systems. Moreover, it is important to understand how the vessel materials and parts contribute to the induced magnetic signature. Additionally, marine vessel designers should be aware of the possible magnetic risks associated with different vessel parts. Propeller shafts and rudders are the major vessel parts that are mainly made of steel. While modeling and measurement of marine vessel induced magnetic signatures have been demonstrated and studied extensively by Isa et al. [1], [6], JC Aird [7], I. Gloza et al. [8], [9], Holmes [10], [11], [12], P. Jankowski et al. [13], X. Brunotte et al. [14], and G. Rosu et al. [15], they mainly focused on the overall vessel geometry, hull thickness, materials, and even inside ship equipment, while the effect of propeller shafts and rudders has not been studied. Unshielded by the hull, the propeller shaft and rudder intensify the geomagnetic field in their corresponding regions, resulting in a deviation of the induced magnetization from the pre-existing conditions prior to their existence; the latter effect is under-evaluated and poorly described in the literature. While most studies employ either 1D as single-line curves or 2D as contour plots to depict magnetic signatures, a 3D visualization technique was employed throughout this study in both numerical and experimental datasets. 3D visualization allows for enriched high-fidelity signature details and an in-depth study. The purpose of this study is to extrapolate the 3D induced magnetic signature and to analyze the difference between the signature components in two different cases: a vessel without propeller shaft and rudder and the same vessel with propeller shaft and rudder. Numerical modeling was conducted using full-scale ship dimensions and finite-element analysis (FEA), while measurements were carried out on a 1:100 physical scaled-vessel model. The measured and evaluated signatures will be used to investigate the effect of these particular underwater geometry vessel details on the induced magnetic signature of the full-scale vessel, and to demonstrate the extent to which the effect has an impact on the vessel’s magnetic detectability for magnetic threats. For decades, scaled vessel models have been extensively employed for the reproduction and extrapolation of marine vessel magnetic signatures [12]. Signature measurements of a properly scaled vessel model were used to verify the numerical model. A numerical investigation of different scales was conducted, and a physical scale modeling technique was discussed. The study shows that early in design phase, signature measurement of scaled vessel model associated with numerical modeling may considerably reduce the time and cost of the initial estimation of a vessel’s vulnerability to being either destroyed or detected. Finally, this study suggests solutions for the studied effect.

II. MAGNETIC SIGNATURE NUMERICAL MODELING

Numerical modeling of marine vessel magnetic signatures must process parameters such as vessel geometry and ferromagnetic material properties; and numerically evaluate the disturbances in the geomagnetic field in the vicinity of the marine vessel based on Maxwell’s equations. Finite element method (FEM) software packages are continually being enhanced to eliminate the modeling difficulties associated with magnetic signature evaluation. FEM can solve Maxwell’s differential equations using numerical techniques along with discretizing geometries [12], [14], [16].

A. THEORETICAL BASIS

Marine vessel magnetization has a slow-varying nature; hence, it can be considered static and time-independent. The region surrounding the marine vessel was current-free. Therefore, the magnetostatic form of Maxwell’s equations is used as follows:

\[ \nabla \times \vec{H} = 0 \]  
\[ \nabla \cdot \vec{B} = 0 \]

where \( \vec{B} \) is the magnetic flux density, and \( \vec{H} \) is the magnetic field intensity. Because \( \vec{H} \) is irrotational, it can be expressed as the negative gradient of the scalar magnetic potential \( V_m \), and is given by

\[ \vec{H} = -\nabla V_m \]

Magnetic field intensity can be alternatively expressed by the magnetic flux density as follows:

\[ \vec{B} = \mu \vec{H} = \mu_r \mu_0 \vec{H} \]

where \( \mu_0 \) is the absolute permeability constant, and \( \mu_r \) is the relative permeability constant. Substituting in (3), \( V_m \) can be derived as

\[ -\nabla \cdot (\mu_r \mu_0 \nabla V_m) = 0 \]

This is simply the Laplace equation. Unique solutions can be obtained by solving the Laplace equation. Analytical solutions can be obtained for a spherical or ellipsoidal model of a vessel. Practical vessel geometry is complex, and a numerical solution is employed to solve the problem of magnetic disturbances. The FEM approximates solutions to Maxwell’s equations by discretizing the space inside and outside the vessel, including the hull. The scalar magnetic potential can be evaluated at each node in space and interpolated solutions are generated at locations between the nodes [12], [15]. Some of the numerical vessel modeling challenges and how to alleviate them will be demonstrated in the following parts [12], [14].

B. THE REDUCED SCALAR POTENTIAL APPROACH

The reduced scalar potential approach was used because of its ability to separate the external field from the vessel magnetic field [12], [14]. To use the reduced scalar potential, a source term is added, which is the background (geomagnetic) field. Equations (3) and (5) can be rewritten as

\[ \vec{H} = \nabla V_m + \vec{H}_b \]
\[-\nabla \cdot (\mu_r \mu_0 \nabla V_m + \vec{B}_b) = 0 \] (7)

where \(B_b\) and \(H_b\) are the background geomagnetic flux density and the field intensity, respectively. The latter equation is known as the magnetic flux conservation formula, and it introduces the hull material relative permeability constant as a parameter.

COMSOL Multiphysics software uses the magnetostatic form of Maxwell’s equations as a basis for the numerical solution, along with the AC/DC module and built-in magnetic fields with no current interface (mfnc). The software employs the reduced magnetic potential approach, or alternatively, a reduced field formulation, as in (6) and (7), to solve for the potential \(V_m\) corresponding to the anomaly in the reduced field, from which the induced magnetic signature of the vessel is evaluated. In the numerical solution, the previous set of differential equations was transformed into a set of complex linear equations. To avoid complexity and significant errors during numerical solutions, necessary approximations are performed [17], [18].

C. THE THIN SHELL PROBLEM

A major feature of the hulls of marine vessels is that they are built from steel sheets in the form of iron plates. The iron plate (also known as the thin shell) problem represents a challenge in the numerical evaluation of magnetic signature because of the high aspect ratio characteristic of marine vessels; therefore, it must be alleviated before solution.

To solve the latter problem, the hull of a marine vessel is handled as a boundary surface, that is, the thin shell boundary condition is used as magnetic shielding condition, which also introduces the hull thickness of the vessel as a parameter, and is given by

\[ n \cdot (B_1 - B_2) = \nabla_T d_s B_T \] (8)

\[ H_T = -\nabla_T V_m + \vec{H}_b^T \] (9)

where \(B_1\) and \(B_2\) are the internal and external magnetic flux densities, respectively, \(V_T\) is the tangential gradient operator, \(n\) is the normal vector, \(d_s\) is the hull thickness of the vessel, and \(H_bT\) is the background tangential field intensity vector [12], [14], [17], [18], [19], [20].

D. THE OPEN BOUNDARY PROBLEM

The space outside the hull of the vessel is infinite, that is, the problem is an open boundary problem [12], [14]. To obtain a unique solution and further reduce complexity, a magnetic insulation boundary condition was also added. The latter condition assumes that the exterior boundaries of the computation space are insulating for the reduced magnetic flux density, and is given by

\[-n \cdot \vec{B} = 0 \] (10)

To alleviate the issues regarding the complexity of numerical solution that was aimed at evaluating the induced magnetic signature, the utilized modeling software has integrated the previous domain equations and boundary conditions as a comprehensive approach [12], [14], [16], [17], [18], [19], [20].

III. THE STUDY DESIGN

To facilitate the study, essential items are addressed, such as the proposed scenarios, selected vessel shape and dimensions, selected scale, scaling effect, and 3D extrapolated signature mapping. These items are elaborated as follows:

A. PROPOSED SCENARIOS

Two scenarios will be employed for the numerical evaluation of magnetic signatures as well as for the measurement of magnetic signatures. The scenarios are:

1) SCENARIO 1

In this scenario, the vessel has no propeller shaft or rudder.

2) SCENARIO 2

In this scenario, the vessel has one propeller shaft and one rudder, both of which are attached to the hull of the vessel.

B. EXTRAPOLATED SIGNATURES

Tri-axial field signatures (longitudinal, athwartship, vertical, and total field signature components) from both the simulation and experimental results were extrapolated through numerical modeling and measurements for the proposed scenarios. 3D high-fidelity mapping of the magnetic signature was used in this study, thus allowing for a comprehensive visualization and understanding of each signature component.

C. SELECTED VESSEL

This study utilized a general-purpose vessel with a flat-bottom hull. It was selected to study the effect of underwater geometry features such as propeller shaft and rudder on magnetic signature due to flux intensification. The dimensions of the full-scale vessel are listed in Table 1.

D. SELECTED SCALE

The scale selected for the signature measurements in this study was 1:100. The model scales used for modern vessels

| DIMENSION | VALUE (METERS) |
|-----------|---------------|
| Ship Length (upper deck) | 120 |
| Width (Beam) | 20 |
| Draft | 5 |
| Height (upper deck to bottom) | 20 |
| Bottom Length | 60 |
| Bottom Width | 10 |
| Bridge Section Dimensions | 20 m x 20 m x 20 m |
| Hull Thickness | 0.05 |
ranged from approximately 1:30 to 1:150. The scaled vessel model should be large enough to accurately represent the magnetic characteristics of the vessel, but small enough to be easily handled by the model platform. Typically, magnetic models are between one and four meters long [12], [21].

E. SCALING EFFECT

A mathematical solution for signature components based on Maxwell’s equation applied to an ellipsoidal shell model found that the signature remained unchanged when the permeability-thickness product remained constant during the calculations. This statement is accurate for a realistic vessel’s hull whose thickness is small compared to its width. This is important when developing a marine vessel physical scale model (PSM) [12].

The scaling technique of the full-scale vessel model is based on the permeability-thickness modeling technique [12]. The basis for applying this method is that the product of the relative permeability of the scaled model and the hull thickness of the same model is preserved as follows:

$$ t_m \times \mu_m = \frac{t_f \times \mu_f}{S} \tag{11} $$

where $\mu_m$ is the relative permeability of the scaled model, $t_m$ is the hull thickness of the scaled model, $\mu_f$ is the relative permeability of the full-scale vessel, $t_f$ is the hull thickness of the full-scale vessel, and $S$ is a scaling factor. This method preserves magnetic properties of the model while utilizing a wide range of materials in the fabrication of scaled vessels [12]. A properly designed and constructed physical-scaled vessel model can be used to verify the numerical modeling. The purpose of model verification is to verify that Maxwell’s equations have been correctly applied to the numerical solution, and to verify the accuracy of signature computations carried out by the modeling software [12], [22].

The above statement was numerically investigated before conducting the study to accurately model the magnetic signatures extrapolated from a full-scale vessel model. Three different scales for the same numerical model of the first scenario were tested using COMSOL Multiphysics modeling software. The numerically evaluated signature components for the tested scales remained almost unchanged in terms of both peak values and shapes. The scales tested were 1:1 (full-scale vessel), 1:50, and 1:100, respectively. An important point to consider was that the hull-scaled permeability-thickness product was kept constant, and that (11) was verified. Table 2 summarizes the geometric parameters of the numerically tested scaled models, and Table 3 lists the corresponding numerically evaluated signature components.

Throughout the study and according to the above investigation, numerical modeling of the magnetic signature was performed on the full-scale vessel model whereas measurements were carried out on a properly scaled physical model.

In the numerical solution, the selected observation depth is 15 m below the keel, which is the lowest point in the vessel’s hull, and 15 cm below the PSM’s keel for the measurements.

### Table 2. Geometry parameters of the numerically tested scaled models.

| Scale | Vessel length | Vessel width | Hull thickness | Hull Permeability | Observation Depth | Domain (W x D x H) |
|-------|---------------|--------------|----------------|-------------------|-------------------|-------------------|
| 1:1   | 120 m         | 20 m         | 5 cm           | 1048              | 15 m              | 190 m x 142 m x 90 m |
| 1:50  | 240 cm        | 40 cm        | 4 mm           | 262               | 30 cm             | 380 m x 284 m x 180 m |
| 1:100 | 120 cm        | 20 cm        | 2 mm           | 262               | 15 cm             | 190 m x 142 m x 90 m |

### Table 3. Numerically evaluated signatures for different scales.

| Symbol | Peak Field | Scale 1:1 | Scale 1:50 | Scale 1:100 |
|--------|------------|-----------|------------|-------------|
| $B_z$  | Upper Peak | 27.1      | 37.1       | 37.1        |
|        | Lower Peak | 26.7      | 26.7       | 26.7        |
| $B_y$  | Upper Peak | 5.84      | 5.78       | 5.84        |
|        | Lower Peak | -5.79     | -5.83      | -5.79       |
| $B_x$  | Upper Peak | -30.8     | -30.8      | -30.8       |
|        | Lower Peak | -48       | -47.9      | -48         |

For an average vessel draft of 5 m, the observation depth was selected as close as possible to the vessel’s beam which is the standard measuring depth [19].

### IV. NUMERICAL SETUP

For both scenarios, numerical modeling was conducted using the COMSOL Multiphysics modeling platform, the details of which are as follows.

3D modeling was selected as the first step. Then, in the selected physics tree, the AC/DC module (magnetic fields, no current section) was selected. The selected study was general and stationary.

In the model builder, global definitions are used to define parameters such as geomagnetic field, total length, total width, total height, and domain dimensions.

In the geometry section, the vessel was built using a built-in CAD module. In addition, the domain boundaries are selected in this step. A union of the built items is formed, and then the exterior boundaries of the air (and water) domain are hidden to show only the vessel as shown in Figs. 1 and 2.

In the materials section, two materials are defined for relative permeability: the first is for the vessel’s hull and the second is for the domain.

In magnetic fields, no current section, a reduced field solution is selected, and the background magnetic field vector $H_b$ is specified in the (x, y, and z) components.

In the latter section, other features are also used; the magnetic flux conservation feature, which uses the constitutive $B-H$ relation and $\mu_r$ from the material section as defined earlier. The external magnetic flux density feature imposes...
boundary conditions that match the specified background field, and the magnetic shielding feature models a thin layer of high-permeability material, such as the metal constituting the vessel’s hull. Hull thickness was defined in the latter feature. The imposed equations are (2), (4), (6), (8)–(10).

The mesh setting was selected as a user-defined mesh, the element size was calibrated for general physics, and the size is selected as predefined extra fine. The meshing of the numerical model is shown in Fig. 3.

Upon setting these selections, the software determines the element size parameters. The meshing parameters for the two numerically modeled scenarios are listed in Table 4. The meshing statistics for the two modeled scenarios are listed in Table 5.

The next step is to compute the model to obtain the results. The results in the form of the magnetic scalar potential, magnetic flux density, or magnetic field intensity for each point within the domain can be obtained. Then, post-processing is conducted to view the required results in 1D (curve), 2D (contour or surface plot), or 3D plot groups, as needed. Fig. 4 shows the longitudinal component signature 3D plot group with contours, a color table, and surface flux lines. Fig. 5 shows the selected cut plane to view the surface plot of the magnetic signature components at the required depth.
The hull relative permeability was 1048 and was calculated using (11).

The background (geomagnetic) field vector was 28.8 A/m (as measured in the measurement location) in both the vertical and the longitudinal directions.

V. EXPERIMENTAL SETUP
For both scenarios, the scaled model was positioned and secured on the platform midpoint, and then the sensor scanned a (1 cm × 1 cm) grid measurable area in the horizontal plane beneath the model at a specific distance that represents the depth under the scaled vessel’s keel. A scan sequence was started at a specific position of the model relative to the sensor, and then other scan sequences were successively generated. This process generates a data matrix representing the magnetic field in a horizontal plane at a specific depth [12], [21].

A. THE PHYSICAL SCALE MODEL
Fig. 6 shows the fabricated 1:100 scaled vessel models of the two scenarios with and without the shaft and rudder. Dimensions of the PSM along with both shaft and rudder, were all scaled to the same ratio. The hull relative permeability of the PSM is 262 while the hull thickness is 2 mm.

B. THE PLATFORM
The platform, shown in Fig. 7, was made fully wooden and without nails; only wood glue was used during fabrication to avoid any magnetic disturbances. The dimensions (L×W×H) are (200 cm × 200 cm × 145 cm), and two wooden solid parallel beams were secured across the platform to carry the scaled ship model during measurements. The beams height can be changed vertically to enable different measurement depths, when required. The horizontal plane measurement grid height was 110 cm above ground.

The grid measurable area has (X, Y) coordinates from (0, 0) to (188, 140) in centimeters, yielding a matrix of 26,649 scan points, thus enabling high-fidelity signature mapping. The scaled model and the measuring platform were both oriented northward, and 1728 equidistant scan points were selected for measurements, allowing for high resolution for the mapped signature components. The platform and PSM were kept horizontal during the measurements.

C. MEASUREMENT LOCATION
The measurement area was selected based on the principle of a magnetically clean area, where the ambient field was unchanged during the testing periods and no metallic objects were in the vicinity of the measuring equipment.

In addition, no buried cables or pipes passed underneath the ground. The ambient field at the test site was measured approximately 36 µT in both the vertical and the longitudinal directions, respectively [12], [21].

D. THE SENSOR AND DATA ACQUISITION UNIT
Magnetometers can detect and measure the tri-axial geomagnetic field strength. The tri-axial field strength is then converted to three separate voltages, which are further processed and finally converted to a digital output. The sensor chipset was HMC5883L, range (± 1.3 Gauss) or ± 130 µT or ±130,000 nT with a precision of 100 nT. The sensor was calibrated prior to measurements. The sensor was then connected to the data acquisition unit (DAU) which was further connected to the PC. The DAU is nonferrous, and connecting cables are twisted copper wires [12], [21].
TABLE 6. Comparison between measured and simulated results.

| SYMBOL | PEAK FIELD | SIMULATED (µT) | MEASURED (µT) |
|--------|------------|----------------|---------------|
|        |            | SCENARIO 1     | SCENARIO 2    | SCENARIO 1   | SCENARIO 2   |
|        |            |               |               |              |              |
|        |            | LONGITUDINAL COMPONENT |           |               |
|        |            | $B_x$ Upper Peak | 37.1         | 37.1          | 39.2         | 39.2         |
|        |            | $B_x$ Lower Peak | 26.7         | 26.6          | 29.8         | 28.3         |
|        |            | ATHWARTSHIP COMPONENT |           |               |
|        |            | $B_y$ Upper Peak | 5.84         | 5.83          | 4.88         | 4.9          |
|        |            | $B_y$ Lower Peak | -5.79        | -5.85         | -5.94        | -5.94        |
|        |            | VERTICAL COMPONENT |           |               |
|        |            | $B_z$ Upper Peak | -30.8        | -30.7         | -29.9        | -28.1        |
|        |            | $B_z$ Lower Peak | -48          | -48           | -47.4        | -47.4        |
|        |            | TOTAL FIELD COMPONENT |           |               |
|        |            | $B_z$ Upper Peak | 58.5         | 58.7          | 59.2         | 59.3         |
|        |            | $B_z$ Lower Peak | 43.3         | 43.2          | 44.9         | 42.6         |
|        |            | TOTAL PEAK FIELD | 15.2         | 15.5          | 14.3         | 16.7         |

VI. RESULTS AND COMPARISONS

Tri-axial field signatures (longitudinal, athwartship, vertical and total field signature components) from both the simulation and experimental results of both scenarios are presented, and then arranged as shown in Figs. 8 - 19. Table 6 lists a summary of the comparison results.

In each of these figures, the bow direction is shown, the vessel is oriented along the x-axis. The unit length were one centimeter for the scaled model and one meter for the simulated model. During the measurements, the sensor was placed 15 cm below the PSM keel. The midpoint of the scaled model was positioned at the midpoint of the platform measurement area.

A. RESULTS

For both scenarios, datasets of signature components for the scaled vessel measurements and numerical solution of the full-scale vessel are 3D plotted, rearranged, and shown as follows:

1) INDUCED LONGITUDINAL MAGNETIC SIGNATURE $B_x$

2) INDUCED ATHWARTSHIP MAGNETIC SIGNATURE $B_y$
3) INDUCED VERTICAL MAGNETIC SIGNATURE $B_z$

4) TOTAL INDUCED FIELD SIGNATURE $B_T$
B. RESULTS DISCUSSION

The results from both numerical modeling and measurements are summarized in Table 6. It is clear from the above-mapped signatures that the numerically evaluated signatures have slight differences between the two scenarios. However, differences were apparent between the measured signatures of both scenarios. The differences are as follows.

1) NUMERICAL SIGNATURES

At the selected depth, there were slight differences between the signature components of both scenarios regarding the upper and lower peak values for the signature components \( B_x, B_y, B_z \), and \( B_t \). The absolute differences between the numerical signature components of the two scenarios were 100, 60, 100, and 200 nT, respectively. All differences were minor and the difference between the athwartship components was the least.

The inducing Earth (background) field vector was originally set up in the longitudinal and vertical directions and not in the athwartship direction. Consequently, in the numerical solution and even with an athwartship component change between scenarios, it should be the least.

There are multiple reasons for the minor differences between the two scenarios in the numerical solution. Necessary approximations must be performed using FEM software in a numerical solution. The accuracy of the COMSOL Multiphysics software has been discussed by Wang et al. [19], which has already alleviated the thin sheet boundary problem by adding the magnetic shielding condition along with the magnetic insulation boundary condition and the utilization of the reduced field formulation; thus, software approximations are inevitable. Hence, differences may not be prominent when it comes to underwater protruding details such as the propeller shaft or rudder in the numerical solution at the selected depth. Despite the approximations, the software is still a powerful tool in the numerical evaluation and prediction of the induced magnetic signature of the vessel.

A major parameter that predominantly affects signature component peak values is the observation depth. During the study, the observation depth for numerical modeling was 15 m, which was selected as close as possible to the standard depth for signature measurement [19].

Other depths such as 7 and 10 m are also typical realistic depths for vessel cruising. Signature modeling for both scenarios at such depths was numerically investigated and results are 3D plotted. Figs. 20 and 21 show the 3D mapped total field components of the two studied scenarios at 10 m and 7 m depths, respectively. Now, the total peak fields for 10 m depth are 23.5 \( \mu T \) for the first scenario and 24 \( \mu T \) for the second scenario, i.e. 500 nT increase, between the two scenarios. The total peak fields for 7 m depth are 31.9 \( \mu T \) for the first scenario and 33.0 \( \mu T \) for the second scenario, i.e. 1100 nT increase, between the two scenarios. Additionally, in the second scenario and at an observation depth of 7 m, saliency appears in the lower peak of the total field signature, as shown in Fig. 21. In the numerical solution, the studied effect is more significant as the observation depth is reduced below the standard depth while maintaining a typical cruising depth range.

The magnetic mine actuation sensitivity settings may be 250, 500, 1000, 2000, or 3000 nT, and the setting is selected according to the operational requirements [10]. In addition,
2) MEASURED SIGNATURES

For the selected vessel average dimensions and depth, the peak values of the experimentally extrapolated signatures in both scenarios were in the range indicated by Daya et al. [22]. The absolute differences between the two measured scenarios for the longitudinal, athwartship, vertical, and total field signature components were 1500, 20, 1800, and 2300 nT, respectively. In terms of peak values, the differences between the measured signatures for both scenarios are prominent for longitudinal, vertical, and total field components ($B_x$, $B_y$, and $B_t$). The difference between the measured athwartship components ($B_y$) was minor and remained the least as the inducing background Earth field was mainly in the longitudinal and vertical directions during measurements. The difference is more prominent when it comes to the total field ($B_t$), particularly within the ship stern region where the shaft and rudder are installed.

The difference is characterized by an increased saliency that is exhibited by the existence of the shaft and rudder in the second scenario, as shown in Figs. 10, 13, 16, and 19. The differences are indicated by the dotted circles.

3) MEASURED VERSUS SIMULATED SIGNATURES COMPARISON

For the first scenario, in Figs. 8, 11, 14, and 17 in which the measured and simulated signature components are 3D mapped concurrently and by referring to Table 6, the differences between the measured and predicted values for the signature components ($B_x$, $B_y$, and $B_z$) are 7.9%, 16%, and 1.9%, respectively, referring to the peak field [12]. Similarly, for the second scenario, in Figs. 9, 12, 15, and 18, the differences between the measured and predicted values for the signature components ($B_x$, $B_y$, and $B_z$) were 5.3%, 15.7%, and 5.4%, respectively. Most magnetic detection tri-axial magnetometers are used in a total field configuration by computing the vector sum of its components [10]. For the first and second scenarios, differences between the measured and predicted values of the total field component ($B_t$) were 2.7% and 1%, respectively.

All values of the above differences showed values below 10% referred to the peak field [12], except for athwartship components in both scenarios.

This can be explained by that the scaled vessel model has some permanent magnetization mainly in the athwartship direction. Permanent magnetism has been extensively studied by Holmes [10], [11] and may typically contribute to 20% of the total static magnetization as indicated by Daya et al. [22]. To consolidate the above explanation, another simulation is carried out for the first scenario; in this case, a vessel magnetization component is added in the athwartship direction which is equal to 60 A/m. The latter numerical results, in comparison to the measured results of the same scenario, are both mapped and shown in Fig. 23. The difference between the athwartship signature components is reduced to 4.7% instead of 16%.

the field sensor may be a tri-axial vector magnetometer or a total field magnetometer [10], [22]. This implies that the propeller shaft and rudder have considerable effects on the magnetic detectability of the vessel.

The numerically extrapolated signatures for the selected vessel appear to be in good accordance with either peak values or shapes, as discussed by Daya et al. [22]. Moreover, the numerical results showed a good match with those extrapolated from the measurements. Daya et al. [22] explained that the shapes of the marine vessel’s induced magnetic signature components are not very different from signature components obtained by modeling the vessel as a hollow ellipsoid and are even closer to those computed by FEM. This was numerically investigated using a hollow ellipsoidal shell model with dimensions similar to those of the selected vessel model. Fig. 22 shows three total field components of the first scenario in the measurements, a simulated full-scale vessel, and a simulated ellipsoid with similar dimensions to the full-scale vessel.

![FIGURE 21. Total field component numerical modeling of the two scenarios at 7 m depth.](image1)

![FIGURE 22. Three total field components of the first scenario in measurements (upper), in simulation (middle), and a simulated ellipsoid with similar dimensions to the full-scale vessel (lower).](image2)
Additionally, the athwartship component has the least effect on the total field signature, not only because of its smallest peak magnitudes, but also because of the locations of its peaks. Figs. 24-27 show the signature contour plots of the second scenario.

The peaks of the longitudinal, vertical, and total field components all coincide with the vessel’s longitudinal axis, which is the x-axis, while the four peaks of the athwartship component are shifted in the y-axis direction by approximately 16 m and 30 m in both directions. This shows that the athwartship component itself has the least effect on the total field signature and that its change has a minor effect between the two scenarios when compared to the other components. For the given inducing background field vector, the magnitude of the athwartship component is theoretically zero along the longitudinal x-axis.

A significant note regarding measured signatures is the corrugations shown mainly at the sides of the measured 3D plots and not shown in the simulated signatures for both scenarios. The scaled vessel was subjected to several welding processes during fabrication, as is the case in a real vessel. Hence, corrugations may be explained by the presence of magnetic field abnormalities on the surface of the magnetic material, caused by welding residual stresses. The structure of the magnetic domains of the material and their direction are influenced by these stresses, as explained by Luming et al. [23]. Moreover, Holmes [10] and Jankowski and Woloszyn [13] indicated that in practice, a vessel is not uniformly magnetized because of the irregular distribution of steel throughout the volume of the vessel, which contributes to non-uniform magnetization. As a result, the shapes of real ship signatures are not as simple as expected or are approximated in numerical solutions. Additionally, Daya et al. [22] indicated that meaningful shapes of magnetic signature components of a marine vessel can only be obtained through measurements.

Based on the presented data, it was shown that propeller shaft and rudder intensify the geomagnetic field in their region, causing the induced magnetization to deviate from the pre-existing condition prior to their existence.

Fig. 28 and Fig. 29 show the intensification of both surface flux lines and domain flux lines for the studied scenarios.
Marine vessel safety against magnetic detection is becoming an increasingly important issue. It is important to understand how the vessel materials and parts contribute to the induced magnetic signature. In this study, the effect of flux intensification due to the propeller shaft and rudder on the 3D induced magnetic signature of a marine vessel was investigated.

The study illustrated the usefulness of high-quality 3D signature mapping of two different scenarios in the evaluation of the effect of existence of the propeller shaft and rudder on the vessel signature profile. It was demonstrated that the studied effect has an appreciable extent to the magnetic detectability of the vessel for magnetic threats.

Although prominent, the effects of the propeller shaft and rudder on the magnetic signature are under-evaluated and poorly described in the literature.

Numerical modeling was conducted using full-scale vessel dimensions and FEA, while measurements were carried out on a 1:100 physical-scaled vessel model.

The scaling technique was investigated to properly design and fabricate a vessel-scaled model. A properly designed and constructed physical-scaled vessel model is used to verify the numerical model.

For both scenarios, datasets of signature components for the scaled vessel model measurements and the numerical model in terms of peak magnitudes and shapes showed a good correlation between the two sets.

In the measurements, the studied effect on the signature profile was prominent and was characterized by increased saliency in the signature components when compared between scenarios.

In the modeling, this effect was less prominent. The reasons for this have been discussed and investigated. Modeling software approximations are inevitable. The observation depth effect on the numerical solution was investigated and shown to be highly important; the lower the depth, the higher the degree of agreement was shown between both the numerically extrapolated and measured signature profiles.

Because accurate data and meaningful signature profiles can be obtained from the signature measurements of a vessel scaled model, early in the design phase of a newly designed marine vessel, signature measurement of the scaled vessel model associated with numerical modeling may considerably reduce the time and cost of the initial estimation of a vessel’s vulnerability for being either destroyed or detected.

Moreover, the influence of varying vessel structural items like hull material or underwater geometrical features, on its magnetic detectability can be examined during the design phase.

Larger vessel signatures should be avoided to provide maximum protection for vessels; therefore, the study suggests solutions for this effect, either by considering the utilization of non-magnetic materials for the propeller shaft and rudder or by being independently considered during the design of a signature silencing system.

It is highly recommended that marine vessel permanent magnetism be checked and removed properly prior to measurements of induced magnetism.

Finally, further studies should be conducted on the induced magnetic signature of vessels with electric pod propulsion systems, which may include electric motors with permanent
magnet rotors, and to investigate their anticipated possible effects on the vessel’s induced magnetic signature.

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