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Prediction of the ship's permanent magnetization

Applied on CFAV Quest

M. Birsan

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2008-186

November 2008

Canada

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Abstract

DRDC Atlantic has an ongoing program looking at developing integrated signature management (ISM) techniques for a variety of platforms. This includes the conversion of the measured platform signatures into source strengths, creating a time-history of these source strengths, and advising the Canadian Forces on how to reduce the detection ranges of these platforms.

Military submarines and surface ships are regularly subjected to a treatment called “deperming” that seeks to design the vessel’s permanent magnetization for optimal magnetic silencing. At present, during a ranging operation the permanent magnetization is inferred qualitatively from the performances of the degaussing coils. This study sets out to quantitatively predict the vessel permanent magnetization as the difference between the total (un-degaussed) and the induced magnetization using a combination of measured magnetic signatures and magnetic modeling.

A variety of models describing the ship’s magnetization have been developed starting from a single magnetic dipole to sophisticated distributions of magnetic sources. Depending on the complexity of these models, they describe the signature of the magnetized ship at large or small distances from the sensors. Two methods are proposed that correlate the modeling parameters with the ship magnetization for a correct interpretation of the signature. Due to the ship self-demagnetization effect, the induced magnetization is not known. For this reason, a numerical model of the ship was created using finite elements to evaluate the induced magnetization.

This report details the techniques and algorithms used to determine the ship magnetic parameters as part of techniques that could be incorporated into an ISM capability.

Résumé

RDDC Atlantique gère un programme permanent dont le mandat est de mettre au point des techniques de gestion intégrée des signatures (GIS) pour une gamme de plates-formes. Cela comprend la conversion des mesures de la signature des plates-formes en données sur l’intensité des sources, la création d'un diagramme illustrant l'évolution de l'intensité de ces sources et la prestation de conseils aux Forces canadiennes sur les façons de réduire la portée de détection de ces plates-formes.

Les bâtiments de surface et les sous-marins militaires sont régulièrement soumis à une immunisation magnétique permanente, opération qui consiste à régler le magnétisme permanent d’un bâtiment de manière à en atténuer la signature magnétique de manière optimale. Lors des opérations de télémétrie actuelles, le magnétisme permanent est déduit par inférence qualitative à partir du rendement des bobines démagnétisantes. La présente étude a pour but de prédire quantitativement le magnétisme permanent d’un bâtiment donné en calculant la différence entre le magnétisme total (non démagnétisé) et induit, grâce à une combinaison de mesure et de modélisation de signatures magnétiques.

Du dipôle magnétique unique aux distributions de sources magnétiques très élaborées, toute une gamme de modèles décrivant le magnétisme du bâtiment ont été développés. Selon leur degré de complexité, ces modèles décrivent la signature du bâtiment magnétisé soit à une grande ou à une petite distance des capteurs. Deux méthodes qui permettent d’interpréter correctement la signature du bâtiment en établissant une corrélation entre les paramètres de modélisation et le magnétisme du bâtiment ont été proposées. En raison de l'effet d'auto-démagnétisation des bâtiments, le magnétisme induit est inconnu. Pour pouvoir l'évaluer, un modèle numérique du bâtiment a donc été créé à l'aide d'éléments finis.

Le présent rapport explique en détails les techniques et les algorithmes qui ont été utilisés pour établir les paramètres magnétiques du bâtiment et qui pourraient être intégrés aux techniques de GIS.

Executive summary

Introduction

Since a naval vessel contains ferromagnetic material it becomes magnetized in the presence of the Earth's magnetic field. The strength of this magnetic field can be measured by transiting over an array of sea-floor magnetometers that measure the variation of the magnetic field components as a function of time. These variations are known as the magnetic signature of the vessel.

The magnetic signature of Navy vessels is of particular importance because sea mines use the magnetic signal as a trigger mechanism. The ship magnetization has two parts: induced and remanent (permanent). To make the ship "magnetically silent", the overall ship magnetization is compensated by the placement of on-board degaussing coils. Their purpose is twofold: (1) to actively oppose the magnetization induced by the ambient magnetic field, dependent on the orientation of the vessel, and (2) to statically compensate the permanent magnetization. Due to the different nature of the induced and permanent magnetizations, the degaussing coils have separate turns to compensate these effects separately.

The permanent magnetization accumulates over many months and is difficult to predict. At some stage, the permanent magnetization can reach a level impossible to be compensated with degaussing coils due to their limited power. Consequently, military ships are regularly subjected to a treatment called "deperming" that seeks to design the vessel's permanent magnetization for optimal magnetic silencing. Thus, the estimation of the permanent magnetization is important because it allows one: (i) to determine the currents of the corresponding degaussing coils, and/or (ii) to decide if the vessel requires a deperming operation.

At present, during a ranging operation the permanent magnetization is evaluated qualitatively from the performances of the degaussing coils. This study sets out to quantitatively predict the vessel permanent magnetization as the difference between the total (un-degaussed) and the induced magnetization using a combination of measured magnetic signatures and modeling.

Results

A variety of models describing the total ship's magnetization have been developed ranging from a single magnetic dipole to sophisticated distributions of magnetic sources. Depending on the complexity of these models, they describe the signature of the magnetized ship at large or small distances from the sensors. Two methods are proposed that correlate the modeling parameters with the ship magnetization for a correct interpretation of the signature.

Due to the ship self-demagnetization effect, the induced magnetization is not known and it cannot be measured. For this reason, a numerical model of the ship was created using finite elements to evaluate the induced magnetization. The model was calibrated using a set of experimental data.

Knowing the induced magnetization, the calculation of the permanent magnetization can be performed during every ranging operation following the measurement of a pair of North and South runs. The report presents an example of such calculation and compares the results with previous measurements obtained with the Magnetic Anomaly Detection system.

Future work

It was shown that the separation of the induced and permanent magnetizations could be done by measurements at a fixed range that possesses the capability to remove the Earth's local magnetic field. Such ranges exist in US, UK, Norway and Germany. It will be of interest to compare the present results with those obtained directly from measurements.

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Sommaire

Introduction

En raison des matériaux ferromagnétiques qu’ils contiennent, les bâtiments militaires se magnétisent lorsqu’ils sont en présence du champ magnétique de la terre. La puissance de ce champ magnétique peut être mesurée lors de passages au-dessus d’une batterie de magnétomètres disposés sur le fond marin, qui mesurent la variation des composantes du champ magnétique en fonction du temps. Ces variations correspondent à la signature magnétique du bâtiment.

La signature magnétique des bâtiments de la Marine revêt une importance capitale, car les mines sous-marines sont déclenchées par signaux magnétiques. Le magnétisme d’un bâtiment se divise en deux types : induit et rémanent (permanent). Pour rendre un bâtiment « magnétiquement silencieux », il faut compenser son magnétisme global en plaçant à son bord des bobines démagnétisantes. Ces bobines servent à deux choses : d’abord, (1) à s’opposer activement au magnétisme induit par le champ magnétique ambiant, selon l’orientation du bâtiment, et ensuite, (2) à compenser statiquement le magnétisme permanent. En raison de la nature différente du magnétisme induit et du magnétisme permanent, les bobines démagnétisantes tournent séparément pour compenser ces effets séparément.

Le magnétisme permanent s’accumule sur une période de plusieurs mois et est difficile à prédire. Il peut même finir par atteindre un niveau si élevé qu’il devient alors impossible à compenser avec des bobines démagnétisantes, lesquelles ont une puissance limitée. Par conséquent, les bâtiments militaires sont régulièrement soumis à une immunisation magnétique permanente, opération qui consiste à régler le magnétisme permanent d’un bâtiment de manière à en atténuer la signature magnétique de manière optimale. L’estimation du magnétisme permanent est donc importante, car elle permet : (i) de déterminer les courants des bobines démagnétisantes correspondantes et (ii) de décider si le bâtiment doit être soumis ou non à une immunisation magnétique permanente.

Lors des opérations de télémétrie actuelles, le magnétisme permanent est évalué par inférence qualitative à partir du rendement des bobines démagnétisantes. La présente étude a pour but de prédire quantitativement le magnétisme permanent d’un bâtiment donné en calculant la différence entre le magnétisme total (non démagnétisé) et induit, grâce à une combinaison de mesure et de modélisation de signatures magnétiques.

Résultats

Du dipôle magnétique unique aux distributions de sources magnétiques très élaborées, toute une gamme de modèles décrivant le magnétisme total du bâtiment ont été développés. Selon leur degré de complexité, ces modèles décrivent la signature du bâtiment magnétisé soit à une grande ou à une petite distance des capteurs. Deux méthodes qui permettent d’interpréter correctement la signature du bâtiment en établissant une corrélation entre les paramètres de modélisation et le magnétisme du bâtiment ont été proposées.

En raison de l’effet d’auto-démagnétisation des bâtiments, le magnétisme induit est inconnu et ne peut être mesuré. Pour pouvoir l’évaluer, un modèle numérique du bâtiment a donc été créé à l’aide d’éléments finis. Ce modèle a été étalonné à l’aide d’un ensemble de données expérimentales.

Lorsque le magnétisme induit est connu, le magnétisme permanent peut être calculé durant toute opération de télémétrie, suite à la mesure d'une paire de passages nord-sud. Le rapport présente un exemple d'un tel calcul et compare les résultats obtenus avec des mesures antérieures effectuées grâce au système de détection d'anomalies magnétiques.

Travaux futurs

Il a été démontré qu'il est possible de séparer le magnétisme induit du magnétisme permanent en effectuant des mesures dans un endroit fixe où le champ magnétique local de la terre peut être neutralisé. De tels endroits existent aux États-Unis, au Royaume-Uni, en Norvège et en Allemagne. Il serait intéressant de comparer les résultats actuels avec ceux obtenus par mesures directes.

Birsan, Marius. *Prédiction du magnétisme permanent des bâtiments : Applique sur BAFC Quest* – RDDC Atlantique, MT n° 2008-186. RDDC Atlantique, 2008.

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1. Introduction

Since a naval vessel contains ferromagnetic material it is magnetized in the presence of the Earth's magnetic field. The strength of this magnetic field can be measured by transiting over an array of sea-floor magnetometers that measure the variation of the magnetic field components as a function of time. These variations are known as the magnetic signature of the vessel.

The ship magnetization has two parts: induced and remanent (permanent). The induced magnetization represents the reaction of the ferromagnetic material to the ambient field. The permanent magnetization corresponds to the magnetic fields from within the magnetic material of the vessel. In general, the remanent and induced field vectors point in different directions and the resultant direction of magnetization is a combination of these two vectors.

The magnetic signature of Navy vessels is of particular importance because sea mines use the magnetic signal as a trigger mechanism. The deployment of magnetic sensing marine mines around ports and major shipping lanes can cause great damage to naval and merchant vessels. In order for a ship to pass safely it is necessary to camouflage the vessel from magnetic detection. To make the ship "magnetically silent", the overall ship magnetization is compensated by the placement of on-board degaussing coils. Their purpose is twofold: (1) to actively oppose the magnetization induced by the ambient magnetic field, dependent on the orientation of the vessel, and (2) to statically compensate the permanent magnetization. Due to the different nature of the induced and permanent magnetizations, the degaussing coils have separate turns to compensate their effects separately.

The permanent magnetization accumulates over many months and is difficult to predict. At some stage, the permanent magnetization can reach a level impossible to be compensated with degaussing coils due to their limited power. Consequently, the permanent magnetization of naval vessels is regularly reset to a known value, or reduced as much as possible, in a procedure known as deperming. For this deperming process, the estimation of the permanent magnetization is important because it allows one: (i) to determine the currents of the corresponding degaussing coils, and/or (ii) to decide if the vessel requires a deperming operation.

As mentioned above, a correct degaussing procedure requires the separation of the contributions of the two magnetizations to the total magnetic signature. This can be done by measurements, if the range possesses the capability to remove the Earth's local magnetic field, and thus remove the influence of the induced magnetization. Because it is not possible to make these measurements in Canada (they exist in US, UK, Norway and Germany), this study proposes to evaluate the permanent magnetization by using a mixed procedure based on measurements and a mathematical model of the ship.

At present, the ship's permanent magnetization is evaluated qualitatively during the magnetic ranging. It becomes evident that the permanent magnetization reaches an intolerable level when the degaussing currents cannot decrease the magnetic signature below a certain level. This study proposes a quantitative evaluation of the ship's permanent magnetization by subtracting the component due to the induced magnetization from the total (un-degaussed) ship's magnetization.

Due to the unknown ferromagnetic content of the ship and to its irregular shape (self-demagnetization effect), the induced magnetization is not parallel to the Earth's magnetic field and its strength is not known. For this reason, the proposed method makes use of the finite element (FE) method to model the ship's induced magnetization. In a previous study [1], it was shown that the effect of the induced magnetization may be well modeled in a generic Canadian Patrol Frigate (CPF) using FE method, and the model was validated by measurements. On the other hand, our lack of information regarding the magnetic materials, their magnetic history, and magnetization process inside the ship makes it impossible to model the effect of the permanent magnetization.

The total magnetization of the ship is obtained from the measured undegaussed magnetic signature. Two methods are presented that estimate the magnetization magnitude and direction from the ship's signature measured at different distances from the sensors. The first method is suitable for measurements taken during the magnetic ranging, while the second method applies for the data obtained at larger distances, for example, using the magnetic anomaly detection (MAD) technique. These are inverse problems and several studies exist that determine how well a certain type of source distribution can represent the ship magnetic signature with varying distances [2, 3].

2. Modeling ship's magnetization

A ship is a non-uniformly magnetized body that can be thought as an unknown set of magnetic sources distributed inside the hull. In order to model this complicated magnetized ship, it is necessary to determine the locations, magnitudes and orientations of a reduced number of sources that are both responsible for, and consistent with, a set of experimental measurements. Such problems are termed 'inverse problems' and are generally solved by minimizing a cost function that is usually some norm (most commonly L2) of the residuals.

As emphasized above, the magnetic source distribution calculated by inversion reflects only the measurements and cannot be associated with the actual magnetization at a certain location inside the hull. Our lack of knowledge about the local magnetization on board of the ship imposes the restriction in describing the magnetic state of a vessel by using only macro-scale quantities. Thus, the (macro-) magnetization of a ship is a vector characterized by its magnitude and orientation and both these quantities are assumed constant during the time of measurement. Because of this property, the modeling parameters as a whole should reflect the total magnetization, irrespective of the number of sources, their distribution, or measurement distance.

How the ship's magnetization is modeled depends on the characteristic of its magnetic signature, which varies with the distance between the ship and the sensors. At large distances (in term of the main geometric dimension of the ship), the magnetic properties may be represented by a single dipole. At smaller (medium) distances, such representation is inadequate and a distribution of a variety of types of sources (*e.g.* spheres, ellipsoids, etc.) is used to represent the complex structure of the field. As a rule of thumb, the overall dimension of the source gives the distance that separates the two representations. At short distances (1 – 5 meters) from the ship, the magnetic measurements will depend not only on the overall magnetization, but also on the actual geometrical features of the ship surface. This later case will be treated in a separate report where the distribution of dipole sources will be replaced by the magnetic charges distributed on flat-panel elements representing the hull.

2.1 Medium range magnetic properties of a ship

As measured at medium range, the ship magnetic signature is far from being similar to the one created by an equivalent magnetic dipole. In this case, the ship appears to be formed by a multitude (60 in this report) of magnetic sources of various magnitudes and orientations. To analyze this signature we use a distribution of magnetic dipoles (spheres), and the aim of the inverse modeling is to estimate the magnitudes of the sources placed at known locations. Once the magnitude of each source is calculated, the total magnetization in each direction is estimated as the sum of the partial magnetizations in that direction.

The coordinate system used in this report is given by the ship reference frame with the X-axis corresponding to the longitudinal direction, the Y-axis to the athwartship direction, and the Z-axis (downwards) perpendicular to both X and Y. Using the measured data, the magnetic moments were calculated by inverting the magnetic fields (B_X, B_Y, B_Z) given by the formula:

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \sum_i \frac{\mu}{4\pi r'^5} \begin{pmatrix} 2x'^2 - y'^2 - z'^2 & 3x'y' & 3x'z' \\ 3x'y' & 2y'^2 - x'^2 - z'^2 & 3y'z' \\ 3x'z' & 3y'z' & 2z'^2 - x'^2 - y'^2 \end{pmatrix} \begin{pmatrix} M_{i,x} \\ M_{i,y} \\ M_{i,z} \end{pmatrix} = \mathbf{A}\,\mathbf{M} \tag{1}$$

$$r' = \left(x'^2 + y'^2 + z'^2\right)^{1/2} = \left((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right)^{1/2}$$

where r' is the distance between the sensor and the i-th magnetic dipole, and μ is the permeability of the medium.

The system of equations (1) was inverted using the Tikhonov regularization algorithm, which reduces to the least-squares method for the well-conditioned system. The inversion problem is reduced to a linear system of equations:

$$\mathbf{M} = \left(\mathbf{A}^T \mathbf{A} + \lambda\right)^{-1} \mathbf{A}^T \mathbf{B} \tag{2}$$

where the vector **M** contains the magnetic source distribution, the vector **B** contains the measured magnetic field values, **A** is the design matrix that brings the physics to the problem, and the term λ is the regularizing operator. The Tikhonov's regularization parameter, λ, is determined by the L-curve method described in [5]. The regularization was necessary to avoid the long-known problem of non-unique oscillating solutions in which the data values appear well fitted in a least-square sense, but are characterized by a very unrealistic or wildly varying distribution of sources in which adjacent sources have opposite signs.

Of course, it is possible to use less magnetic sources, with larger separation distance, to obtain a well-conditioned system given by equation (1), but in this case some features of the magnetic signature may not be well reproduced.

The use of spheroids (ellipsoids) instead of spheres as magnetic sources did not offer any advantage in modeling the magnetic signature at medium distances. An exact solution of the magnetic field created by a prolate spheroid using spherical harmonics is known [4], but we chose a multipole expansion. The first non-zero moment is the dipole. Due to symmetry, the octupole is the next non-zero moment, and it is a rank 3 tensor with 27 components (only 6 independent). The terms of this tensor are not specified here, but note that its field dies off as r^{-5}. The rapid falloff of the octupole term with distance means that once the sensor distance exceeds a few (spheroid) body lengths, the field is essentially dipolar.

2.2 Long range magnetic properties of a ship

At distances larger than the main dimension of the vessel the magnetic signatures are similar to the one produced by an equivalent magnetic dipole. Such a signature may be generated from multiple paths of an aircraft carrying a magnetic anomaly detection (MAD) system. The flight altitude of the aircraft during the MAD operation is between 80 and 120m.

In principle, if the location of the dipole is known, the vessel magnetic moment could be obtained from equation (1) by direct inversion of matrix **A** (i = 1, in this case). However, the position of the magnetic center (similar to the gravitational center) of the vessel is not known, and the results obtained by direct inversion are very sensitive to the data errors. For this reason, an iterative inverse 3-D magnetic interpretation method was preferred, which is presented in this section. In addition to the magnetization moment, the algorithm estimates the position of the center of magnetization. The X and Y coordinates of the center can be accurately estimated from a contour plot of the magnetic field data. The Z coordinate is not easily estimated, so various values must be tried until the algorithm converges.

In this method, the magnetic anomaly created by the vessel is approximated by the series derived from its expansion into multi-poles and retaining moments up to the second order. Then the moments appearing in the series expansion are inverted from the magnetic anomaly and used to compute the magnitude, orientation, and center of the source. The method is linear and does not require any explicit assumption of the geometry for the source. It is particularly suited to interpret isolated or disjoint, but spatially correlated sources.

A brief description of the method is presented here and the details are found in [6]. The vertical field anomaly created by a body with volume v_0 and magnetization **M** constant in direction is given by:

$$B_Z(\mathbf{r}) = \int_{v_0} \mathbf{M}(\mathbf{r}') \frac{\partial}{\partial m'} \Phi(\mathbf{r},\mathbf{r}') dv_0 \qquad \Phi(\mathbf{r},\mathbf{r}') = \frac{z - z'}{\left[(x-x')^2 + (y-y')^2 + (z-z')^2\right]^{3/2}}$$

$\Phi(\mathbf{r}, \mathbf{r'})$ is the Green function with **r** = (x y z) and **r’** = (x’ y’ z’) being the position vectors of the observation point and of a generic point inside v_0, respectively. In addition, the direction of **M** defined by the declination, d, and inclination, i, so that the direction cosines are:

$$a = \cos d \ \cos i \ ; \qquad b = \sin d \ \cos i \ ; \qquad c = \sin i$$

The magnetic anomaly is approximated by expanding $\Phi(\mathbf{r}, \mathbf{r'})$ in the Taylor series about $\mathbf{r'_0}$:

$$B_Z \cong \Phi^X M_0^X + \ldots + \Phi^{XY}\left(M_X^Y + M_Y^X\right) + \ldots + \Phi^{ZZZ}\left(\frac{1}{2}M_{ZZ}^Z - \frac{1}{2}M_{XX}^Z - M_{XZ}^X\right) \tag{3}$$

where:

$$\Phi^{XYZ} = \frac{\partial^3 \Phi}{\partial x' \partial y' \partial z'} \Big/ \mathbf{r}' = \mathbf{r}'_0$$

M’s are the magnetic moments defined, for example, by formula:

$$M_{XY} = \int_{v_0} (x' - x'_0)(y' - y'_0) \mathbf{M}(\mathbf{r}') \, dv_0 \ ; \qquad M_X^Y = M_X \, b = \sin d \ \cos i \int_{v_0} (x' - x'_0) \mathbf{M}(\mathbf{r}') \, dv_0$$

The algorithm iteratively estimates **M** from the system (3) starting with an arbitrary center of expansion. The first-order moments are zero when the center of expansion coincides with the center of the dipole moment. A new center of expansion is calculated to decrease the first-order moments until a stopping condition is met.

2.3 Self-demagnetization effect

In the presence of an inducing magnetic field, **H**, the magnetization, **M**, acquired by a volume of magnetic material is:

$$\mathbf{M} = \chi\mathbf{H} = \chi\left(\mathbf{H}_0 + \mathbf{H}_S\right) \quad (4)$$

where χ is the magnetic susceptibility, $\mathbf{H}_0$ is the Earth's magnetic field, and $\mathbf{H}_S$ is an anomalous field associated with the magnetic material in the region. For low values of the susceptibility ($\chi < 10^{-2}$ SI), the anomalous field may be neglected and the direction of magnetization is then parallel to the Earth's field. The strength of magnetization is known if the susceptibility is provided.

If the susceptibility becomes larger, then the magnetic field at any location in the medium can be significantly affected by the induced magnetization in neighboring material. Locally, **H** is reduced substantially from $\mathbf{H_0}$, and the magnetization is lower than expected. Hence, the phenomenon is referred as self-demagnetization.

Self-demagnetization causes magnetizations to rotate away from the external inducing field and causes the amplitude of the magnetic response to scale non-linearly with susceptibility. These effects are highly dependent on the shape of the susceptibility distribution and they complicate interpretation of the magnetic data.

Once the relative permeability ($\mu_r = 1+\chi$) exceeds a few hundred units, the induced magnetization becomes virtually independent of susceptibility (but it is still dependent on the shape of the body). This is the case for bulk steel bodies that typically have susceptibilities of several hundred to over a thousand. Unfortunately, the previous magnetic measurements [1] on a Canadian Patrol Frigate show a susceptibility of about 130 SI units, mainly because of the non-magnetic volumes inside the vessel. This means that, for a vessel, the induced magnetization is dependent on both susceptibility and shape. Thus, the shape-only dependency formula used in a previous report [7] is only a rough approximation.

Analytical modeling methods that account for self-demagnetization effect are limited to simple bodies, such as ellipsoids, where the geometry of the body is represented by a few parameters [4]. For arbitrarily shaped bodies with non-uniform distribution of the internal magnetic masses, one has to rely on the numerical modeling methods, such as the finite element (FE) method, to include self-demagnetizing effects in the calculation of the induced magnetization.

3. Permanent magnetization of CFAV Quest

3.1 Principle of calculation

Measurement of magnetic signature in Canada is done at an underwater range where the ship passes perpendicularly over a number of vector sensors aligned East-West. Usually, the total ship magnetisation is decomposed into components defined in a Cartesian co-ordinate system related to the ship (Figure 1): X-axis corresponding to the longitudinal (L) direction, Y-axis to the athwartship (A) direction, and Z-axis perpendicular to both X and Y (V). The abbreviations used are ILM, IAM, IVM, where, for example, IAM stands for the induced athwartship magnetisation, and so on.

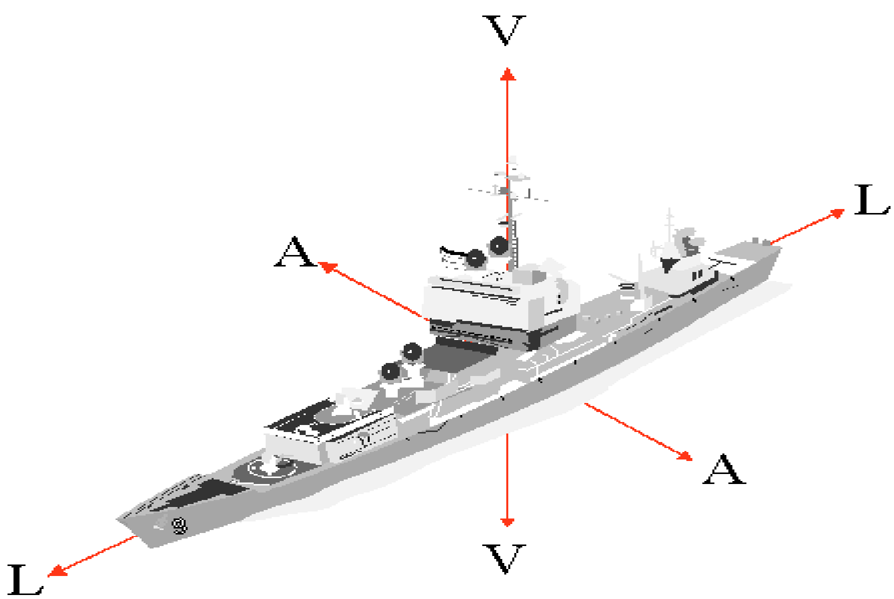

Figure 1. *Coordinate system of the ship's magnetization.*

When the ship changes course from North to South, the X-component of the Earth's magnetic field changes sign from plus to minus. Consequently, the components of the total magnetization of the ship for these runs are:

$$M_X^N = M_X^I + M_X^P$$
$$M_X^S = -M_X^I + M_X^P$$
$$M_Y^S = M_Y^N = M_Y^P \tag{5}$$
$$M_Z^N = M_Z^S = M_Z^I + M_Z^P$$

where M_K^N and M_K^S (K = X, Y, Z) are the ship total magnetization during the North and South runs, M_K^I is the induced magnetization, and M_K^P is the permanent one.

From the North and South signatures one can determine the total intensity of the magnetic source that causes them using one of the methods presented above. Then, equation (5) allows the calculation of each component of the magnetization in the X and Y ($M_Y^I = 0$) directions, but cannot separate the induced and permanent magnetization in the Z direction.

To address this problem, a method is proposed in this report that estimates the Z component of the induced magnetization using the finite element (FE) model of the ship subject to an induced magnetic field that produced the measured values. The measurements were made at the Bedford Bay range (Lat. 44° 41' N, Long. 63° 37' W) where the Earth's magnetic field parameters (from the World Magnetic Model) are: total field = 53796.9 nT, inclination = 69.34°, and declination = 0°, because the ship is oriented towards the magnetic North (the declination to the geographic North is d = -19.02°). This gives the following values of the ambient field in the measurement coordinate system: H_X = 14.68 A/m, H_Y = 0 A/m and H_Z = 39.06 A/m.

A model representing the CFAV Quest-induced magnetization was generated using the FE-based commercial software FLUX-3D (Figure 2). The geometry of the FE model accurately describes the ship ferromagnetic hull and its internal structure including the magnetic masses representing the engines, propulsion system, machinery, but the susceptibility of the materials is unknown. As explained above, the calculation of the induced magnetization on a model with arbitrary susceptibility distribution will provide erroneous results.

The variety, the distribution, and the quantity of magnetic materials on a ship make the individual measurement of susceptibility impossible. If it is not possible to obtain an accurate FE magnetic model at the micro-scale level, the FE model can be improved to reproduce, with reasonable accuracy, the overall magnetic state of the ship (the one that is generating the measurement data.

Analyzing the un-degaussed North-run and South-run signatures, they are composed of separate magnetic fields measured at the sensors:

$$\begin{aligned} B_K^N &= I_K^X + I_K^Z + P_K^X + P_K^Y + P_K^Z \\ B_K^S &= -I_K^X + I_K^Z + P_K^X + P_K^Y + P_K^Z \end{aligned} \tag{6}$$

where K = X, Y, Z, I_K^X is the K field component produced by the induced magnetisation in X direction, P_K^X is the K field component produced by the permanent magnetisation in X direction, and so on. For a perfect North or South run, I_K^Y is zero because the Earth's magnetic field in the athwartship direction (H_Y) is zero.

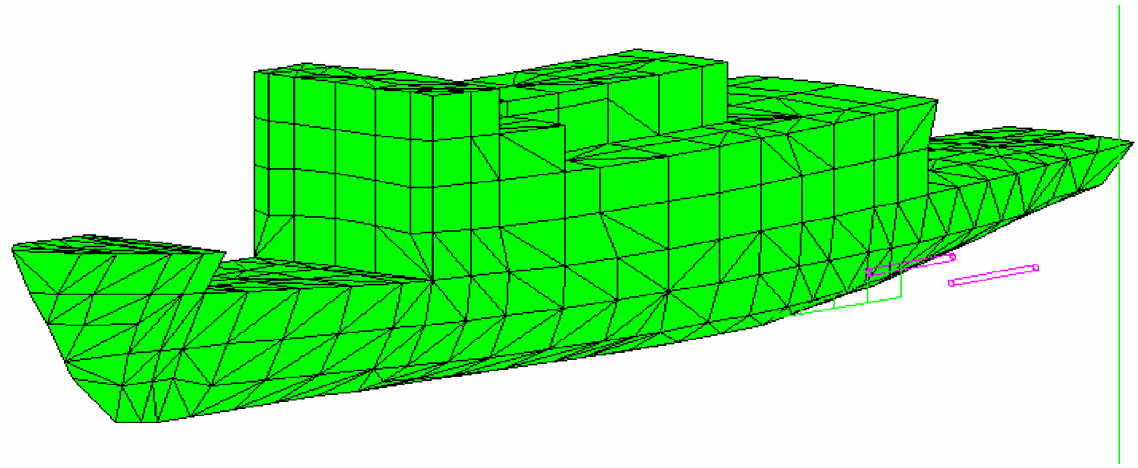

Figure 2. *FE model of the CFAV Quest.*

Taking the difference between the North and South run pairs one obtains the signature produced only by the induced longitudinal magnetisation, M_X^I, produced by the horizontal component of the Earth's magnetic field at the location where the measurements were taken:

$$\mathbf{I}^X = \left(\mathbf{B}^N - \mathbf{B}^S\right)/2 \tag{7}$$

where the indices K was omitted. Thus, we have a set of experimental data that allows us to adjust the magnetic parameters of the model, by a trial and error process, until a reasonable accuracy is achieved between the measured and calculated values of the magnetic anomaly components produced by the horizontal magnetic field.

Once the FE model is adjusted to fit the experimental data, it can be used to generate the signature produced solely by the induced magnetization of the ship at the Halifax location, H_X = 14.7A/m. The same inversion procedure as above may be applied to the three orthogonal components of this signature to obtain the parameters of the induced magnetization. This FE model allows the estimation of the angle between the induced magnetization and the external applied field taking into account a realistic self-demagnetizing effect of the ship. Both the vessel shape and the susceptibility, at the macro-scale level, of the model correspond to the real parameters.

3.2 Results and discussion

The calculation of the total magnetization starting from the measured data was performed for the CFAV Quest, using both methods presented above.

For the first method, the magnetic sources were located inside the hull consisting of a distributed set of 60 dipoles (spheres) each of which had different vector magnetization, (M_X, M_Y, M_Z). Sources were located evenly every 4m along the X-axis with Y = ±4m, and Z = -2 and +4m. In this reference frame, where the water level is considered to be at Z = 0m, the depth of the sensor array is z = 17m. For this case, the magnetic signature data was collected at the magnetic range.

The second method was applied on a set of data representing the ship's magnetic signature when the distance to the sensors is increased to 100 meters. For the sake of consistency, it is preferable that the ship magnetic parameters at this distance to be inferred from a signature generated by the same sources as the above. To obtain the desired set of data, the vertical-component magnetic data measured at the range is transformed into that that would be measured at a distance deeper (z-axis being positive downwards) with 83m using the "upward continuation" operation.

Upward continuation transforms the magnetic anomalies measured on one surface to those that would be measured on another surface farther from the source. The mathematical foundation of this transformation is the Green's third identity [8]. If the magnetic field is measured on a level surface at $z = z_0$ and the field is desired on at a single point $(x, y, z_0 + \Delta z)$ above the level surface, where $\Delta z > 0$, this value is given by the upward continuation integral:

$$B_Z(x, y, z_0 + \Delta z) = -\frac{\Delta z}{2\pi} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{B_Z(x', y', z_0)}{\left[(x-x')^2 + (y-y')^2 + \Delta z^2\right]^{3/2}}\, dx'\, dy' \qquad (8)$$

Because $B_Z(x, y, z+\Delta z)$ at any point is the weighted average of all values of $B_Z(x, y, z)$, the upward continuation is a smoothing operation. In practical applications, some approximations will be required because it is impossible to know the field anomaly precisely at each point of an infinite plane. It is important to know the field well beyond the lateral extent of all magnetic sources, a recommendation difficult to implement in the case of a ship's magnetic signature. However, equation (8) was applied on the measured vertical magnetic signature to obtain a new set of data at a larger distance from the sensors. Then, equation (3) was used to calculate the position, orientation and magnitude of the corresponding magnetic source.

As an example of the calculation, these two methods were applied on a set of magnetic data collected during the Quest trial in October 2007 and the results are shown in Table 1. For the North and South runs M_X, M_Y, and M_Z represents the components of the total magnetization. Also shown in Table 1 are the coordinates of the magnetic center (the location of the equivalent dipole) for the long-range measurements. Then, equation (7) was used to obtain the signature produced by the longitudinal-induced magnetization that allows us to adjust the magnetic parameters of the FE model.

The validation of the FE model is an iterative process based on the comparison between the measured and calculated signature. Building a realistic FE model is very time consuming because of the multitude of parameters that need to be adjusted. The I_X^X signature of the validated FE model is presented in Fig. 3 (a) in comparison with the experimental data, Fig.3 (b). The real magnetic signature is not symmetrical relative to the X-axis, but it is tilted about 6° from the North-South direction due to a flaw in the data acquisition software. Otherwise, the two signatures are very similar.

Table 1: Calculated components of magnetization and the dipole center.

Total magnetization	M_X (kA-m^2)	M_Y (kA-m^2)	M_Z (kA-m^2)	X, Y (meters)	Z (meters)
Medium range (North Run)	475.4	7.3	646.4		
Long range (North Run)	480.5	6.9	650.8	2.1, -0.3	100.5
Medium range (South Run)	31.4	-7.8	634.5		
Long range (South Run)	31.4	-8.6	639.5	0.5, -0.5	100.9
Induced only:	M^I_X	M^I_Y	M^I_Z		
FEM validation H_X = 14.7A/m	225.4	-0.87	3.47		
FEM induced for H_X and H_Z =39A/m	223.8	-0.12	279.3		

The data analyzed represents the real signature recorded when the ship crosses the sensors array navigating North-South with the help of a GPS system. This means that the results will be affected by the tracking errors and Table 1 is representative only for one set of data. The quality of the results depends on how well the North and South signatures overlap (Eq.7). Unfortunately, due to navigation conditions, the real data is never perfectly reproducible, so that the results will slightly fluctuate depending on the North-South data pair chosen for calculation. This disadvantage could be eliminated with a fixed ranging facility.

The induced magnetization of the FE model, (M^I_X, M^I_Y, M^I_Z), in Table 1 was calculated from the calibrated model. An indication of how well the model reproduced the real ship is the good agreement between the longitudinal magnetization of the real ship (M^I_X = 222.0 kA-m^2) as calculated with equation (5) and the one from the FE model (225.4 kA-m^2) after the fitting of the measured and calculated data.

From this table one can calculate the orientation of magnetization as it is given by the inclination and declination relative to the magnetic North direction:

$$i = \arctan\left(\frac{M_Z}{\sqrt{(M_X)^2 + (M_Y)^2}}\right); \quad d = \arctan\left(\frac{M_Y}{M_X}\right) \tag{9}$$

This formula gives the orientation of the induced magnetization (i = 51.5°, d ≈ 0°) relative to the orientation of the ambient field (i = 69.3°, d = 0°) when the CFAV Quest is oriented North-South in Halifax. For this location only, the inclination angle represents a parameter that can be used in the calculation of the permanent magnetization at any time.

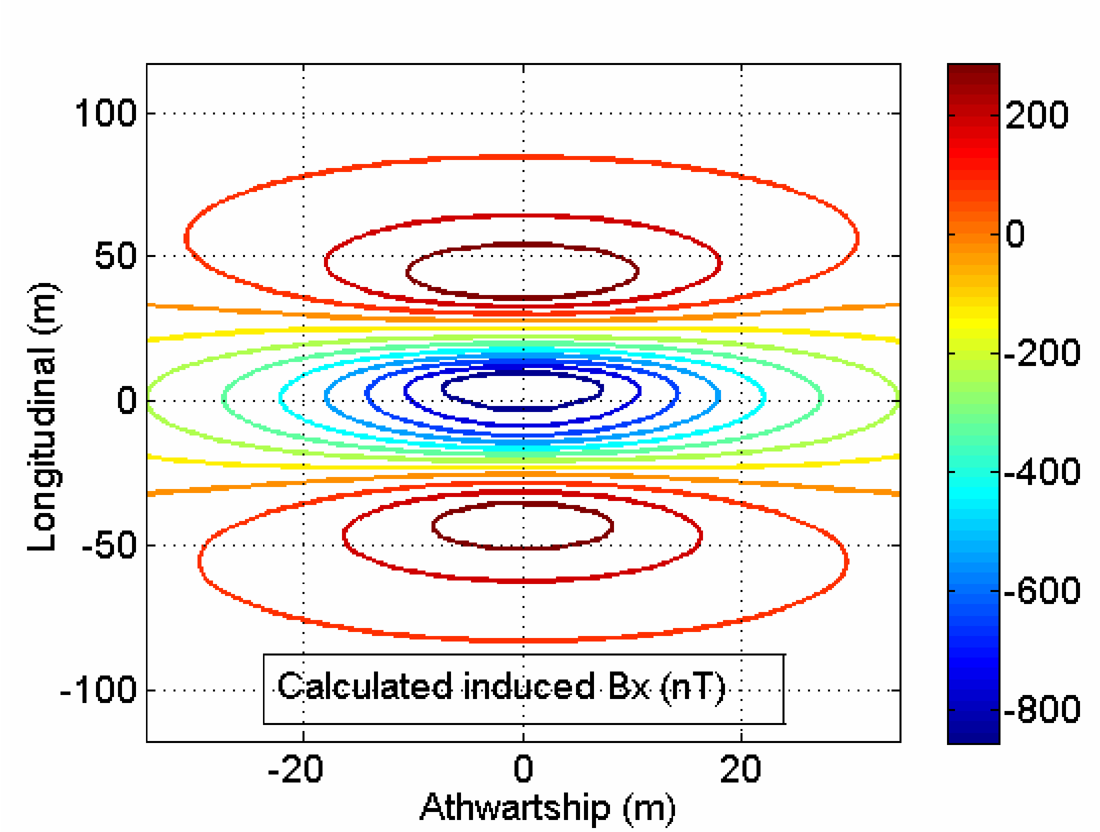

Figure 3 (a). *Calculated I_X^X signature from the FE model.*

For this set of data, the estimated permanent magnetization of CFAV Quest in October 2007 as calculated from eq.5 is: $M_X^P = 253$, $M_Y^P = 0$, $M_Z^P = 368$ kA-m^2.

The results presented here can be compared with the magnetic parameters for CFAV Quest obtained from the MAD measurements as shown in [7]: $M_X^P = 320$, $M_Y^P = -72$ kA-m^2 are the components of the permanent magnetization, and $M_Z = 730$ kA-m^2 is the total magnetization for an arbitrary orientation of the ship in the Earth's magnetic field. These values correspond to the magnetic state of CFAV Quest in October 2002 and they are higher than the present values. The value of the permanent magnetization is time dependent, thus the difference in measurement may be real. One possible reason for the lower magnetization values in 2007 is that, during the time, the degaussing coils were activated and the permanent magnetization of the vessel may have decreased, at least in the Z direction.

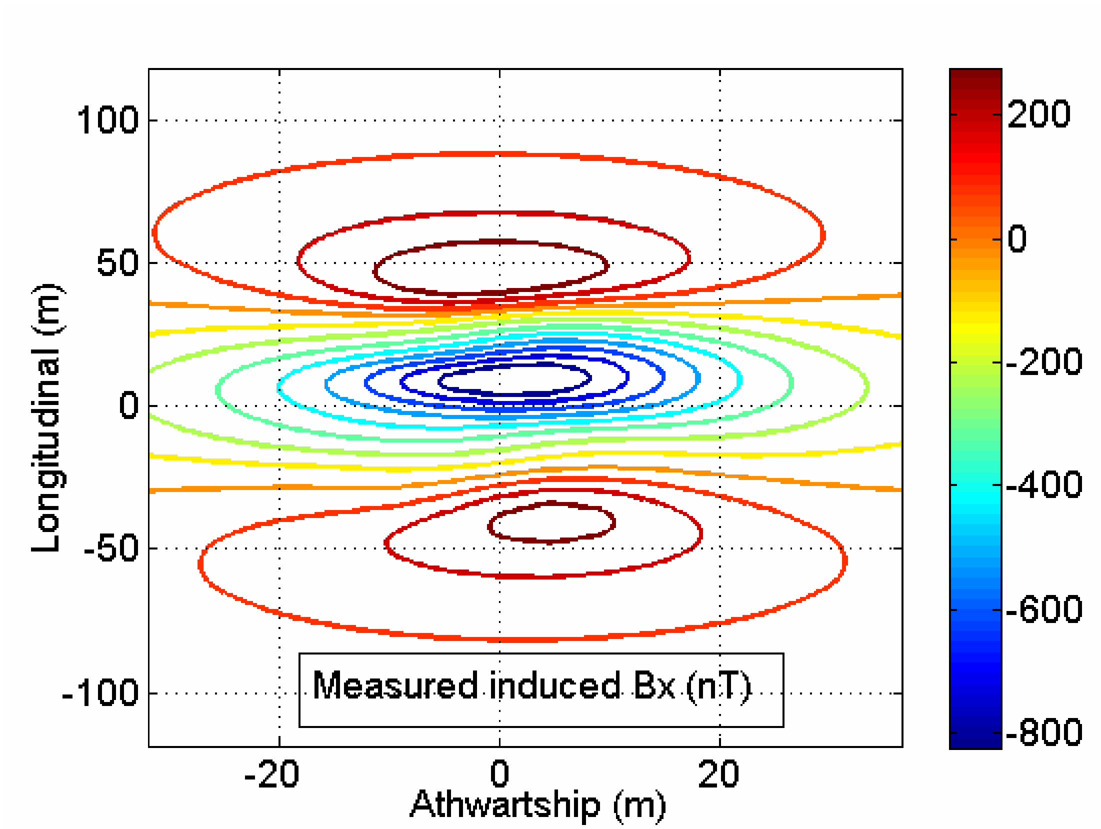

Figure 3 (b). *Induced I_X^X signature from measurements (equation 7).*

The measurements are affected by the tracking errors, so more pair of runs used for calculation will improve the statistics. Unfortunately, there are not enough ranging data to allow a good variance analysis. However, to take into account the measurement errors, repeated calculations using multiple sets of North and South runs data obtained from the magnetic ranging in 2006 and 2007 gave values of M_Z, the total magnetization in the Z-direction, between 630 and 680 kA-m^2, and of M_X^I between 215 and 240 kA-m^2.

While the permanent magnetization of the ship can change in time, the same is not true for the induced magnetization. According to equation (4) in [7] and the calculated value of C_L = 0.52, the induced magnetization in the longitudinal direction from the MAD measurement should be M_X^I = 421.2 kA-m^2. This value was calculated in [7] using data obtained for various orientations of the ship and is much higher (almost double) than the value presented in this report, which was calculated from the North and South runs.

The MAD measurements are taken during the passage of the aircraft close to the ship when the total field anomaly is recorded. This is equivalent to measuring the ship signature at the range using only one axis of one sensor, when much information is lost in comparison with a multi-sensor 3-axial measurement. Even though the tracking errors would be zero, a single-axis single-sensor measurement does not provide enough information to reconstruct the whole signature. Thus, the magnetization is only approximately calculated in this case.

The method presented here offers more accuracy in the calculation of the ship magnetization because it utilizes all the information contained in the signature. This includes the signature produced by the longitudinal-induced magnetization that can be directly obtained from the range data using equation 7.

4. Conclusion

This report presents a method that helps determine if the permanent magnetization plays a significant role in generating the magnetic anomaly by the presence of a ship in the Earth’s magnetic field. The components of the permanent magnetization were extracted from the total magnetization in conjunction with the induced magnetization that was computed by a commercial FE software package FLUX-3D.

The only induced magnetisation effect that can be measured is the signature produced by the ILM and this effect was used to calibrate the FE model. Once the FE model is validated, it can contribute to a realistic prediction of the ship’s induced magnetization.

The total magnetization of the ship is estimated from the source distribution that is both responsible for and consistent with a set of experimental measurements. This is an inverse problem solved by the two proposed methods.

Using this method, the permanent magnetization of CFAV Quest during a trial that took part in Halifax was calculated and compared with previous results obtained from MAD measurements. In comparison to the previous method, the method presented here is more accurate because the calculation of the self-demagnetization effect takes into account both the shape and the magnetic susceptibility of the ship, and it utilizes all the information contained in a signature as collected from a multi-sensor 3-axial range.

In Halifax, the self-demagnetization effect rotates the induced magnetization of CFAV Quest about 20° from the direction of the external field (see equation 9). Knowing this angle, the calculation of the permanent magnetization can be performed during every ranging operation following the measurement of a pair of North and South runs.

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List of symbols/abbreviations/acronyms/initialisms

DND	*Department of National Defence*
CFAV	*Canadian Forces Auxiliary Vessel*
IAM	*Induced Athwartship magnetization*
ILM	*Induced Longitudinal Magnetization*
IVM	*Induced Vertical Magnetization*
MAD	*Magnetic Anomaly Detection*

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DRDC Atlantic has an ongoing program looking at developing integrated signature management (ISM) techniques for a variety of platforms. This includes the conversion of the measured platform signatures into source strengths, creating a time-history of these source strengths, and advising the Canadian Forces on how to reduce the detection ranges of these platforms.

Military submarines and surface ships are regularly subjected to a treatment called “deperming” that seeks to design the vessel’s permanent magnetization for optimal magnetic silencing. At present, during a ranging operation the permanent magnetization is inferred qualitatively from the performances of the degaussing coils. This study sets out to quantitatively predict the vessel permanent magnetization as the difference between the total (un-degaussed) and the induced magnetization using a combination of measured magnetic signatures and magnetic modeling.

A variety of models describing the ship’s magnetization have been developed starting from a single magnetic dipole to sophisticated distributions of magnetic sources. Depending on the complexity of these models, they describe the signature of the magnetized ship at large or small distances from the sensors. Two methods are proposed that correlate the modeling parameters with the ship magnetization for a correct interpretation of the signature. Due to the ship self-demagnetization effect, the induced magnetization is not known. For this reason, a numerical model of the ship was created using finite elements to evaluate the induced magnetization.

This report details the techniques and algorithms used to determine the ship magnetic parameters as part of techniques that could be incorporated into an ISM capability.

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magnetic characterization, magnetic silencing, degaussing, deperming operation

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