A Complete Underwater Electric and Magnetic Signature Scenario Using Computational Modeling

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Abstract

Computer modeling has been extensively used to predict the performance of Cathodic Protection systems, associated electric and magnetic signatures, and Degaussing systems. This paper shows a complete Underwater Electric and Magnetic Signature scenario by combining the CRM in the water, the Hull Structure Magnetic Field, and the Magnetic Field from the Earth's Field Effect left over after Degaussing (DG ON), into one comprehensive Underwater Magnetic Signature. New approaches and computational tools, such as boundary elements and optimization techniques, will be used together to generate the complete scenario. In addition, the influence of the signature created by the rotating propeller shaft on the electric and magnetic field and the impact on the surrounding electric and magnetic field will be predicted. The application will also show new tools, which can be used to quickly compute changes in the field and visualize the results.

All of this will be presented with a realistic model of a navy cargo ship that will include sacrificial and impressed current, the real shape propellers, traditionally simulated as discs, and standard requirements for maximum allowance of damaged areas.

1 Introduction

The goal of this paper is to present practical computational modeling methods used to estimate a naval vessel’s Total Underwater Electric and Magnetic (UWEM) signature profile, and provide robust countermeasures system designs to meet UWEM signature goals applied to naval vessels.
This goal will be achieved by presenting methods of modeling each major contributing component of Total UWEM signature, and methods of modeling and designing each countermeasures system. Optimization techniques will also be presented to create a robust countermeasures system designs, specifically the techniques used in ICCP system design for signature management. The results of such an exercise on a large naval surface vessel, specifically a fleet replenishment oiler will be presented.

2 Scope of the Paper

Due to time constraints, this paper will NOT discuss in detail the validations and proofs of concept of using FEM and BEM computer modeling to predict UWEM signatures of naval vessels. Just note here that computational methods discussed in this paper are either directly or indirectly validated to actual ship signatures, Physical Scale Models (PSM), or both, EXCEPT:

1) Modeling and predicting stray fields from internal equipment at reference depth, after shielding effects from the hull and hull structure, using FEM tools, and
2) Modeling the effect of various shaft grounding methods on the Alternating Electric (AE) and Magnetic (AM) fields at reference depth, using BEM tools.

For this presentation we are assuming the value of QUALITY IN = QUALITY OUT. All required data, material properties, and constraints used in the modeling were obtained from a quality source and were suitable for use in this modeling exercise.

3 Total UWEM Signature

Total UWEM Signature is comprised of the Electric and Magnetic Signature Components of the various sources listed below, added together using the principles of superposition and vector addition, when evaluated at a distance far enough away from the hull of the vessel to be considered "far field". There is a "standard" distance that is of interest and use to naval military vessel signature systems design, which is called the "reference depth". This depth is far enough away from the vessel to be considered far field, yet close enough to the hull to be considered a dangerous distance for electrically and magnetically activated and triggered weapons such as mines and torpedoes. The various sources contributing to Total UWEM at reference depth are:

Static Magnetic (SM) Signature due to Earth's Magnetic Field – This SM signature arises from the disturbance of the earth's magnetic field when a vessel with significant ferrous content (ship) is placed in the earth's field. There are two major components to this SM field source:

1) Induced Magnetism from the ferrous content of the ship –based on orientation and location in the earth's magnetic field (ie, latitude, longitude, and heading).
2) Permanent Magnetism of the ship that was created inadvertently during construction of the ship, changed inadvertently during rough traveling and combat operations, and/or changed purposefully during deperming treatments.

Alternating Magnetic (AM) Signature due to Earth's Magnetic Field – This AM signature arises from the disturbance of the earth's magnetic field when a vessel with significant continuous conductive surface areas (ship) is moving in the earth's field in such a way as to change the conductive area perpendicular to the direction of the earth's magnetic field. The change in area perpendicular to the magnetic field creates Eddy Currents in the conductive surfaces, which in turn, create Magnetic Fields much like current through coils. These currents are alternating, creating AM fields. There are two major contributors to this AM field source:

1) The rolling, pitching, and yawing of the ship
2) Orientation and location in the earth's magnetic field (ie, latitude, longitude, and heading).

Static and Alternating Electric and Magnetic (SM, SE, AM and AE) Signature due to Stray Fields – These sources from Stray Fields are propagating sources (not sources that are injecting current into the seawater) that arise from various equipment inside or outside the hull of the vessel

Signatures Due to Galvanic Corrosion and Corrosion Control (CP, ICCP) - – Think of the galvanic process of naval vessel corrosion as a battery effect – the inside of the battery is the dissimilar metals, the ICCP anodes, and the seawater, while the outside of the battery is the propeller shaft and the hull return path to the bare metals and the ICCP anode power supplies. SE, SM, AE and AM signature components arise from the effects of corrosion and corrosion control:

Static Electric (SE) Signature due to Corrosion and CP, ICCP – This SE signature arises from the creation of electric dipoles along the hull of the vessel (bare steel, anodes, and propellers), as well as currents in the seawater from the movement of ions from anodic sources of dissimilar metals (steel in hull and hull appendages) and corrosion control current (ICCP) anodes to cathodic sources of dissimilar metals (NABR and other metals in propellers).

Corrosion Related Magnetic (CRM) SM Signature due to Currents in Seawater- Traditionally, this SM signature component has been labeled CRM. This SM signature arises from the creation of currents in the seawater from the movement of ions from anodic sources of dissimilar metals (steel in hull and hull appendages) and corrosion control current (ICCP) anodes to cathodic sources of dissimilar metals (NABR and other metals in propellers).

Hull Structure Magnetic (MGSTR) Static Magnetic (SM) Signature Due to Currents Returning Through The Hull Structure - This SM signature arises from the return currents in the shaft and hull structure from the propeller to the anodic sources (steel in hull and hull appendages, sacrificial anodes, and/or ICCP power supplies). **MGSTR+CRM=Total CRM SM Signature**

Alternating Electric (AE) Signature Due to the Rotating Shaft – This AE signature arises from the modulating effect of the changing of resistance value between the shaft and the hull structure. This resistance modulation causes modulation of the current in the shaft and modulation of the hull potential (and, consequently, modulation of the Electric Field), and all of these components modulate at the same harmonic frequencies

Alternating Magnetic (AM) Signature Due to the Rotating Shaft – This AM signature arises from the same modulating effect of the changing of resistance value between the shaft and the hull structure, when the shaft is rotating. The resistance modulation causes modulation of the current in the shaft and modulation of the hull potential (and, consequently, modulation of the Magnetic Field), and all of these components modulate at the same harmonic frequencies.

Alternating Electric (AE) Signature Due to the Current Ripple on the Output of the ICCP Power Supply – This AE signature arises from the modulating effect of the output current ripple being injected into the seawater from the ICCP anodes. The current modulation causes a modulating AE signature at the same frequencies as the current ripple, and harmonics.

Alternating Magnetic (AM) Signature Due to the Current Ripple on the Output of the ICCP Power Supply – This AM signature arises from the same modulating effect of the output current ripple being injected into the seawater from the ICCP anodes. The current modulation causes a modulating AM signature at the same frequencies as the current ripple, and harmonics.

4 Countermeasures For Total UWEM Signature

The main purpose for design of all UWEM countermeasures systems is to reduce the magnitude of the signature at some reference depth, change the shape of the signature component to counter any sensor classification algorithms, or eliminate the signature component, if possible. With that in mind, there are 8 major systems/methods that are presently employed for Total UWEM signature countermeasures:

Degaussing (DG) Systems – DG systems are comprised of current carrying DG coils placed within a naval vessel to create SM and AM fields that oppose (and, thus, reduce) SM and AM signatures created by sources that DO NOT inject current into the seawater (radiating sources), such as SM and AM signatures from the Earth’s Magnetic Field, SM and AM signatures from Stray Field sources, and SM signatures from MGSTR fields. Algorithms in the control unit of the DG system (s) adjust the currents injected into the DG coils.

Deperming Treatments – Some navies (like the USN, for example) have facilities available that have the capability to impress a large Alternating Magnetic Field surrounding a vessel, to “magnetically shake” the ferrous content of the vessel, which alters the Permanent Magnetization of the vessel to a predictable and semi-reproduceable state, creating a predictable Permanent SM signature magnitude, shape, and orientation. This allows the DG system designer to design a DG system that can accurately compensate for SM signature due to the predictable Permanent Magnetization in anticipation of a specific deperming treatment. There are various deperming methods and treatment facility capabilities, and some methods and facilities can also significantly reduce the magnitude of the SM signature by significantly reducing the Permanent Magnetization of the vessel.

Impressed Current Cathodic Protection (ICCP) Systems – The main purpose of the ICCP system is decrease the potential of the steel on the entire hull surface to push the polarization of the steel into the cathodic range, and protect the steel from galvanic corrosion. The ICCP system decreases the hull potential through the use of passive (sacrificial anodes) and active (current power supplies and anodes) current sources, “sacrificing” current to the propellers in place of the hull steel ions, while decreasing the potential of the surrounding material. The ICCP system uses reference cells placed along the hull of the vessel to read the potential of the hull, and its control system adjusts the power supply output current to bring the reference cells within their “set point” voltage. Since the SE and SM signatures created from ICCP systems are from current injected into the seawater, the degradation of the signatures over distance is much less than “radiating” (non-injection) sources, and DG systems cannot adequately counter these signatures over varying distances. To minimize these SE and SM signatures, the ICCP system is designed to both minimize the amount of current needed to protect the entire hull and to minimize the magnitude (distance between poles) of the electric dipoles along the hull.

Shaft Grounding Systems- Instead of relying on the high resistance, modulating grounding of shaft currents to the hull via shaft bearings (which also damage the bearings), a separate, “dedicated” shaft grounding device is supplied to minimize the value of the shaft resistance to hull ground, protect the bearings, and minimize or eliminate any modulation of the resistance value. One type of shaft grounding system is Passive Shaft Grounding (PSG), which uses a combination of metal conductive straps (slip rings) with conductive brushes between the shaft and a ground cable connected directly to the hull. Another type of shaft grounding system is Active Shaft Grounding (ASG), which uses slip-ring sensors connected to the shaft to measure the potential difference between the shaft and hull, which in essence senses the variation in current along the shaft, then uses a power supply to draw proportional current through a second slip-ring assembly. This system works as a current bypass for the shaft bearings, and, in essence, acts as a short between ground and hull.

Low Ripple ICCP Power Supplies – ICCP Power Supplies are designed to have very low ripple on their output, to significantly reduce the AE and AM signatures due to ICCP Power Supply output ripple. Note that for the same reason, DG Power Supplies are also designed to have very low ripple on their output.

Electromagnetic (EM) Shielding of Equipment on Vessels – In order to reduce SE, SM, AE and AM signatures from Stray Field Sources in the far field (reference depth), certain equipment on board the vessel may utilize EM shielding to reduce radiation outside the hull.

Use of Low Permeability Materials – To reduce SM and AM fields from the Earth’s Field effect and/or from Stray Field Sources, ship designers may employ low permeability materials in the ship and/or equipment construction. This use of low permeability materials is common in design of minesweepers (GRP, wood or Aluminum hulls) and minesweeping equipment (stainless steel, plastic, etc).

Equipment and Cable Wiring Design to Reduce Radiating EM Fields – To reduce SM, SE, AM and AE fields due to Stray Field sources such as ship wiring and rotating machines, the equipment is designed to counter its own radiating fields (i.e., two rotating sources placed next to each other, but in opposite directions), while the ship’s wiring is run to minimize the area between a hot lead and its return conductor (i.e., twisted pairs, return loops for DC feeds being run in the same wireway as the lead loop).

Placement of Equipment on the Vessel- In order to reduce SE, SM, AE and AM signatures from Stray Field Sources in the far field (reference depth), certain offending equipment on board the vessel may be placed farther up in the vessel (farther from ABL), or into certain locations, to reduce magnitude of signature at reference depth.

4 Ultra EMS’ Computational Modeling Suite For Total UWEM

Ultra EMS is able to model Total UWEM signature and design a Total Suite of Countermeasures Systems via computational methods by using a combination of commercially available SW modules (FEM, BEM and graphing/computation) and an in-house Optimization and Ship/Sub Specific Suite of SW called FEMAP.

These modules are:

1) **Vector Fields OPERA 3D TOSCA, ELEKTRA-SS, and ELEKTRA-TR FEM software –** For the modeling of SM and AM signatures due to radiating sources (not injected into seawater) EXCEPT MGSTR. The VF suite is also used in the design of the following countermeasures: DG systems, adding the signature effects of Deperming Treatments, EM shielding, use of Low Permeability materials, equipment design, and power wiring design.
2) **C M BEASY CP Solver, CRM Solver, Polarization Database, Structure Magnetic Field, CP Optimization, BEASY GID, Contour Viewer, Characterization Tool, and Dipole Estimation Tool BEM software –** For the modeling of SE, SM, AE and AM signatures due to Corrosion, CP and ICCP systems, Shaft Grounding, and ICCP Ripple. The BEASY suite is also used in the Design of the following countermeasures: CP and ICCP systems, PSG and ASG systems, and ICCP Power Supplies' Ripple Specifications.
3) **Microsoft EXCEL –** Used for databasing, compiling, adding and presenting Total UWEM signature data, as well as the countermeasures system designs and their effect on signatures. Provides data in a format that can easily be read, converted, and displayed by anyone working with or receiving the UWEM signature data or countermeasures systems specifications.
4) **ULTRA FEMAP Optimize, Convert, Modify, Combine, DG System Database, Polarization Database, and Ship/Equipment Signatures Database for Ship/Submarine Specific DG System Design and Optimization, and Total UWEM Signature Calculation -** Developed as plug-ins to the third party software to make ship/sub specific modelling tasks, as well as algorithms to allow for DG system design optimization, automated as push button tasks, allowing for up to 90% reduction of modelling time and flexibility of handling design changes and reporting the Total UWEM signature effects**.** Ultra Experience in Modelling and Ranging is utilized as databases for future modelling tasks, allowing for a high level of confidence in the model results.

5 Total UWEM Prediction and Design of Countermeasures

In an ideal situation, it is clear that the combined use of Physical Scale Modeling (PSM), Measured Properties of Material to be used in ship construction, Measured Signatures of Equipment to be used on the ship, Range Data of similar ship classes, and Computational Modeling is the perfect scenario to provide extremely accurate predictions of Total UWEM signatures for a specific ship design, and to provide extremely efficient and effective Countermeasures Systems Designs. The signature data and actual material properties measurements increase the accuracy and quality of the predicted signatures (QUALITY IN = QUALITY OUT).

In a well-funded, long-term, ship signatures design project (1 or more years), particularly for a brand-new ship class that is very different from existing classes of ships, or for a very low or very new level of signature control and limits, the following method is employed to predict Total UWEM signature and design countermeasures:

1) Use Computational Modeling to create Baseline FEM/BEM Models of the ship, and Baseline DG/ICCP/SG and other countermeasures system designs, and determine signature levels that can be met economically (cost, weight, risk, etc). Use the data collected from equipment measurements, materials measurements, and range data of similar ship classes as inputs.
2) Create PSM models of the ship and baseline countermeasures systems, based on the results of the Item 1 exercise, and verify similar results (or use the results as feedback to improving the BEM and FEM models).
3) "Calibrate" the Computational Models based on the results of Item 2, and use Computational modeling to rapidly model and handle all changes imposed during the design phase of the ship. Also, use Computational Modeling to simulate many various

environmental scenarios, including worldwide operation in many different seawater, depth, and sea state conditions, as well as paint damage scenarios.

4) Towards the end of the Design Phase, when most changes are incorporated into the ship and the countermeasures systems, update the PSM models to reflect all of the changes and verify the results of the Computational Modeling performed in Item 3. Use the PSM results as feedback to "calibrate" the Computational Models again.
5) Use the "calibrated" computational models to rapidly support evaluation of all changes made to the ship and/or systems during the construction phase
6) Use ship ranging and calibration for final validation of the effort.

More often than not, funding and time is not available for PSM and, usually, for equipment and materials measurements. Consequently, the demand is high for the ability to create accurate, robust Total UWEM signature analyses and countermeasures designs without the need to create PSM models and collect specific equipment range data. The expected result is the ability to provide reasonably accurate, robust, and practical countermeasures designs (via a combination of Computational Modeling and existing data on similar ship classes, equipment, and materials) that can be guaranteed to meet the Total UWEM signature requirements applied to the ship being built, without gross over-designing and over-compensating for inaccuracies.

In fact, for most of the world's navies, this is the situation when predicting and designing for changes to existing ship classes, for feasibility studies of new ship classes, for new ship system technical proposals and quotes, and for new ship preliminary designs.

The tools and methods of Computational Modeling used by Ultra EMS enables it to provide the desirable level of accurate, robust, and practical countermeasures designs, whose performance can be guaranteed, in a very fast amount of time (weeks), for low cost. The Computational Modeling enables fast turn-around for proposals, quotes, feasibility studies, and preliminary design efforts, as well as even faster turnaround (days) to support changes during design and construction phases. The low cost of the Computational Modeling provides the design and construction change support as part of a countermeasure system equipment offering, enabling complete "turnkey" support of our manufactured countermeasures systems. The increased accuracy gained by using this approach to Computational Modeling enables competitive bidding for turnkey countermeasures systems, by minimizing over-design and over-compensation.

6 Computational Modeling for UWEM Signature of a Fleet Replenishment Oiler

The following is an outline of specific Computational Modeling Methods used in predicting the Total UWEM Signature of a fleet replenishment oiler, and in designing the countermeasures to be deployed on the oiler to manage the Total UWEM signature.

Collection of Ship Data- The Oiler is the first of a new ship class, but is designed based on a revised version of an earlier class of oilers (Figure 1).

Figure 1 Similar Class Of Fleet Oiler

The ship's specifications, ship's preliminary drawings, types of materials used in the hull structure and superstructure, major equipment to be installed, propulsion, typical cargo, and general arrangement (GA) were provided. As a summary, the ship dimensions are: Ship length LOA : 174 m, Ship length at waterline: 162 m, Maximum draft: 8 m, Beam: 23 m, Empty Displacement: 25,000 MT, 1 NABR Propeller with 4 blades, 1 NABR Bow Thruster with multiple (>6) blades, 1 rudder, constructed of mostly Mild Steel with some areas being high strength AH36 steel. Major Equipment and Propulsion Units are similar or the same as those used in similar ship classes, and the GA is similar to other classes. The ship will NOT be depermed in any way. The ship will be constructed in modules that are worked in many various orientations, including upside down, until the modules are combined on the drydock that is facing in a North Direction in a Western European shipyard. The signature requirements that apply to this ship consider the replenishment missions of this vessel, and are applicable to ships used in support roles. The exercise is for the creation of preliminary designs to be used for quotation and specification writing purposes. The total lead time for the exercise is 10-12 weeks.

Based on the above, the following design constraints for the exercise can be determined:

1) The use of range data from similar ship classes will provide an accurate estimate of expected range data for this ship class, due to the similarity of this ship design to previously-ranged ships.
2) The fact that the major equipment is similar to existing ships, and the GA is similar, the levels of signature due to Stray Fields can be accurately estimated without the need for detailed computer modeling of the Stray Fields.
3) The signature limits specified require the prediction of Total UWEM signatures that include Earth's Field Effects, Eddy Currents from Rolling and Pitching, SE SM AE and AM signatures from corrosion and ICCP systems, Shaft Grounding Effects, Stray Fields and ICCP Ripple.
4) However, the required signature limits are sufficiently relaxed to allow for less-complicated, lower cost countermeasures designs that can still meet the requirements.
5) The countermeasures designs must be cost-competitive and low weight, to be considered as a viable option for this ship.

Modeling of Induced SM Signatures due to Earth's Field – Using the FEMAP materials database for permeability estimates, EMS uses the VF modules to create a FEM models of the entire ship and large ferrous equipment, and apply magnetic properties (permeability) to ferrous volumes. Earth's Magnetic Field is applied to the models as external boundary conditions (Hext). EMS uses the principle of superposition to break up earth's magnetic field into x, y and z components, to solve for IVM, ILM and IAM models at a baseline geographic location. FEMAP Modify and Optimize Modules are used to quickly scale the FEM models to compute IVM, ILM, and IAM at selected worldwide locations (Bangkok, Hudson Bay, South Australia, Persian Gulf, Malacca Straits, Straits of Gibraltar, the probable range location). Using EMS-developed techniques and FEM tools provided in VF (general) and FEMAP Modify (ship-specific), the FEM models are simplified to speed the modeling tasks, while keeping the same level of accuracy found in a more detailed FEM model. Results are displayed in the VF OPERA 3D Post-Processer GUI.

Modeling of Permanent SM Signatures due to Earth's Field – Using the range data database, along with the knowledge of the effect of the construction techniques and orientations on the level of permanent magnetization created in the ship structure (and the fact that the ship will NOT be depermed), EMS determines the amount of PVM, PLM, and PAM as a scale value of the IVM, ILM and IAM, and orientates it for the PVM and PLM applied in the NORTH direction, while the PAM is applied in the WEST direction. If the ship was to be depermed, signature data taken from ships of a similar class that was depermed at the same facility and with the same deperming method would be used as the PVM, PLM, and PAM signatures for this ship. Results are displayed in the VF OPERA 3D Post-Processer GUI.

Modeling of Induced AM Signatures due to Rolling and Pitching in Earth's Field – Using the FEMAP materials database for conductivity estimates, the VF modules are used to create FEM models of the entire ship and large conductive areas, and apply conductive and magnetic (permeability) properties to metallic and ferrous volumes. Again, the principles of superposition break up earth's field effects, and applies a changing (sinusoidal) earth's field are used to simulate the changing (sinusoidal) position of the ship relative to the earth's field. In a way, it is rolling and pitching the earth's magnetic field, instead of rolling and pitching the ship in the field. Amplitude and frequency of the varying earth's magnetic field in the models are determined by roll and pitch angle and frequency of the ship case being modeled. Using a specific method of superposition and modeling in VF ELEKTRA SS, EMS is then able to create data that can be used in FEMAP Modify and Optimize to be added directly to the IVM, ILM, and IAM signature data created for the static induced signatures for a baseline geographic location. The Modify and Optimize Modules are then used to quickly scale the FEM models to compute the combined Eddy Current plus IVM, ILM, and IAM at selected worldwide locations (Bangkok, Hudson Bay, South Australia, Persian Gulf, Malacca Straits, Straits of Gibraltar, the probable range location). This specific method developed by Ultra for using ELEKTRA SS FEM models reduces the modeling time by more than 75% compared to that of the method that uses ELEKTRA TR. Results are displayed in the VF OPERA 3D Post-Processer GUI. Microsoft EXCEL is used to display the signatures as histograms and lines along the length of the ship at reference depth.

Modeling of SE, SM, AE and AM Signatures due to Stray Fields- In this case, the expected stray fields signatures will closely resemble existing data of similar ship classes, and will be a small portion of the Total UWEM signature, based on the ship construction, dimensions, and signature requirements. An estimated Stray Field signature is taken directly from the FEMAP range database and used for this vessel. Otherwise, the computational modeling method used would be to create detailed FEM models in VF of each piece of equipment and the surrounding ferrous and metallic hull structure, decks and bulkheads, and use the VF models to predict the signature of each piece of equipment at reference depth. Results are displayed in the VF OPERA 3D Post-Processer GUI. Microsoft EXCEL is used to display the signatures as histograms and lines along the length of the ship at reference depth.

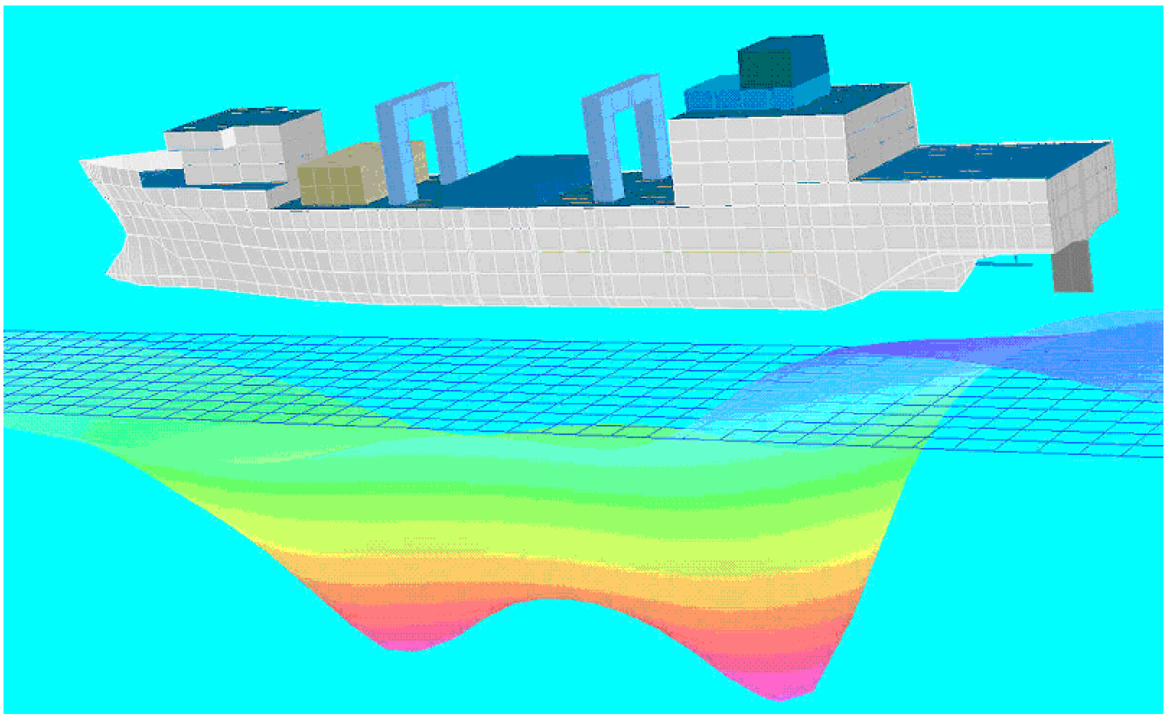

Figure 2 FEM Model Of The Fleet Oiler With The Uncompensated Magnetic Signature At Reference Depth Shown As A 3D Map

Design of a DG System Using Computational Modeling – Based on the results of all the SM and AM signature modeling performed above, and the requirements and restrictions placed on the ship relating to signature limits, cost, weight, footprint, and architecture, EMS uses its Optimize and Modify modules, as well as its DG Power Supply and Cabling Database, to integrate with the VF OPERA modules to design and model the signature effects of a DG system that reduces and modifies the SM and AM signatures due to the above sources below a set of target limits. FEMAP optimizes several system parameters: signature magnitude, signature peaks, signature gradient, DG system weight, power, footprint, complexity, survivability, and cost. FEMAP produces optimization results and DG design parameters in reports that are easily converted to WORD and EXCEL files via the FEMAP Convert Module. Microsoft EXCEL is used to display the signatures as histograms and lines along the length of the ship at reference depth, and used to create tables of DG system design parameters, for use in reports and proposals. In the case of the requirements applying to this oiler, the DG system was designed to reduce the magnetic signature to a level below the signature limits, to allow for a certain level of magnetic signature contribution from the ICCP system. This DG system was designed to allow for a maximum magnetic signature from the ICCP system of 75 nT.

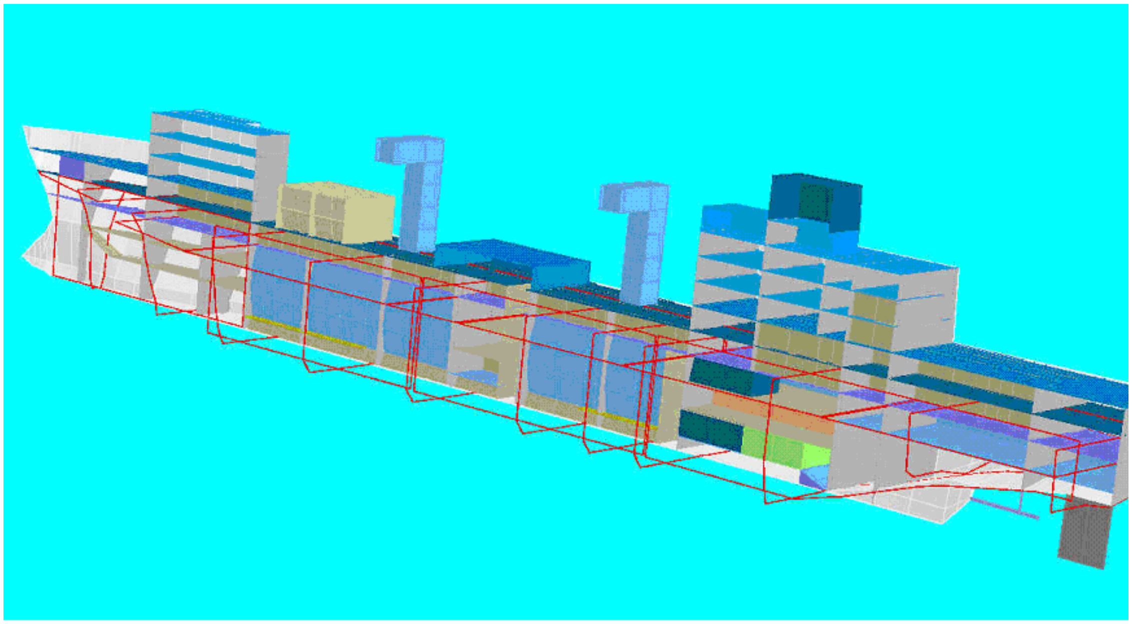

Figure 3 FEM Half-Model Of The Fleet Oiler With MAL DG Coil Runs Shown In Red

PROPOSED DG SYSTEM DESIGN

As a result of the above, a Proposed DG System Design was developed. The design consisted of an MAL Advanced Degaussing (ADG) system, utilizing 7 M coils, 4 A coils (1 forward A coil and 3 pairs of A coils), and 11 L coils), bulkhead mounted, high voltage, individual coil BPAUs (12 KW, +/-30A, 400VDC), and a computer and algorithm-controlled Control System (DCU), creating a minimal-cost, low-footprint, low-weight DG system, with a total DG cable weight of 19 Metric Tons.

Modeling of SE and SM Signatures due to Corrosion- Using a combination of the FEMAP materials database and BEASY Polarization Database, Polarization Curves are determined for the exposed metals, and EMS uses the BEASY user interface, CP Solver, and CRM Solver modules to create BEM models for three paint damage scenarios: 5%, 10% and 17% paint loss. The BEASY Hull Structure Magnetic Field module is used to solve for the MGSTR components of the SM signatures. Results are displayed in the BEASY Contour Viewer Module and in the UI Module. Microsoft EXCEL is used to display the signatures as histograms and lines along the length of the ship at reference depth, to convert all data to the same units, and to calculate Electric Field signature in units of microV/m.

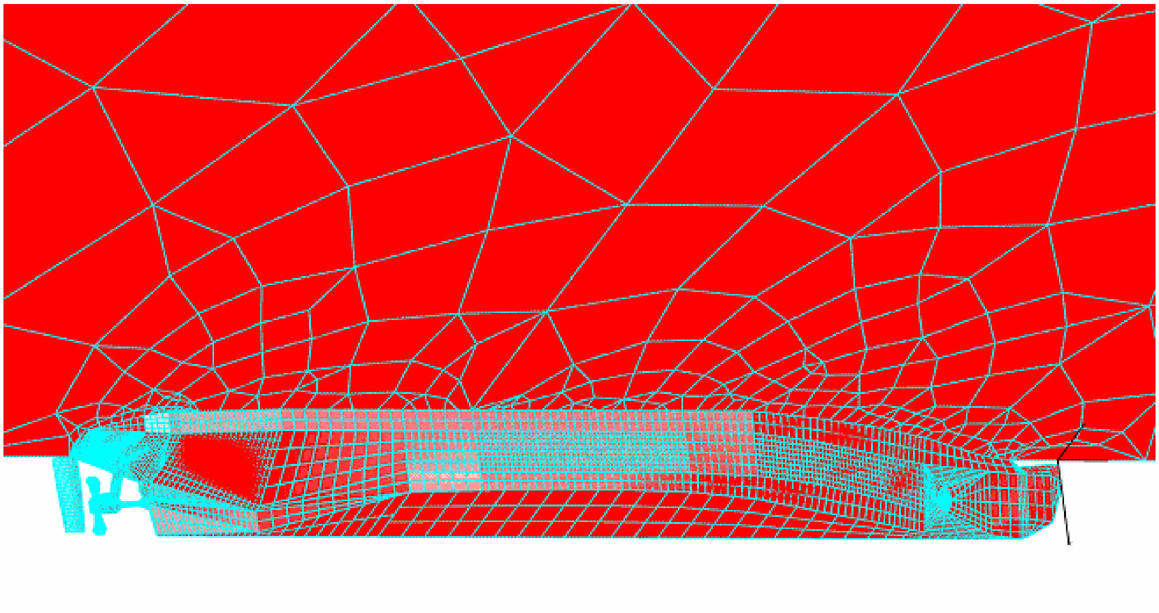

Figure 4 BEM Half-Model Of Fleet Oiler With Sea Surface And Propellers Modeled

Design of an ICCP System Using Computational Modeling – Based on the results of all of the SE and SM signature modeling due to corrosion performed above, and the requirements and restrictions placed on the ICCP design for the ship relating to signature limits, cost, weight, footprint, and architecture, EMS uses the BEASY CP Optimization Module and its FEMAP ICCP Power Supply Database, to design and model an ICCP system that fully protects the entire hull from corrosion, while minimizing the SE and SM signatures created by the ICCP system to a level below a set of target limits. The CP Optimization Module optimizes several system parameters: signature magnitude, signature peaks, protection voltage, and output current. The CP Optimization Module optimizes these parameters by adjusting the output current of each anode, and/or the location of each anode on the hull. The CP Optimization produces optimization results and DG design parameters in reports that are easily converted to WORD and automatically displayed via macros in EXCEL files. Microsoft EXCEL is used to display the optimized signatures as histograms and lines along the length of the ship at reference depth, and used to create tables of ICCP system design parameters, for use in reports and proposals.

FEMAP and its built-in computer modeling and optimization tools is used to design the ICCP system for the AOR. The first design steps are to determine the minimum number of anodes needed, the minimum current output of each anode, and the specific location of each anode on the hull. By determining the above as minimums, the signature of the ICCP system is minimized as well. The optimization tools provide algorithms for minimizing anode currents to achieve protection goals, while minimizing signatures. The optimization tools also provide algorithms for determining ideal anode locations to achieve protection goals, while minimizing signatures. The method followed for the oiler design was:

1) Add zinc anodes to the rudder, propeller shaft, aft stern area above the propellers, the bowthruster tunnel and the ballast tanks, as specified by the ship builder. Run an optimization exercise at maximum (17%) damage to determine an acceptable area of coverage for the zinc anodes, and record hull potential distribution and signature levels. Use this zinc model as a baseline for the ICCP system design models.

2) Try a basic one-zone, 6 anode ICCP system design (current, location of anodes and reference cells) that is used on existing fleet replenishment oilers that are similar in size, displacement, and draft of the ship at the maximum (17%) damage scenario. While the

existing design provided enough current to protect the entire ship hull at the three damage scenarios, the signatures exceeded the limits stated above by a large amount. This system was quickly ruled out as a possible signature design going forward.

3) Choose the number of anodes, and arbitrary locations for each anode, based on good engineering judgment combined with EMS experience on ICCP anode placement. Run a CURRENT optimization exercise at maximum (17%) damage, minimizing the current output of the system to minimize the signatures, while protecting the entire hull.

4) Using the output and models created from 3 above, run an ANODE PLACEMENT optimization exercise at maximum (17%) damage, while simultaneously minimizing the current output of the system to minimize the signatures, and protecting the entire hull.

   At first, a 10 anode, 5 zone (10 reference cells) ICCP system employing 5 power supplies was analyzed through steps 3 and 4, with acceptable results. The final optimized signatures met the limits stated above. However, a re-running of steps 3 and 4 were performed with an 8 anode, 4 zone (8 reference cells) ICCP system employing 4 power supplies, with acceptable results as well. A 6 anode, 3 zone (3 power supplies) system was attempted, but with UNACCEPTABLE signature results.

   It was clear that the 8 anode (4 anodes on each side of the hull), 4 zone (4 reference cells on each side of the hull) ICCP system employing 4 power supplies would be the least costly design that would meet all requirements.

5) Continuing with the 8 anode, 4 zone system, CURRENT optimization exercises were run at 10% and 5% damage scenarios, minimizing the current output of the system to minimize the signatures, while protecting the entire hull. The final optimized signatures met the limits stated above.

6) Using the three optimized solutions for the three damage scenarios for the 8 anode, 4 zone system, candidate reference cell locations were determined by reviewing the hull potential data for hull locations for each zone that experienced the same potential value for every damage scenario, at optimized current values. 4 ideal locations were found and selected. The Set point for each reference cell was selected as the potential value that was achieved in all three damage scenarios.

7) To verify that a PID controller algorithm using set points as the control input for each reference cell would be suitable for the controller SW of the proposed ICCP system, three more exercises were run:

8) From the optimized current settings of the 5% damage scenario, the damage was changed to 10%, and an optimization routine, using set points of the potential values for the reference cells as the goal, was run. The output currents adjusted to values similar to the 10% optimization run earlier (see Item 5 above), and the final optimized signatures met the limits stated above.

9) From the optimized current settings of the 10% damage scenario from 8 above, the damage was changed to 17%, and an optimization routine, using set points of the potential values for the reference cells as the goal, was run. The output currents adjusted to values similar to the 17% optimization run earlier (see Item 4 above), and the final optimized signatures met the limits stated above.

10) From the optimized current settings of the 17% damage scenario from 8 above, the damage was changed back to 5% (representing a maintenance cycle), and an optimization routine, using set points of the potential values for the reference cells as the goal, was run. The

output currents adjusted to values similar to the 5% optimization run earlier (see Item 5 above), and the final optimized signatures met the limits stated above.

It is interesting to note that the highest magnitude (worst-case) Total CRM signatures were observed for the 10% paint damage scenario of the fleet oiler. This was due to the fact that the anode locations were optimized for the 17% damage scenario, and are not perfectly optimized locations for the 10% damage scenario, although the signatures for all damage scenarios are well within desired limits. The highest SE signature magnitudes were observed for the 17% damage scenario, as expected with higher anode outputs.

PROPOSED ICCP SYSTEM DESIGN

As a result of steps 1-10 above, a Proposed ICCP System Design was developed. The following table 1 summarizes the Specifications of the Proposed ICCP System Design:

TANKER PROPOSED ICCP SYSTEM SPECIFICATIONS				
ANODE NUMBER AND LOCATION	X (m), FR#	Y (m)	Z (m)	MAX CURRENT, A
ANODE 1&5, BOW SECTION FOREWARD FROM THRUSTER	-15.72, 205	+1.79, -1.79	3.57 ABL	50 A EACH
ANODE 2&6, MID SECTION CLOSEST TO ANODE 1	-56.5, 150.5	+10.39, -10.39	3.57 ABL	50 A EACH
ANODE 3&7, MID SECTION CLOSEST TO ANODE 4	-105.3, 85.5	+11.25, -11.25	3.57 ABL	50 A EACH
ANODE 4&8, AFT SECTION NEAR STERN	-157.3, 16.5	+3.29, -3.29	2.56 ABL	100 A EACH
REFERENCE CELL NUMBER AND LOCATION	X (m), FR#	Y (m)	Z (m)	SET POINT , V
REF CELL 1&5, BOW SECTION FOREWARD FROM THRUSTER	-9.13, 214	+1.55, -1.55	5.21 ABL	-1.06 TO -1.08
REF CELL 2&6, MID SECTION CLOSEST TO ANODE 1	-63.2, 142	+10.83, -10.83	2.27 ABL	-1.105 TO -1.125
REF CELL 3&7, MID SECTION CLOSEST TO ANODE 4	-113.1, 75.5	+10.89, -10.89	2.44 ABL	-1.105 TO -1.125
REF CELL 4&8, AFT SECTION NEAR STERN	-149.2, 32.5	+8.37, -8.37	5.28 ABL	-1.145 TO -1.165
NOTE: Reference Cells Nos. 5 thru 8 are back ups for 1 thru 4				
ICCP POWER SUPPLIES SPECIFICATIONS				
NUMBER OF POWER SUPPLIES	4			
CURRENT RANGE OF POWER SUPPLIES FOR ANODES 1&5	0-100 A			
CURRENT RANGE OF POWER SUPPLIES FOR ANODES 2&6	0-100 A			
CURRENT RANGE OF POWER SUPPLIES FOR ANODES 3&7	0-100 A			
CURRENT RANGE OF POWER SUPPLIES FOR ANODES 4&8	0-200 A			
OUTPUT CURRENT RIPPLE, %	0.2% OR LESS			
ICCP CONTROLLER SPECIFICATIONS				
NUMBER OF CONTROLLERS, HW	1-4			
CONTROLLER SW ALGORITHM	PID	SET	POINT	IS VOLTAGE
NUMBER OF CONTROLLER ZONES	4			
NUMBER OF CONTROLLER INSTANCES	4			
NOTE: Each Instance Controls one pair of anodes (1 psu) by voltage set point				
via one pair of reference cells				
SACRIFICIAL ANODES	SURFACE AREA sq-m			
RUDDER, STERN AND PROP SHAFT - ZINC (MIL-A-18001-H)	7.0			
THRUSTER TUNNEL AND SEA CHESTS - ZINC (MIL-A-18001-H)	per manufacturer's recommendations			
Ballast tanks, sludge tanks and contaminated water tanks by oil - Aluminum Alloy	per manufacturer's recommendations			

Table 1 Proposed ICCP System Specifications

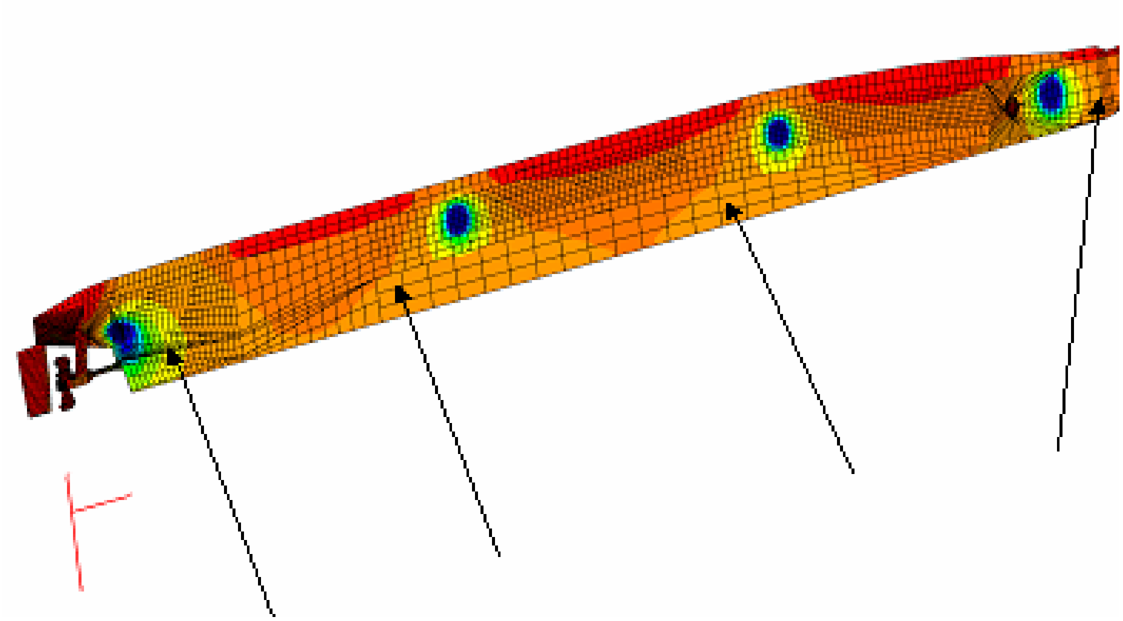

Figure 5 BEM Half-Model Of Fleet Oiler With Hull Potential Distribution (17% Damage), Anodes, And Reference Cell Locations (Arrows) Shown

Modeling of AE and AM Signatures due to Shaft Rotation- Using typical resistance readings for ungrounded (NO ground) shaft to hull readings via the bearings, it was determined that the resistance from shaft to ground in an ungrounded scenario will modulate from almost zero to as much as 500 Kohms. The shaft-to-ground resistance, which is modeled immediately after the cathodic propellers in the "battery" circuit, can be treated as just a linear resistance added to the non-linear Polarization properties of the NABR propellers in the stern of the ship. To model shaft-to-ground resistance in the BEASY BEM modules of FEMAP, the linear shaft resistance was added to the Polarization Curve of the NABR propellers, to a new Polarization Curve for use in modeling shaft resistance of 500K ohms. Since the "normal" Polarization Curve for the NABR does not take into account any shaft resistance, the BEM models already run and reported in the modeling of the SE and SM signatures above cover the signatures when the shaft-to-ground resistance is near zero. The resulting two "snapshots" represent the two peaks in the range of signature values that the AE and AM signatures modulate between. The frequency of the modulation will be factors of the shaft rotation rate. The BEASY UI, CP Solver, and CRM Solver modules were used to create BEM models for the 500k shaft resistance at the various damage scenarios. The BEASY Hull Structure Magnetic Field module is used to solve for the MGSTR components of the 500K signatures. Results are displayed in the BEASY Contour Viewer Module and in the UI Module. Microsoft EXCEL is used to display the signatures as histograms and lines along the length of the ship at reference depth, to convert all data to the same units, to calculate Electric Field signature in units of microV/m, and to compare the magnitude of the signatures at resistance=0 ohms and resistance=500 Kohms. Results of modeling the 500 Kohm shaft-to-ground resistance showed a peak magnitude of the modulating AM signature of 14 nT, which was witnessed at the 17% damage scenario (the most shaft current). The frequencies would be the shaft rotation frequencies and their harmonics. That type of signature was large enough that it could be used as control discriminators in mines, torpedoes, and other weapons with Alternating Magnetic (AM) Field sensors. The same results were determined for the magnitude of the AE signature for the NO shaft grounding scenario.

Design of a Shaft Grounding System Using Computational Modeling – Based on the results of modeling the AE and AM signature magnitudes when NO shaft grounding system is used, it was determined that some sort of shaft grounding system was needed, not only to protect the bearings from damage, but to reduce the magnitude of the AE and AM signatures to an acceptable level. The same BEASY SW modules were used, and the same method of adding the linear shaft ground resistance value for the shaft grounding method being modeled to the Polarization data of the NABR propellers, to determine the magnitude of the AM and AE signatures due to the rotating shaft, when both a PSG and an ASG system was deployed on the oiler.

Using typical resistance readings for Passive Shaft Grounding Systems (PSG) shaft-to-hull readings via the bearings, it was determined that the resistance from shaft to ground in a PSG scenario will modulate from almost zero to as much as 0.001 ohms, when the PSG system is aggressively maintained. However, typical readings of shaft-to-ground resistance on ships employing PSG systems ranged up to 0.05 ohms, when maintained only per the maximum recommended interval. Poorly maintained systems ranged up to the 500 Kohm value. It was determined that the PSG system, when the shaft-to-ground resistance was maintained to be 0.001 ohms, was acceptable for use with the oiler ICCP system, since the magnitudes of the AE and AM signature peaks were very small. However, when the shaft-to-ground resistance reached values of 0.05 ohms or higher, the magnitudes of the AE and AM signatures were determined to be large enough that it could be used as control discriminators in mines, torpedoes, and other weapons with AM or AE Field sensors.

Using typical resistance readings for Active Shaft Grounding Systems (ASG) shaft-to-hull readings via the bearings, it was determined that the resistance from shaft to ground in a ASG scenario will modulate from almost zero to as much as 0.001 ohms maximum. Typical values were lower. It was determined that the ASG system, when the shaft-to-ground resistance was maintained to be 0.001 ohms or less, was acceptable for use with the oiler ICCP system, since the magnitudes of the AE and AM signature peaks were very small. Furthermore, the ASG system automatically adjusts itself and requires much less maintenance than a PSG system.

PROPOSED SHAFT GROUNDING SYSTEM DESIGN

As a result of the above, the Proposed Shaft Grounding Design was developed: While PSG that is aggressively maintained to keep the shaft-to-ground resistance while rotating to a value of 0.001 ohms or less is acceptable, the recommended SG system for the oiler is an ASG system, which will automatically adjust to keep the shaft-to-ground resistance while rotating to a value of 0.001 ohms or less, with dramatically less maintenance.

Modeling of AE and AM Signatures due to ICCP Ripple- Using the BEM modules and the ICCP Power Supply Database, BEM models were created to record the magnitude of the AE and AM signatures created by the ripple of the output current form typical ICCP power supplies. From the database, it was determined that typical ICCP power supplies are designed for very low ripple, with ripple values at 0.2 % or lower. Since the largest modulating effect would be recorded at the largest current output, two more BEM models were created at the the 17% paint damage scenario: one with 0.2% higher current output, and one with 0.2% lower current output. The magnitude of the difference between the two models is the magnitude of the AE and AM fields. The resulting magnitudes of the AE and AM fields were considered acceptably low for this ship design. The design requirement of ICCP power supplies with maximum 0.2% ripple was applied to this ship.

7 Total Un-Compensated and Compensated UWEM Signatures for the Fleet Replenishment Oiler

Using the FEMAP Convert Module, all signatures created in the VF FEM modules and in the FEMAP Optimize and Range Database Modules, which includes worldwide values of combined SM and AM magnitudes for both Un-Compensated (DG OFF) and Compensated (DG ON), are converted into csv format for export into Excel, using comma delimiting.

All signatures created in the BEM modules, including all paint damage scenarios of SM and AM signatures for both Un-Compensated (ICCP and SG OFF) and Compensated (ICCP and SG ON), were exported into Excel. This data was then combined with the magnetic signatures for all paint damage scenarios, worldwide locations, all headings, and the ICCP and ASG system ON. The magnetic signatures are combined with the DG OFF signatures to create two UNCOMPENSATED signature graphs: UNCOMPENSATED IN PHASE and UNCOMPENSATED OUT OF PHASE for worldwide locations. The IN PHASE signature is assuming the positive addition of all AM signature peaks with the SM signatures. The OUT OF PHASE signature is assuming the negative addition of all AM signature peaks with the SM signatures. The difference between these two sets of signatures represent the worst case magnitude of the AM signature, while each separately give snapshots of the most extreme values of the SM signature at a moment in time.

Similarly, once all of the signatures for all paint damage scenarios, worldwide locations, all headings, and the ICCP and ASG system ON are loaded into EXCEL, the magnetic signatures are combined with the DG ON signatures to create two COMPENSATED signature graphs: COMPENSATED IN PHASE and COMPENSATED OUT OF PHASE for worldwide locations. The IN PHASE signature is assuming the positive addition of all AM signature peaks with the SM signatures. The OUT OF PHASE signature is assuming the negative addition of all AM signature peaks with the SM signatures. The difference between these two sets of signatures represent the worst case magnitude of the AM signature, while each separately give snapshots of the most extreme values of the SM signature at a moment in time. These signatures are referred to as the Total Underwater Magnetic (UM) signatures.

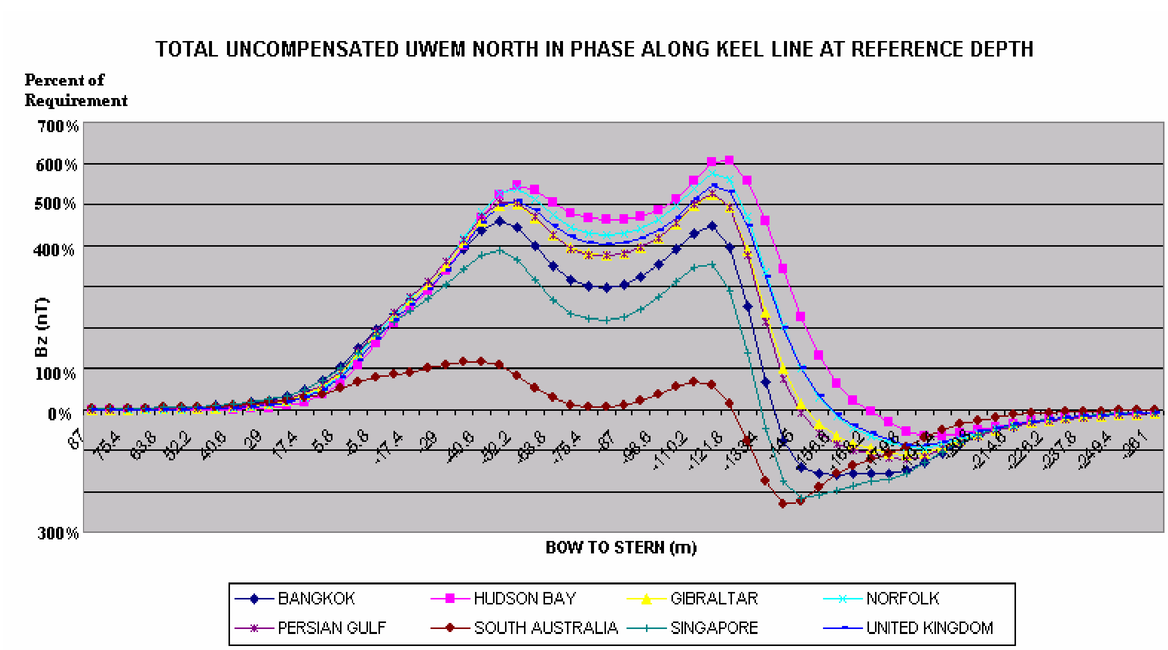

Figure 6 Total Uncompensated In-Phase UM Signature Along Keel Line, For Various Worldwide Locations, North Heading

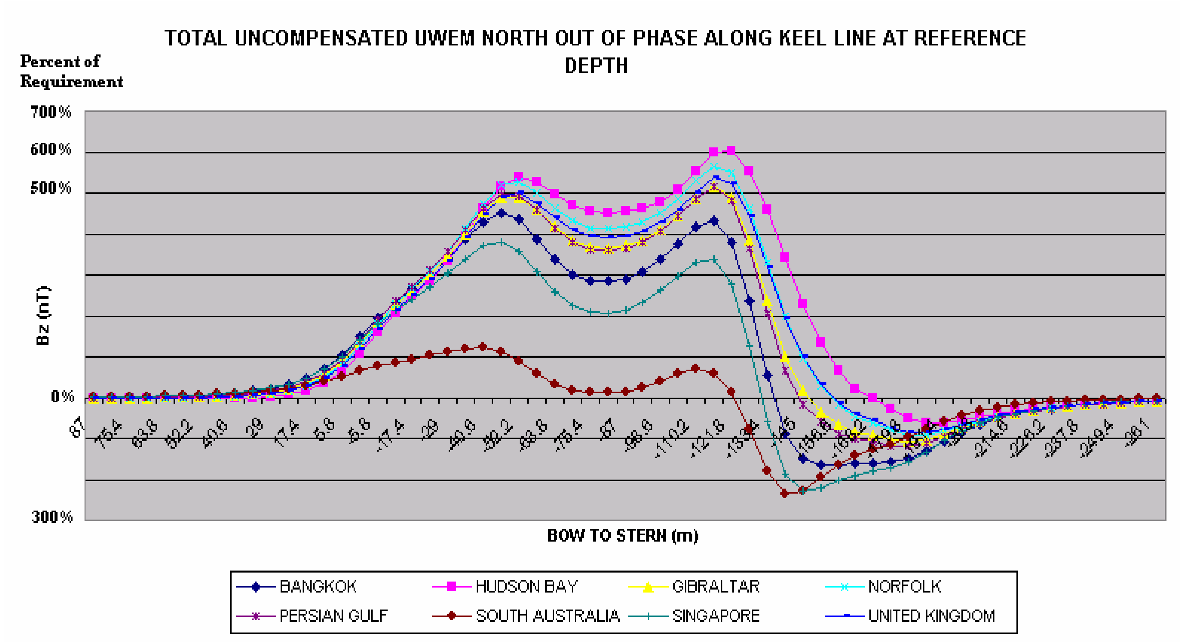

Figure 7 Total Uncompensated Out-Of-Phase UM Signature Along Keel Line, For Various Worldwide Locations, North Heading

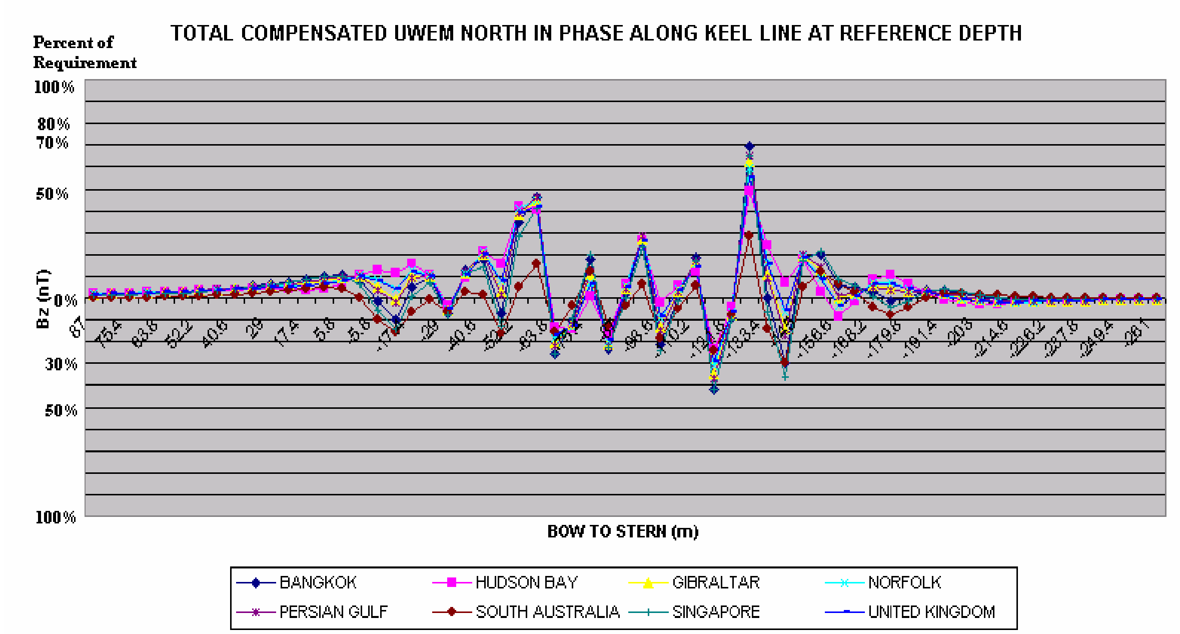

Figure 8 Total Compensated In-Phase UM Signature Along Keel Line, For Various Worldwide Locations, North Heading

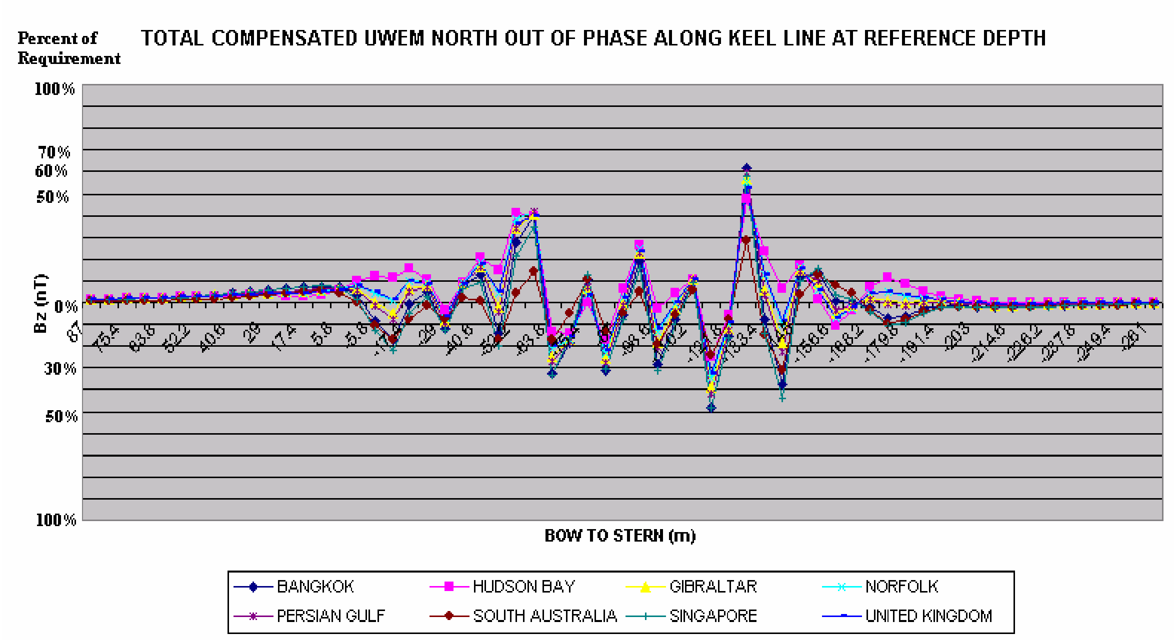

Figure 9 Total Compensated Out-Of-Phase UM Signature Along Keel Line, For Various Worldwide Locations, North Heading

Note that the difference at the keel line magnetic signatures between the IN and OUT of Phase signatures are small when the vessel is in a North or South heading. The magnitude of the total UWEM signature is much larger directly under the keel line in a North-South heading. The differences between IN and OUT-OF-PHASE are greater when the signatures are measured athwartships from the keel line.

When the ship is in a predominantly East-West Heading, there are two effects on the magnetic signature at reference depth: the larger magnitude of the COMPENSATED signature is recorded off of the keel line (in this case, at 4.6 meters to the starboard of the keel line, y=4.6 m), and the change in the signature magnitude between IN and OUT-OF-PHASE is much larger. The following Graphs show this effect on the fleet oiler signatures on a WEST heading in the Straits of Gibraltar.

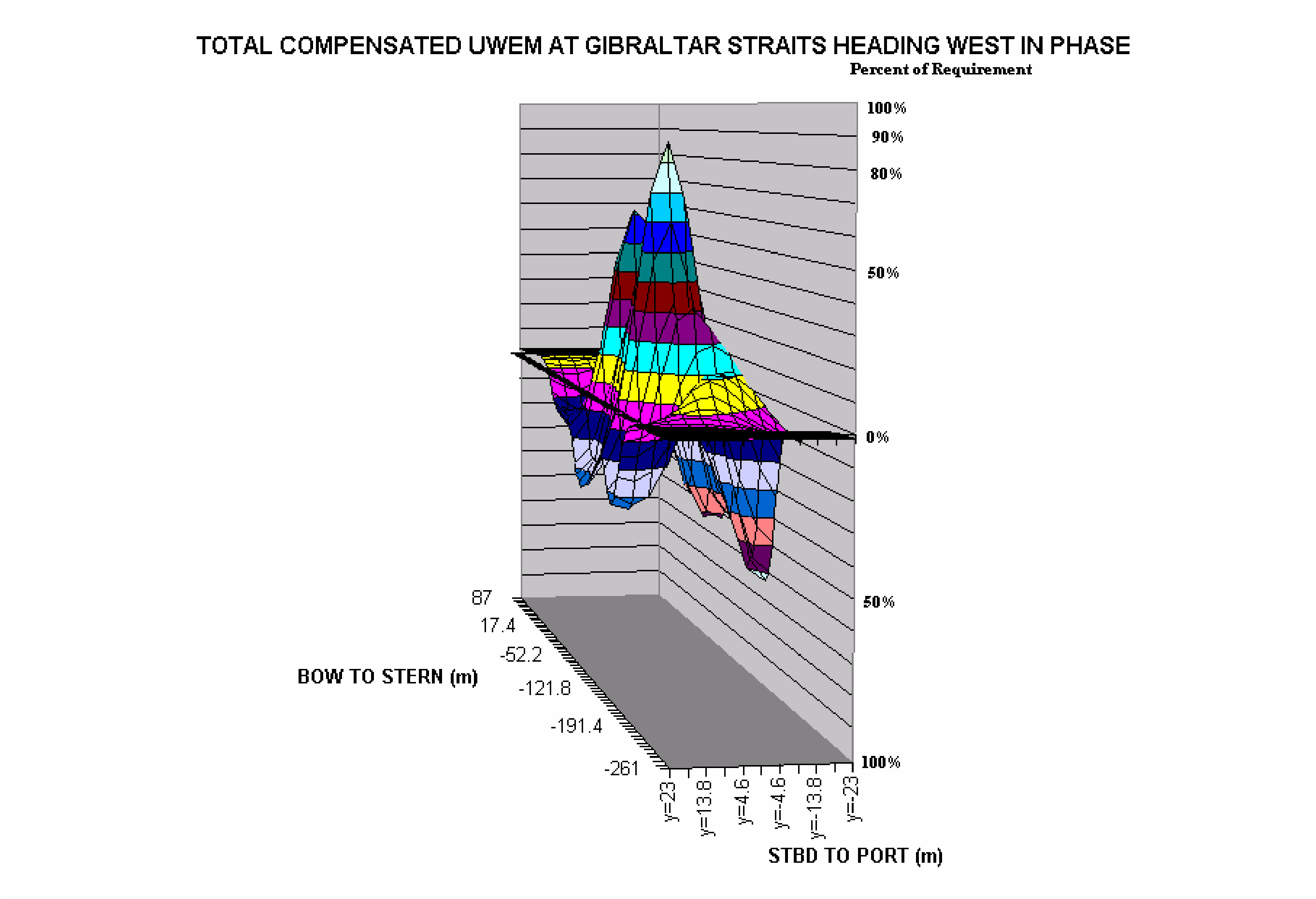

Figure 10 Total Compensated In-Phase UM Signature At Gibraltar, West Heading, At Reference Depth

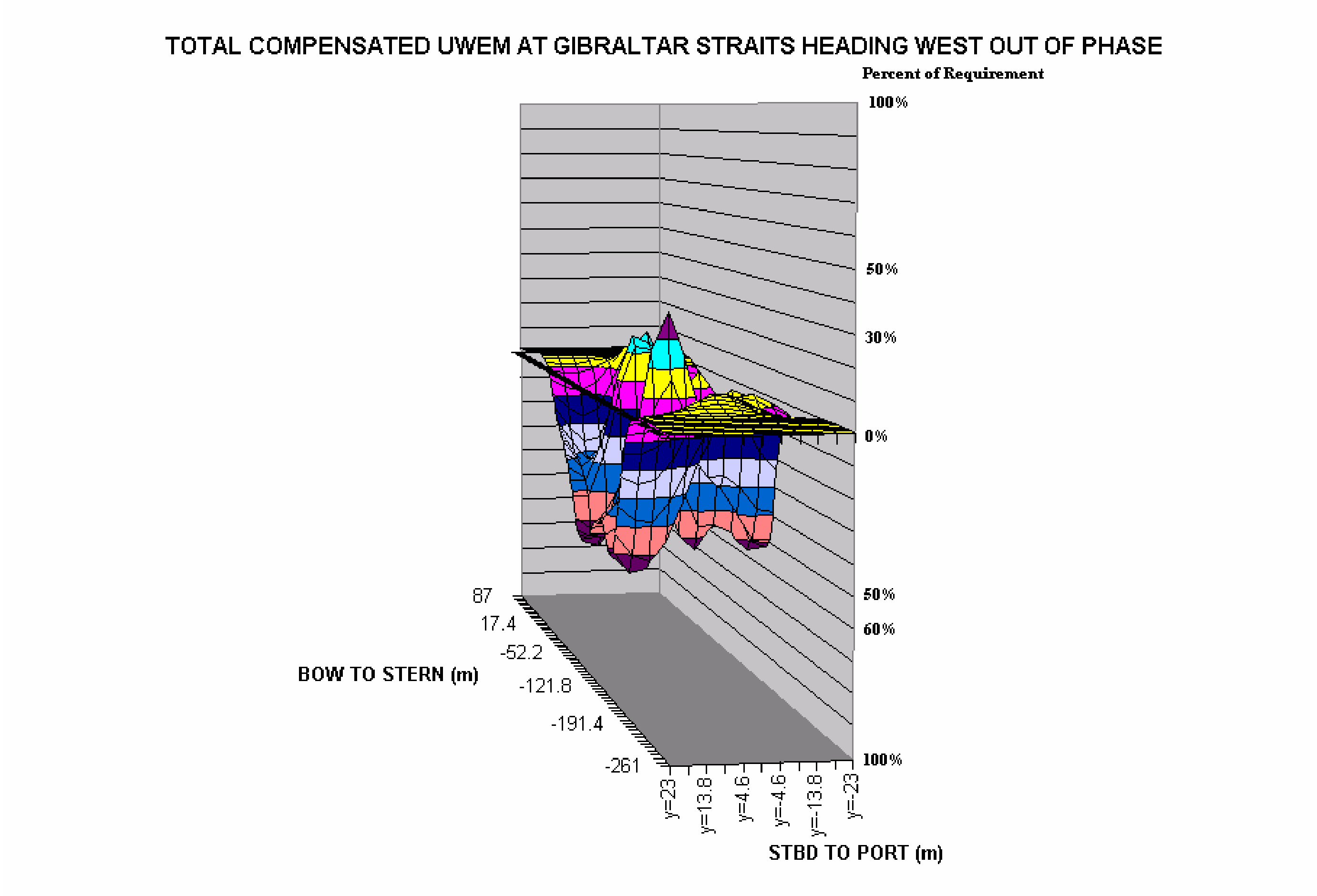

Figure 11 Total Compensated Out-Of-Phase UM Signature At Gibraltar, West Heading, At Reference Depth

The Total Underwater Electric Field (UE) Signature is comprised of the SE field component created by the ICCP system and the AE field components created by the shaft grounding system and the ICCP power supply ripple. The magnitude of the Total UE signature is largest directly under the keel line of the oiler when measured at reference depth.
Similar to the UM signature, once all of the UE signatures for all paint damage scenarios and the ICCP and ASG system ON are loaded into EXCEL, the SE signatures are combined with the AE signatures to create two COMPENSATED signature graphs: COMPENSATED IN PHASE and COMPENSATED OUT OF PHASE, which applies for worldwide locations as worst-case magnitudes. The IN PHASE signature is assuming the positive addition of all AE signature peaks with the SE signatures. The OUT OF PHASE signature is assuming the negative addition of all AE signature peaks with the SE signatures. The difference between these two sets of signatures represent the worst case magnitude of the AE signature, while each separately give snapshots of the most extreme values of the SE signature at a moment in time.

The graph below shows both the IN and OUT-OF-PHASE UE signatures along the keel line of the oiler at reference depth for the 17% damage scenario, which resulted in the highest UE signature magnitude for all damage scenarios. Note that these are the COMPENSATED signatures, with ASG and low-ripple ICCP power supplies.

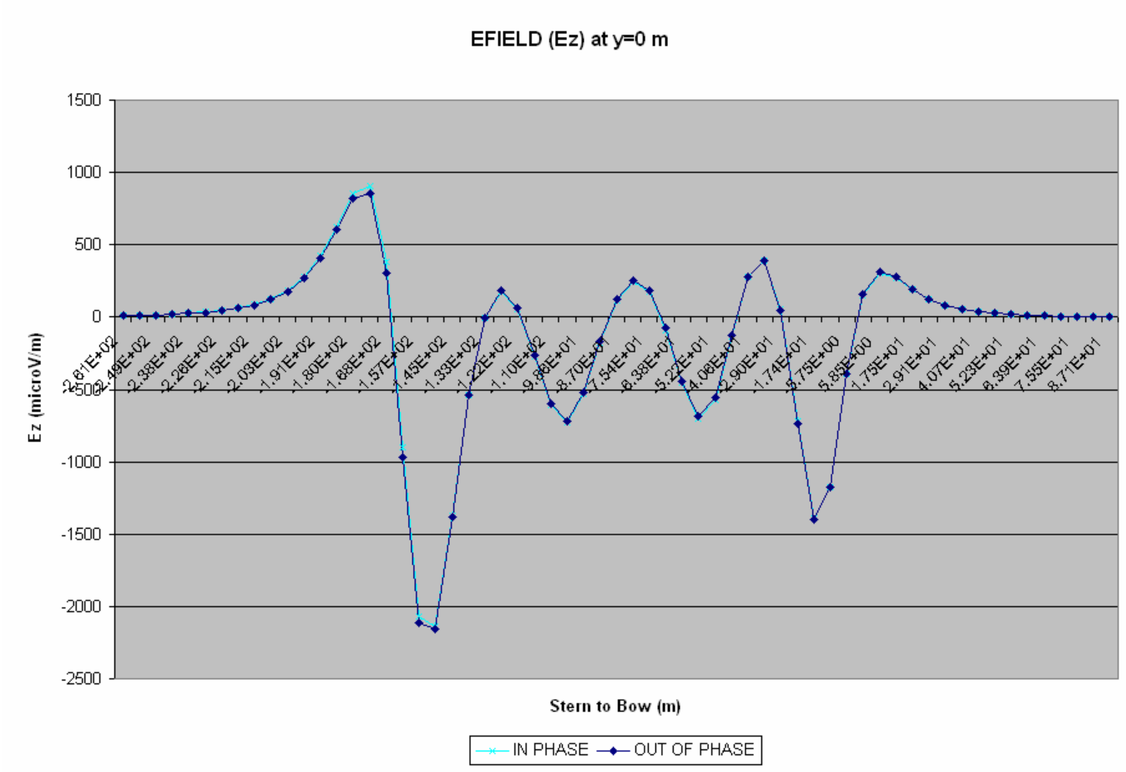

Figure 12 Total Compensated In And Out-Of-Phase UE Signature, All Headings, At Reference Depth

8 Results and Conclusion

The results of the Total Compensated (DG ON, ICCP ON, ASG ON) UWEM signature analysis was that the Magnetic Signature (AM and SM) Components met the limits for magnetic signature applicable to ships used in support roles. At the same time the Electric Field Signature (SE and AE) components were minimized to levels considered safe for the threats assumed for the fleet support missions that the oiler is designed to carry out.

Using a realistic naval vessel as an example, it was shown that it was possible to use Computational Methods to predict all of the Total UWEM signature components, and design and analyze robust and cost-effective countermeasures systems to meet specific UWEM signature requirements. This was shown to be possible when the use of experience, data compiled from previous designs and studies, in-house ship-specific modeling tools, and proven, mature third party BEM and FEM modeling SW is combined into a comprehensive suite of software that is easy to integrate.

In addition, the entire Computational Study was completed over a span of ten weeks, at minimal cost.

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