# Dipole modelling and sensor design

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## Abstract

The truth values used for validation of computational models are measured values from either actual structures or experiments. The accuracy of computational models will depend on the accuracy in which key parameters can be measured. Therefore it is imperative that there is a clear understanding of what and how parameters are being measured. An incomplete understanding of the experimental process, including measurement sensors, will corrupt the computational model validation process.

In this work computational modeling has been used to further the understanding and assist in the design of a sensor used to measure off-board electrical fields. Previously data from a series of dipole models was generated using NRL's physical scale modeling experimental facility. Results were compared with both analytical and computational solutions. Variations were observed between results. Boundary element methods were used to extensively model tank geometry, water depth, sensor orientation and to some degree sensor geometry. It was determined that the sensor as designed was not adequate for the off-board electrical measurements required. In this work boundary element modeling is used to assist in the design of a new off-board electrical field sensor. Dipole models which consider the vertical and horizontal placement of half-cells on the sensor are used to quantify characteristics of the new sensor. Comparisons are provided between analytical, computational and measured results once the sensor design is finalized.
*Keywords: electrical dipole, electrical fields, boundary element modeling, impressed current cathodic protection, physical scale modeling.*

## 1 Introduction

The accepted process for validation of computational models is a detailed comparison of experimental and computational determined values. This

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approach is common to many disciplines. An underlying assumption is that experimental values are true. While the 'truth' of experimental values would appear to be the topic of a philosophical discussion, there are very real factors that may result in the measured value not actually being what the experimentalist intended to measure.

One estimate of the truth of experimental values is often the comparison of these values with analytical or theoretical solutions. This approach is often flawed because of geometric or environmental factors that are simplified in the theoretical or analytical solutions. So in addition to a comparison with analytical values, a detailed understanding of what is being measured and how it is being measured is important. These are things which must be understood before measured values can be used to validate computational modeling processes. If the baseline 'truth' is wrong, the validation process is not valid.

Measured values are a reflection of the real world phenomenon. There are, of course, issues with sensors and measurement systems. Slight chances in environment conditions can also result in larger variations in measured values. Differences in boundary conditions between computational, theoretical, analytical and experimental situations can result in large variations despite the minor nature of boundary condition differences. It is therefore important to evaluate and carefully determine the pedigree of any experimentally measured value. Pedigree means an accurate representation of the environmental and boundary conditions. The pedigree also involves understanding the physical methods used to determine the measured value. It is important to know what values the sensors used are actually measuring and what values reported (and may be commonly talked about as being 'measured') are actually calculated. If a value is calculated, it is important to understand details of the calculations and to know the underlying measured value is. Sensor type and sensitivities should also be known.

This work addresses some of the issues listed above in terms of understanding the physical aspects of the experiment. Computational models are used to establish reasons for variations between theoretical and experimental results. The authors began this investigation into sensor design because of unexplained differences between computational and experimental measured electric field values generated by dipoles [1]. Observed differences were greater than could be explained due to numerical errors or variations in boundary conditions between the two conditions. One aspect in the results that intrigued the authors was the good agreement between theoretical and computational results. Results from both theoretical and computational studies showed significant differences from experimental results.

In this work the computational studies of electric dipoles are compared with physical scale model experimental results measured using a newly design electrical field sensor. In previous work [1] the authors used computational modeling of a dipole to investigate the effect of testing tank geometry, sensor placement and tank wall material/boundary conditions on a simple dipole system. This work addresses issues related to comparison of analytical, computational and experimental electric field results from the previous work.

Computational and analytical results were nearly identical. The sources of variations were traced to sensor design. There are two tracks that could have been taken; to include detailed sensor geometry into the computational model thus resulting in agreement between experimental and computational or to evaluate sensor design. Sensor design was chosen to be evaluated in order to match experimental with theoretical. This is important since these types of sensors will be used in future evaluations of much more complex geometries with the dipole measurements being used as a calibration technology.

## 2 Geometry

The structure evaluated in this work is not a structure in the engineering sense. The geometry evaluated is a dipole. Electric dipoles are a concept that can be found in many textbooks such as [2]. Their geometric simplicity and the availability of analytical solutions make dipoles a good tool for validation of computational and experimental techniques. Electric dipoles are also important because the dipole concept is used for far field modeling of ships and other structures with discrete electrical sources, such as the features of an impressed current cathodic protection system for a ship. Multi-pole (dipoles connected in series like a multi-span beam) models are typically used to determine electrical fields at a distance such that the influence of geometric details is negligible. Details of this modeling approach can be found in [3].

## 3 Dipole model

Computational, analytical and experimental results were obtained for the far-field voltage values for a simple dipole. Model orientations and axis directions are shown in Figure 1. The dipole moment strength was 11.725 $x10^{-3}$ A-m. The source and sink were spaced 250 cm apart at a depth of 82.398 cm below the waterline in a cylindrical tank. The tank diameter is 10 m and is made of galvanized steel. The tank has a 30 mil neoprene liner. The depth of water in the tank is 264.16 cm. The tank water had a scaled conductivity of 1/40 full strength natural seawater. The tank water measured resistivity was 740 ohm-cm. Scaling water conductivity is a standard process in physical scale modeling (see Section 5, Experimental Method). Fresh water is added to a volume of natural seawater until the desired conductivity is reached. An electric field sensor is passed under the dipole centerline at a depth of 47.5 cm. The sensor provided two curves of different potential values; the vertical (z-direction) and longitudinal (x-direction) potentials. This configuration is duplicated in the computational and analytical models.

## 4 Computational and analytical methods

The computational models used in this work were created in MSC PATRAN [4]. The geometry was then translated using an NRL written program to create input files to for the commercial boundary element code BEASY-CP [5]. BEASY-CP provides a solution process for LaPlace's equation. Details of the application of BEASY-CP, and boundary elements in general, to electrical field problems can be found in [6]. The results are post-processed using an NRL customized program that extracts and translates pertinent data for plotting using TECPLOT [7].

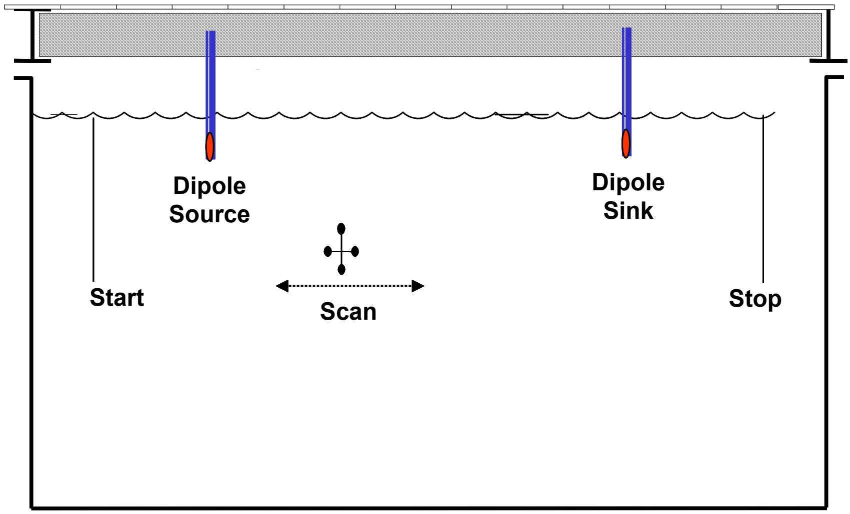


Figure 1: Dipole setup.

The boundary element model of the tank and dipole is shown in Figure 2. The dipole source and sink are modeled as truncated poles in the shape of cylinders (2 mm diameter, 3 mm height). The poles and the tank are meshed using 9-noded quadratic quadrilateral elements. A normal current flux density equal to the dipole strength divided by the surface area of the pole (±24.88 $mA/cm^2$) is applied as the driving force at the source and sink seen in Figure 2. The neoprene liner is represented by zero current flux boundary condition along the tank wall and floor. Internal node points were located along the sensor path.

Analytical solution results are calculated using the FN Remus Characterization Suite [3]. This is a commercial code which calculates fields resulting from dipole or multi-pole models. This model consists of discrete and sea conductivity. The dipole geometry was input directly into the code. A grid of internal points is defined at the sensor path location for calculation of results.

A comparison of calculated, computational from the boundary element model and analytical results are discussed in Section 6, Sensor Design Issues.

## 5 Experimental method

Physical Scale Modeling (PSM) was used to generate measured dipole electrical field values. PSM is an established process based on the physics of electrochemical response which uses scale models to produce information on structures. Structures which have been tested at the NRL Key West facility range in geometric complexity from dipoles to real ship geometries with detailed appendages such as rudders, bilge keels and propellers with moving blades (as seen in Figure 3).

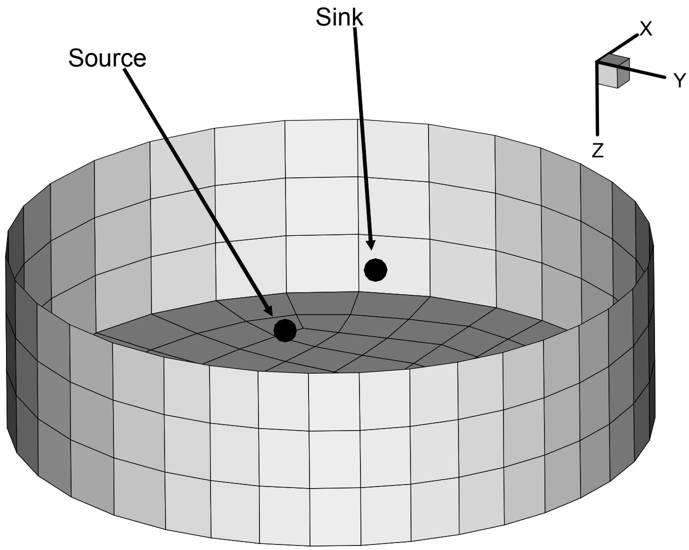


Figure 2: Boundary element model.


Figure 3: Example of a near-exact scale model used in PSM.

PSM has been extensively used in the study and design of shipboard Impressed Current Cathodic Protection (ICCP) systems. For both PSM and the computational techniques, cathodic protection is modeled in the steady state condition and follows Ohm's Law:

$$E = I (R_P + R_{OHMIC}) \qquad (1)$$

where, E = potential (Volts), I = current (Amps), $R_P$ = polarization resistance and $R_{OHMIC}$ = electrolyte Ohmic resistance. $R_P$ can be highly nonlinear and is influenced by environmental conditions. The three basic assumptions in PSM technique are:

- The wetted surface areas and geometry are exact and scaled such that $A_{STRUCTURE} = A_{MODEL} (k)^2$ where A is surface area and k is the scaling factor.
- The current density relationship, $i_{STRUCTURE} = i_{MODEL}$ is true. This means that model size, electrolyte dilution and polarization resistance components obey the scaling law.
- $R_P = \Delta E/i_C$ must be same for the model and full scale system, where ΔE represents the polarization from open circuit corrosion value to the cathodic protection set potential.

PSM technique relies on accurate scaling and accurate reproduction of geometric features at the smaller scale. Model potential, current density and scale factor relationships are described in detail in [8,9].

For the dipole evaluation, a simple electric field test was designed using source and sink poles spaced according to the dipole description given earlier. The scale chosen for modeling (i.e. seawater conductivity level) was 1/40. This scaling was chosen so that there were no boundary effects from the presence of the tank walls. Experimentally determined potential values are presented in Section 6, Sensor Design Issues.

## 6 Sensor design issues

A schematic of the original sensor used in previous work is shown in Figure 4. The sensor consisted of 4 Ag/AgCl half-cells for measurement of potential and was fabricated from a fiber composite. The two curves of differential potential values are the differences of measured values from the half-cells. Dipole generated electric field measurements obtained with this sensor are shown in Figure 5. There is significant variation between calculated and experimental measurements. Prior work investigated variations in sensor orientation as the cause of these variations [1]. Variations in pitch, yaw and roll which were considered to be possible by the experimentalist were evaluated. Even though changes in the calculated peak electrical potential occurred with variations in orientation, the changes did not eliminate the variations observed in Figure 5.

The next step was to focus on sensor design. Once the sensor was examined as a structure rather than seen as 'just' a sensor, design deficiencies became obvious. It has been observed, both experimentally and in computational modeling [10], that minor geometric features can have a significant impact on electrical field values. Shadowing, or blocking of current flow, has been noted for several ship features. The bilge keel was found to be necessary to model both in PSM and computational models, despite its relatively small size compared with the hull structure. It is known to shield areas of the hull from current flowing from anodes. The differences in a model with a bladed propeller and a solid propeller model also deal with the shadowing of regions by the solid structure [11]. Taking these concepts into consideration the experimentalists clearly saw the possibility that portions of the sensor structure were shielding the half-cells.

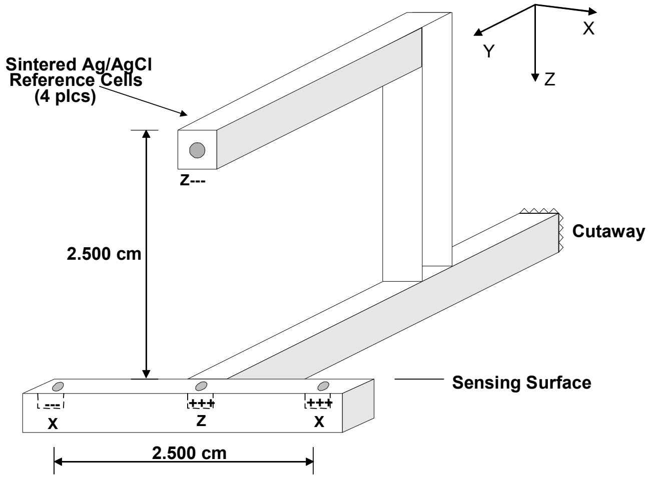


Figure 4: Original electric field sensor.

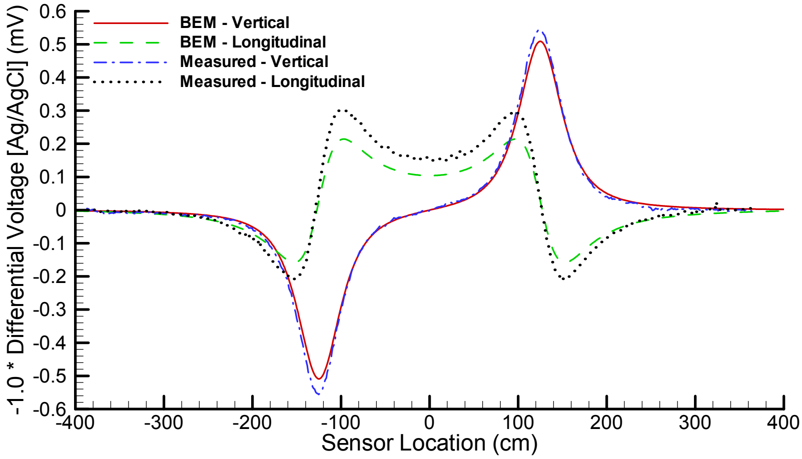


Figure 5: Boundary element (BEM) results versus measured PSM results from the original electric field sensor.

A new sensor was designed that incorporated concepts of shielding and shadowing of regions by the structure. The new sensor consists of 4 A/AgCl half-cells mounted so that they are co-planer. There is no massive structure avoiding any shielding issues. The new sensor is shown in Figure 6.

In order to test the new sensor, a repeat of the dipole experiment was conducted. There were slight modifications to the dipole set up. The dipole moment strength was 11.725 x $10^{-3}$ A-m. The source and sink were placed 250 cm apart at a depth of 75.0 cm below the water line. The tank water level was 262.5 cm. Tank water was again 1/40 scaled natural seawater. The measured resistivity of the tank water was 741 ohm-cm. The same tank was used previously with the same neoprene lining material.

Computational and analytical solutions were repeated with the new dimensions, dipole strength and material properties. Measured and calculated longitudinal and vertical electrical potential profiles are shown in Figure 7. The change in sensor design made a significant difference in observed variations. Maximum differences are reduced to 6.8% for vertical and 4.7% for longitudinal potentials.

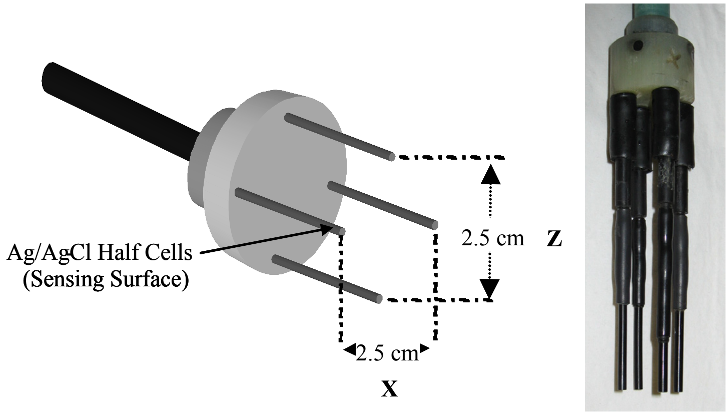


Figure 6: New electric field sensor.

One computational parameter variation run was completed. The nominal distance between half-cells in the new sensor is 2.5 cm. To determine the effect this dimension has on sensor measured values, the horizontal distance was defined as 2.6cm while maintaining the vertical distance between half-cells at 2.5 cm. The maximum difference was reduced to 2.1% for longitudinal potential (reduced from 4.7%). There is no change in horizontal potential differences since no change was made in horizontal dimensions. Therefore accurate sensor fabrication is essential.

There are other issues which may have contributed to the variations between measured and calculated data. The calibration of the electrical field sensor at the tank wall has an influence on measured values. Water stratification, while not typically thought of as occurring in experimental facilities, is a phenomenon that occurs in even shallow waters. Adjustments in raw measured data are also always an issue with any sensors. Even though the agreement is not perfect between experimental and calculated values, the new sensor design improves the fidelity of measured values. Lessons learned in ship analyses were successfully applied in the sensor design process.

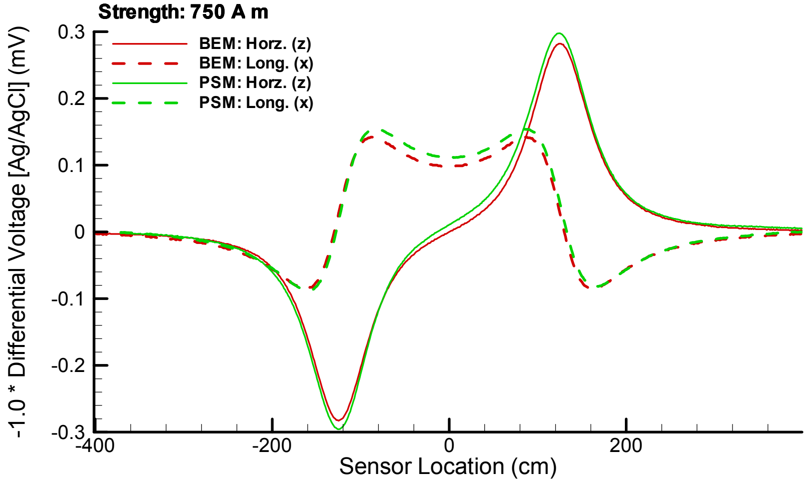


Figure 7: Boundary element (BEM) results versus measured PSM results from the new electric field sensor.

## 7 Summary

Variations between computational, analytical and measured electrical fields for a dipole submerged in scaled seawater were observed in previous work [1]. The source of variation was traced to the design of the sensor used for the experimental measurements. A new sensor was designed with the specific goal of eliminating the geometric issues related to the older sensor design. A comparison of measured and calculated dipole generated electrical fields indicates the new design has met these goals.

The current work in which computational methods are used to verify the accuracy of measured data may seem in conflict with other work by the authors, specifically processes for computational model validation [12]. Rather than think in linear terms of computational, analytical or experimental tracts of study, one should think in terms of understanding a physical problem. In striving to be able to predict physical phenomenon for complex structures there is a triad of knowledge which must be obtained and used. Physical experiments must be understood in terms of simplifications, boundary conditions, sensor capabilities and limitations and environmental factors. Computational methods must be understood in terms of underlying mathematical theories, computational implementation, and implications of modeling decisions (boundary conditions, loads, simplifications, etc). Analytical or theoretical solutions must be understood in terms of assumptions versus real complex structural conditions and the regions of applicability. Experiments, computational methods and analytical methods are tools and must be judicially applied to further our understanding.

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