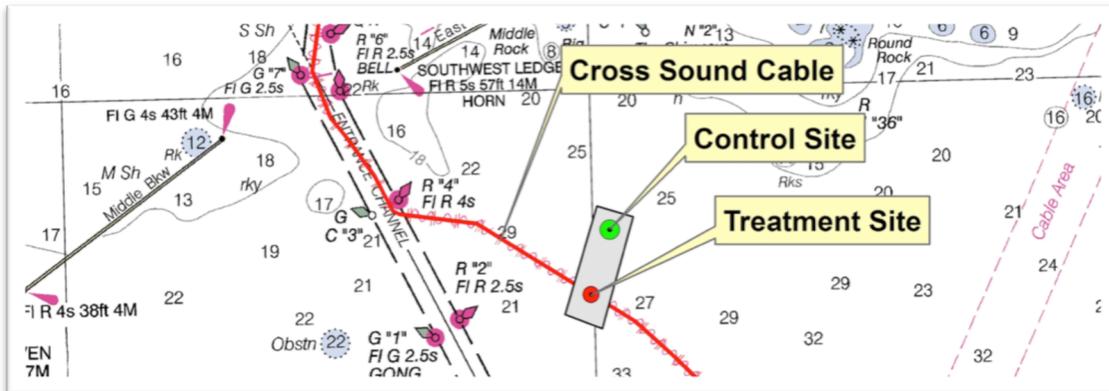


# Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables



U.S. Department of the Interior  
Bureau of Ocean Energy Management  
Office of Renewable Energy Programs



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March 2018

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## ABOUT THE COVER

Cover images:

**Top left:** Deploying the animal enclosure at the Cross Sound Cable study area. *Photo credit: David Robinson, used with permission.*

**Top right:** Preparing for a dive at the animal enclosure. *Photo credit: David Robinson, used with permission.*

**Bottom:** Cross Sound Cable study area, south of New Haven, CT, superimposed on a NOAA chart. *Map credit: Carol Gibson, used with permission.*

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## List of Abbreviations and Acronyms

A	Amps
ABB	Asea Brown Boveri
AC	Alternating Current
AD	Analog-to-Digital
AIC	Akaike Information Criterion
ATR	Acoustic Tag Receiver
AUV	Autonomous Underwater Vehicle
BOEM	Bureau of Ocean Energy Management
CSC	Cross Sound Cable
CT	Connecticut, USA
CI	Confidence Interval
COMSOL	COMSOL Multiphysics Modeling Software
CV	Coefficient of variation
dB	decibel
DC	Direct Current
EMF	Electromagnetic Field
FEA	Finite Element Analysis
FEM	Finite Element Method
FGMRES	Flexible Generalized Minimal Residual Method
FOI	Swedish Defense Research Agency
gls	Generalized Least Squares
glm	generalized linear model
glmmPQL	generalized linear mixed model with Penalized Quasi-likelihood
GPS	Global Positioning System
GSO	Graduate School of Oceanography (University of Rhode Island)
HTI	Hydroacoustic Technology Inc.
HVDC	High Voltage Direct Current
Hz	Hertz
IACUC	Institutional Animal Care and Use Committee
JM	Jennifer Miller (vessel)
kHz	Kilohertz
K-S	Kologorov-Smirnov (two sample test)
kV	Kilovolt
lme	Linear Mixed Effect
MDL	Micro Data Logger
ML	Maximum Likelihood
mT	milliTesla = $T \times 10^{-3}$
MW	Megawatt
mV/m	Millivolt per meter
nT	nanoTesla = $T \times 10^{-9}$
nV	Nanovolt
NY	New York, USA
OWF	Offshore Wind Farm(s)
p	p-value
PSD	Power Spectral Density

pT	picotesla
REML	Restricted Maximum Likelihood
RI	Rhode Island, USA
ROV	Remotely operated vehicle
SE	Standard error
SEMLA	Swedish ElectroMagnetic Low-noise Apparatus
SD	standard deviation
SNR	Signal to Noise Ratio
SR	Shanna Rose (vessel)
T	Tesla – SI derived unit used to measure magnetic fields
URI	University of Rhode Island
UTC	Coordinated Universal Time
$\mu$ T	microTesla = T x 10 <sup>-6</sup>
$\mu$ V/m	microvolt per meter
*.RAT	Raw Acoustic Tag (detection files)
*.tat	Tracked Acoustic Tag file (detection file)
*.t3D	3D tag positioning file
*.mdb	Merged database

## Executive Summary

In 2014, The University of Rhode Island and key partners were contracted by the Bureau of Ocean Energy Management (BOEM) to conduct a two-year study entitled "Electromagnetic Field (EMF) Impacts on Elasmobranch (sharks, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables." The BOEM-URI project had five major components:

1. A synthesis of existing information published subsequent to the report entitled " Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species" (Normandeau et al., 2011) for BOEM on EMF and the potential effects on marine species;
2. Field surveys to characterize the EMF from two high voltage direct current (HVDC) cables; the Cross Sound Cable (CSC) and the Neptune Cable;
3. A computer model to predict the EMF generated by HVDC cables and a comparison of EMF model predictions with EMF field measurements for validation and to determine if the model could be extrapolated to higher capacity cables that are likely to be installed in the future;
4. A statistically robust field experiment that would detect potential effects of EMF from HVDC cables on the movements of marine species (American lobster, *Homarus americanus* and Little skate, *Leucoraja erinacea*) of concern; and
5. An integration, interpretation and evaluation of the multidisciplinary findings.

## Project Context and Subject Review

A comprehensive literature review was conducted as part of the BOEM-URI project, in order to synthesize the knowledge gained since the Normandeau, et al., (2011) report. This review revealed that the understanding of EMF and interactions with marine organisms had improved; however, significant gaps remained in the knowledge base. In terms of the EMF from subsea cables, very few data or studies existed on the effects of the EMF on aquatic species from HVDC cables. Behavioral responses had been observed, but the findings from these studies were limited in their extent and were not able to be used to determine whether impacts of biological significance occur (e.g. changes in the population of a target species). It was hypothesized that benthic and demersal species were more likely to be exposed to higher field strengths from buried cables than pelagic species due to their proximity to the seabed. Both field and laboratory studies were undertaken, but the results were equivocal. There were indications of developmental, physiological, and behavioral effects to low as well as high intensity and/or long duration of EMFs. In accord with the report by Normandeau et al., (2011), consequences of exposure to EMF for sensitive species were most likely to be associated with multiple encounters and a short timescale between the EMF encounters.

Following the literature review, the goals of the URI-BOEM project were to address key knowledge gaps by collecting data on subsea cable EMF emissions for validating models, and to provide the context for assessing whether there were effects of EMF from HVDC cables on the sensitive species of interest. The American lobster and the Little skate were chosen as species of interest and they inhabited the sea bed (benthic) habitats within the Long Island Sound study area. The American lobster is a putative magneto-sensitive species and there is concern that the EMF from the cable might restrict movements and their migration. The Little skate was used as a model organism for the most electro-sensitive taxa, the elasmobranchs, which may be attracted to the EMF of the cable, particularly for benthic species, thereby altering their foraging or movement behavior. Biological effects of these types can be interpreted in the context of the potential to cause biological impacts. The biological field studies were the primary objective of the study and the other components were important secondary aspects largely in support of this objective.

To evaluate the potential effects of EMF on organisms, EMFs should be measured as well as modeled, and those models must be validated. They also need to be contextualized through comparison with both natural fields (e.g. Earth's magnetic field, motion-induced electric fields in the sea) and other anthropogenic EMFs in the area. Therefore, it is necessary to determine the characteristics of the EMF and type of fields produced by different cables, cable networks, number of devices, and associated infrastructure in different locations. It is clear that, according to current knowledge, EMFs can cause some species specific responses. However, there is not enough evidence to date to determine if there are significant negative or positive impacts on the receptor species. A greater evidence base is essential to improve understanding and provide greater confidence in assessing whether there are impacts on species of exposure to anthropogenic EMF.

To address these knowledge gaps requires scientifically and statistically robust studies to determine whether sensitive animals respond to EMF in their environment and if so, how these responses may link to impacts of biological/ecological significance. The field studies reported here focus on some of these knowledge gaps for EMF characteristics and the behavioral responses of sensitive species through targeted research studies.

## **Project Field Studies and Model Development**

**EMF Measurements of Subsea Cables:** Field surveys of EMF for the BOEM-URI project were undertaken on three subsea power cables; two HVDC cables (the Cross Sound Cable with 330 MW capacity, and the Neptune Cable with 660 MW), and one AC cable (the sea2shore cable, 30 MW) completed for the operator National Grid. One significant goal of the project was to standardize a protocol for such EMF surveys and this was achieved with the Swedish ElectroMagnetic Low-noise Apparatus (SEMLA) towed on a sled. This device proved to be a sensitive, reliable, accurate and cost-effective method for conducting EMF surveys of subsea power cables in water depths of less than 50 meters.

The DC magnetic fields measured deviated from the background magnetic field in the range of 0.4-18.7  $\mu\text{T}$  for the Cross Sound Cable (CSC) and 1.3-20.7  $\mu\text{T}$  for the Neptune Cable. The observed variation was attributed primarily to variations in burial depth along the cable route. Significant AC magnetic and electric fields were observed to be associated with both DC power cables. This result was not expected. The maximum observed AC values along the cable axis were 0.15  $\mu\text{T}$  and 0.7 mV/m for the magnetic and electric fields respectively, for the Cross Sound Cable, and 0.04  $\mu\text{T}$  and 0.4 mV/m respectively, for the Neptune Cable. Furthermore, the cross section of the EMF peaks exhibited by the DC subsea power cables were broader than anticipated at both the CSC and the Neptune Cable. The DC and AC magnetic fields reached background levels on either side of the cable on a scale of c.a. 5 and 10 meters from the peak observed value respectively, whereas the AC electric fields reached background on a scale of 100 meters from the peak value. Peak observed values occurred almost directly above the cable axis location; there was an offset of <1m where the cable was twisted. The observation that AC fields with broad areas of EMF distortion are associated with DC cables increases the complexity of interpreting the outputs of the studies of the biological effects of EMFs from DC cables. The AC electric fields associated with the AC sea2shore cable (1-2.5 mV/m) were higher than the unanticipated AC electrical fields produced by the DC cables (0.4-0.7 mV/m). The magnetic field produced by the AC sea2shore cable (range of 0.05-0.3  $\mu\text{T}$ ) was ~10 times lower than modeled values commissioned by the grid operator, indicating that the three-conductor twisted design achieves significant self-cancellation.

**EMF Computer Simulation and Modeling:** An approach for modeling the EMF of HVDC cables was developed using COMSOL, a commercially available software package. COMSOL was used to model the EMF of both the CSC and the Neptune cable. The DC model values were found to be comparable to EMF values observed in the SEMLA surveys, with similar maximum/minimum values across simulated transects. Furthermore, simulations of the Neptune cable also verified that the model

could be scaled up to larger capacity HVDC cables. These results demonstrate that the COMSOL model can be an effective tool in modeling and simulating the EMF for underwater HVDC cables for the DC component. Prior to the field surveys there was no expectation that AC fields would be associated with a DC cable therefore the AC fields were not predicted in the model because the model was not set up to estimate them.

**Animal Experiments on the Cross Sound Cable:** The field experiment using large netted enclosures was developed to assess the behavioral response of the target species, the migratory American lobsters (*H. americanus*) and electro-sensitive Little skate (*L. erinacea*) when exposed to the EMF from the Cross Sound Cable. The experiment employed novel 3D acoustic telemetry to quantify animal movements. One enclosure was deployed on the CSC and exposed to EMF (treatment, enclosure B) and the other enclosure was deployed at a site 358 m away with no EMF but with similar environmental conditions (control, enclosure A). Animals were released in groups at one enclosure followed by the other and the sequence of exposure was alternated (Sequence 1: B then A, Sequence 2: A then B) to avoid experimental bias and allow for individual variability in behavior. All individuals were only used once at each enclosure.

The *in situ*, high frequency 3D positional data were highly accurate (the beacon tag had <5 cm resolution in each dimension). The positional data on individuals at both enclosures were used to assess differences in behavioral parameters in *H. americanus* and *L. erinacea*. The behavioral parameters chosen were ecologically relevant in terms of their relative influence on energy or time expenditure of the animals. For the analysis, the behavioral parameters were compared between enclosures to determine whether a significant change in movement behavior/activity occurred which could be associated with a potential attraction or avoidance to the EMF emitted by a cable. The parameters assessed were: the total distance traveled per day, the speed of movement, the height from the seabed, 170 -180° changes in the direction of travel (termed large turns) and the spatial distribution of animals within the enclosures. Together these parameters were compared between enclosures to determine whether *H. americanus* and *L. erinacea* activity and movement changed in response to the EMF from an active subsea HVDC cable.

Throughout the lobster study, the cable was fully powered at 330 MW, 1175 Amps. Within the treatment enclosure (B), the lobsters were exposed to a total magnetic field gradient of 47.9 to 65.3  $\mu\text{T}$  which was a maximum deviation of 14  $\mu\text{T}$  from the Earth's magnetic field (51.3  $\mu\text{T}$ ). The lobsters explored the perimeter of both enclosures as expected, however, at the treatment enclosure (B) they made more use of the central space of the enclosure. At the treatment enclosure (B) the lobsters were on average closer to the seabed (14%) than when in the control enclosure (A) and exhibited a greater proportion of large turns when exposed to the treatment enclosure second in the sequence (34 % compared to 16% for the control being second in the sequence). However, there was no evidence of these changes in behavior being associated with zones of high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF within the treatment enclosure (B). Furthermore, the spatial distribution of the lobsters was significantly different at the treatment enclosure when compared to the control enclosure. *Homarus americanus* exhibited a statistically significant, but subtle change in behavioral activity when exposed to the EMF of the HVDC cable, which operated at a constant power of 330 MW (1175 Amps). The lobsters were exposed to a maximum total magnetic field of 65.3  $\mu\text{T}$ . The cable did not however, present a barrier to movement.

During the skate study, the power in the cable was variable. The cable most frequently transmitted electrical current at 16 AMPs (at 0 MW, 37.5% of time), 345 AMPs (100 MW, 28.6%) and 1175 Amps (330 MW, 15.2%), corresponding to a magnetic field of 51.6, 55.3 and 65.3  $\mu\text{T}$  and deviations from the Earth's magnetic field of 0.3, 4.0 and 14  $\mu\text{T}$  respectively. Even when the power in the cable was 0 MW, there was still a 0.3  $\mu\text{T}$  deviation of the Earth's magnetic field. Overall, the cable was powered 62.4% of the study (compared to 100% for the lobsters), and stronger effects on the behavior of skates (*L. erinacea*) were observed. The skates made full use of the space within both enclosures. At the treatment enclosure (B) the skates traveled between 20% and 93% further than when at the control enclosure (A). The

increased distance traveled was more pronounced when exposed to the treatment enclosure (B) first in the sequence. The mean speed of the skates was reduced (29%) at the treatment enclosure (B) when second in the sequence. Regardless of the sequence of exposure, the skates were closer to the seabed at the treatment enclosure (35%) and exhibited a larger proportion of large turns (38%). Independent of the enclosure, the Sequence 2 skates (A then B) showed a decreased proportion of large turns (20%) compared to Sequence 1 skates (B then A). The increased distance traveled and higher proportion of large turns were both associated with zones of high EMF ( $>52.6 \mu\text{T}$ ) at the treatment enclosure (B) where the skates were more frequently recorded and spent more of their time.

The skates at the treatment enclosure (B) traveled further but at a slower speed, closer to the seabed and with an increased proportion of large turns, which suggests an increase in exploratory activity and/or area restricted foraging behavior. Additionally, there was evidence that the increased distance traveled and increased proportion of large turns was associated with the zone of high EMF ( $>52.5 \mu\text{T}$ ) where they were more frequently recorded and spent more time. The sequence of exposure was important in some but not all of the behavioral parameters assessed; this result may have been confounded by the variable power in the cable but cannot be separated from the prior exposure to the enclosure environment. Regardless of the variable power in the cable, a significant behavioral difference at the treatment enclosure (B) was detected when compared to the control enclosure (A). This difference is indicative of a strong behavioral response by the skates to the EMF of the CSC. However, the CSC itself did not represent a barrier unable to be crossed by the skates.

## Data Integration and Interpretation

The BOEM-URI project utilized a multidisciplinary research approach to advance the current state of knowledge by addressing questions associated with anthropogenic EMFs emitted by HVDC subsea cables with a specific focus on the potential effects on sensitive benthic marine species. *In situ* measurements of EMF from subsea power cables were important since they revealed the presence of an AC field from an HVDC cable which would not be predicted by models. The context of the EMF emitted would be incomplete in terms of the biological relevance, if relying on models alone. The combination of using the SEMLA for accurate field measurements of EMFs emitted by cables with suitable electrical engineering models are recommended in the future. This approach will support model development and provide a more accurate representation of the EMF emissions from subsea cables, which is required for assessing their potential impacts on the marine environment.

The magnitudes and variability of the EMFs emitted by the subsea cables were dependent on the power transmitted as well as the depth of burial, and were within the range of biologically relevant EMF intensities. The enclosure field studies conducted in this project provided clear evidence of a behavioral response when receptive animals encountered the EMF. However, the assessment of biological impact of a single HVDC cable under the conditions studied would most likely be assigned as minor. This assessment was based on the cable not representing a barrier to movement but causing a relative change in activity in the cable zone with associated higher energetic costs likely for the animals (particularly the skates) compared with expected normal behavioral activity. In the future when there are more cables installed with a higher power rating, the potential for impact will change. Therefore, there is a need to assess behavioral responses to higher EMFs emitted since they will potentially enter the upper range of detection and may cause a further altered response in EM-receptive animals, such as a change from attraction to avoidance of the EMF.

Determination of the effect of the measured and predicted variability of these EMFs on ecologically important responses by electro- and magneto-sensitive species can be achieved using enclosure-type studies and laboratory dose-response experiments can provide knowledge on species ranges of detection of EMFs and potential thresholds of detection and response. Data on the probability of animals encountering multiple EMFs should also be collected and used in encounter predictions, this will need

free ranging studies of receptive species. Altogether these aspects are important for applying to species specific impact assessments of encounters with EMF.

## Summary of Major Findings

1. The EMF associated with HVDC cables was specifically measured *in situ* by the sensitive SEMLA device, which highlighted the presence of unexpected AC components in the EMF emissions for both the CSC and Neptune Cable. DC and AC magnetic fields extended out to 5 and 10 m from either side of the cables respectively, whereas the AC electric fields extended out to 100 m from either side of the cable. On the other hand, the AC fields of the HVAC sea2shore cable were generally ten-fold lower than model predictions.
2. The COMSOL model provided good estimates of the magnitude and shape of DC fields from HVDC cables, and is scalable to higher capacity cables.
3. The novel acoustic telemetry approach worked well to track movements of marine animals with much higher accuracy (<5 cm for beacon tag) and frequency (<3 second interval) of recorded positions than previous studies which were limited to an accuracy of <1m and frequency of <3 minutes.
4. The field-deployed animal enclosures and acoustic telemetry method developed and fully tested in this study successfully allowed the collection of *in situ*, high frequency three-dimensional positional data on individual animals at both an experimental treatment enclosure on the power cable and an enclosure at a control site for reference.
5. *Homarus americanus* (the American lobster) exhibited a statistically significant but subtle change in behavioral activity when exposed to the EMF of the HVDC cable, which operated at a constant power of 330 MW (1175 Amps). At the treatment enclosure (B), lobsters were on average closer to the seabed and exhibited a higher proportion of changes in the direction of travel (termed large turns), when second in the sequence, compared to the control enclosure (A). They also made more use of the central space of the treatment enclosure (B) compared to the control (A).
6. *Leucoraja erinacea* (the Little skate) exhibited a strong behavioral response to the EMF from the CSC. The cable was powered for 62.4% of the study and most frequently transmitted electrical current at 16 Amps (at 0 MW, 37.5% of time), 345 Amps (100 MW, 28.6%) and 1175 Amps (330 MW, 15.2%). In comparison to the control enclosure (A), the skates at the treatment enclosure (B) traveled further but at a slower speed, closer to the seabed and with an increased proportion of large turns which suggested an increase in exploratory activity and/or area restricted foraging behavior. The increased distance traveled and increased proportion of large turns was associated with the zone of high EMF (>52.5  $\mu$ T, i.e. above the Earth's magnetic field) where they were more frequently recorded and spent more time.
7. For both species, the behavioral changes have biological relevance in terms of how the animals will move around and be distributed in a cable EMF zone. The EMF associated with the CSC did not constitute a barrier to movements across the cable for either lobsters or skates.

## 1.0 Introduction

### 1.1 Project Background

In 2011, Normandeau Associates, Inc. and their colleagues published a report for the Bureau of Ocean Energy Management (BOEM) entitled "Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species" (Normandeau et al., 2011). This report synthesizes the existing state of knowledge in 2011 about anthropogenic electromagnetic fields (EMFs) that have been introduced into the marine environment, primarily by submerged power transmission cables, and the potential for EMFs to cause ecological effects or impacts on marine organisms. The primary conclusion of the report was that little was known about potential ecological effects or impacts from EMFs, and that with the proliferation of offshore renewable energy facilities, exposure of marine organisms to EMFs will significantly increase.

The report by Normandeau et al., (2011) consists of six major topic areas. First, the report synthesizes existing information on the types and designs of power transmission cables and models the expected EMFs from representative cables. Second, it reviews the information on the electro- and magneto-sensitivity of a range of marine organisms, including elasmobranchs, other fish, marine mammals, sea turtles, and invertebrates. Third, it uses the sensitivity information in conjunction with the EMF model results to evaluate the level of confidence and the state of knowledge at the time of the report provides for impact assessment. Fourth, the report assesses the data gaps in our knowledge of EMFs produced by power cables and marine biology, which is needed for impact assessment, and recommends future research priorities. Fifth, it describes potential EMF mitigation strategies (and their secondary impacts), and approaches to monitoring their effectiveness. Finally, the report discusses the potential for cumulative effects on marine organisms from exposure to multiple submerged power cables in the future. Key findings about each of these topics are summarized below.

**Power Cables:** Normandeau et al., (2011) noted that although alternating current (AC) power transmission cables are the industry standard for offshore renewable energy facilities, direct current (DC) cables will be used more often for future projects that are located further offshore. Modeling approaches are used to assess the EMFs produced by multiple cable types. The EMF characteristics were found to be a function of cable design (materials, and cable separation in dual cable designs), voltage carried by the cable, orientation to the Earth's geomagnetic field for DC cables, frequency for AC designs, and burial depth. In general, fields were at a maximum directly above cables and declined rapidly with both vertical and horizontal distance from the cable. Although, Normandeau et al., (2011) called for the development of sensors capable of measuring EMFs from submerged power transmission cables, actual observations of EMFs were not part of their report.

**Magneto- and Electrosensitive Marine Species:** Normandeau et al., (2011) reported on the magneto- and electrosensitivity of a wide range of marine organisms. The report noted that a magnetic sense is present for marine mammals, sea turtles, many groups of fishes (including elasmobranchs), and for several invertebrate groups. Electrosensitivity is well known for elasmobranch fishes, some bony fishes and perhaps some decapod crustaceans. Some studies suggest that EMFs cause behavioral effects in marine organisms, whereas others do not. Overall, EMFs associated with DC cables were modeled as higher than those associated with AC cables of similar voltages, and research suggests that marine organisms are more likely to detect and change behavior in response to the EMFs produced by DC cables.

Case studies of a number of representatives of different marine phylogenetic groups were done to assess potential effects/impacts from exposure to EMFs from submerged power cables. These case studies indicated that elasmobranchs and sea turtles were the most likely groups to be affected by exposure to

power cable EMFs. Electrosensitivity is widespread among the elasmobranchs and magnetosensitivity is widespread among sea turtles. For many other groups there are more data gaps than data.

**Data Gaps and Research Priorities:** Normandeau et al., (2011) defined a number of major data gaps and research priorities in studies of the potential effects of EMFs generated by submerged power transmission cables on marine organisms. Data gaps include: 1) more detailed information on cable project characteristics (design, burial depth, layout, shielding, and loading) early in the permitting process that would allow detailed modeling of proposed cables; 2) observational studies of EMFs from existing cables that could be used to validate/improve model estimates of EMFs; and 3) development of better sensors to measure AC and DC electric fields in the marine environment.

Major knowledge gaps exist for most marine species in our understanding of their electro- and magnetosensory capabilities and their behavioral responses to EMFs from submerged power cables are not well studied. The report indicated that future research that is focused on behavioral responses to anthropogenic EMFs of known characteristics is a high research priority. Critical groups for this type of research were identified as elasmobranchs, sea turtles, and decapod crustaceans.

**Mitigation and Monitoring:** Normandeau et al., (2011) notes that because so little was known about effects/potential impacts of EMFs on marine organisms it would have been premature to define how much mitigation of EMFs was necessary. Nonetheless, the report specified a number of cable design considerations that could mitigate EMFs without incurring major costs. However, some mitigation measures like deeper burial of cables can cause significant secondary environmental damage on at least short time scales.

Monitoring efforts were viewed as best directed toward EMF measurements to determine the efficacy of mitigation actions once a project is in operation. Pre- and post-construction monitoring was recommended for areas of habitat important to potential EMF sensitive species.

**Cumulative Impacts:** One area of concern identified by Normandeau et al., (2011) was the potential for cumulative impacts from repeated exposure of marine organisms to EMFs from either the same cable, or from multiple cables. Species that spent several different life stages in the same area adjacent to a cable would be an example of the former, whereas migratory species that cross multiple cables would be an example of the latter.

## **1.2 Project Inception, Purpose, and Relationship to Normandeau (2011) Report**

In 2014, BOEM contracted with the University of Rhode Island to conduct a two-year study entitled "Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables." The report by Normandeau et al., (2011) provided an excellent point of departure for the project, since it identified number of research priorities and data gaps, discussed above, that needed to be addressed to improve the state of knowledge regarding EMF effects on marine organisms. Specifically, the BOEM-URI project had five major components:

1. A synthesis of existing information published subsequent to the Normandeau et al., (2011) report to BOEM on EMF and the potential effects on marine species;
2. Field surveys to characterize the EMF from two high voltage direct current (HVDC) cables; the Cross Sound Cable (CSC) and the Neptune Cable;
3. A computer model to predict the EMF generated by HVDC cables and a comparison of EMF model predictions with EMF field measurements for validation and to determine if the model can be extrapolated to higher capacity cables that are likely to be installed in the future;

4. A statistically robust field experiment that would detect potential effects of EMF from HVDC cables on the movements of marine species (American lobster, *Homarus americanus* and Little skate, *Leucoraja erinacea*) that are representative of groups of marine organisms identified to be of concern by Normandeau et al., (2011); and,
5. An integration, interpretation and evaluation of the multidisciplinary findings.

One research priority identified by Normandeau et al., (2011) was to acquire more observational data of EMF (magnetic and electric fields) from a number of undersea power cables (particularly DC cables) using a sensitive, accurate, reliable, and cost effective survey method. The BOEM-URI project addressed this priority by doing a comparative survey of EMF produced by the Cross Sound Cable (CSC) using a remotely operated vehicle (ROV) equipped with a magnetic field sensor, and sled-mounted and towable custom sensors (the SEMLA- Swedish ElectroMagnetic Low-noise Apparatus) developed by FOI (the Swedish Defense Ministry Research Laboratory) for measuring low magnetic and electric fields in the marine environment. The ROV approach proved inadequate, whereas the SEMLA proved extremely effective in providing EMF measurements in water depths up to 40m.

A second research priority identified by Normandeau et al., (2011) was to be able to model the EMF produced by future cables based on the design characteristics of the cable. The BOEM-URI study addressed this priority by obtaining a commercially available software package, COMSOL, and developing a protocol for estimating EMF using this package. The estimates derived from COMSOL for the CSC were comparable to measurements obtained using the SEMLA.

A high research priority identified by Normandeau et al., (2011) was to obtain additional data on the behavioral effects on marine organisms caused by EMF from subsea power cables. They noted that because DC fields were more likely than AC fields to cause biological effects, and that model values and observations of the EMF produced by most DC cables exceeded the threshold of electrosensitivity of many marine organisms, that more studies of behavioral effects must be done prior to doing a credible impact assessment. The BOEM-URI project developed a unique approach that used tagged organisms, allowing high resolution/high accuracy monitoring of movements using acoustic telemetry in netted enclosures deployed along an EMF gradient, to study the behavioral responses of the test organisms American lobster and Little skate. Using this approach, behavioral effects for both species were documented.

The research priorities highlighted by Normandeau et al., (2011) were addressed through a multidisciplinary research approach. The BOEM-URI project integrated the findings from *in situ* measurements of EMF, which were used to validate the EMF modelling and then together they provided the appropriate EMF context for the field experiments used to determine the behavioral responses of sensitive animals. Integration across the whole project provided important advances in knowledge and addressed priority knowledge gaps associated with anthropogenic electromagnetic fields (EMF) and their effects on the marine environment.

### **1.3 Report Organization**

This report contains an Executive Summary and thereafter is organized into seven chapters. Chapter 1 provides introductory background material and a description of the project's inception, goals, and relationship to the report by Normandeau et al., (2011). Chapter 2 is a synthesis of existing knowledge on EMF that emphasizes information that has become available since the publication of the report by Normandeau et al., (2011). Chapter 3 summarizes the results of the field surveys of the magnetic and electric fields produced by two DC subsea power cables ("Cross Sound Cable" (CSC) and "Neptune Cable"), and an AC subsea power cable ("sea2shore"). Chapter 4 summarizes modeling studies of the CSC using a commercially available software package (COMSOL). Chapter 5 presents the results of a field study conducted at the CSC location in New Haven, Connecticut to examine possible effects of EMF

produced by the CSC on the test organisms, American lobster and the Little Skate. Chapter 6 discusses lessons learned from the project, and Chapter 7 provides an integration of the research findings.

Three appendices supplement this report: 1) the project field plan, and associated comments provided by the project's Scientific Advisory Review Board and other reviewers (Appendix 1); 2) a dive safety plan, approved by the URI Diving Control Board (URI DCB) (Appendix 2); and 3) the project animal welfare plan approved by the URI Institutional Animal Care and Use Committee (URI IACUC; Appendix 3).

## **1.4 References**

Normandeau, Exponent, T. Tricas, and A. Gill. 2011. Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA. OCS Study BOEMRE 2011-09.

## **2.0 Synthesis of Existing Information**

At the beginning of the project, an up to date review of literature pertaining to the subsea cable effects of electromagnetic fields (EMF) on marine species was conducted using the Normandeau et al. (2011) report (for which Gill was a co-author) as a baseline for the synthesis of existing knowledge, circa 2011. The Normandeau et al., (2011) report was summarized in Section 1.0 of this report as background for the initiation of the current project. What follows is a synthesis of recent studies from 2011 onwards of the effects of EMF on marine and aquatic species, and new information on the EMF associated with HVDC cables. The review of environmental effects of electromagnetic emissions is divided into four topic areas: 1) the current understanding of EMF levels and methods for measuring and modeling EMF; 2) knowledge on interactions of EMF with marine and aquatic organisms; 3) consideration of scaling and cumulative effects; and 4) current knowledge gaps.

### **2.1 Method to update literature review**

A systematic search of terms was made for the post Normandeau et al., (2011) years of 2011 to date. A total of sixty three publications, either journal articles, reports or conference proceedings, were selected based on their relevance to the topic and used for the updated review.

Search terms AND/OR, and combinations thereof used (within Scopus + Google Scholar):

- subsea cable/s electromagnetic field/s
- marine subsea electromagnetic field/s
- marine EMF
- HVDC cable/s environment
- animal migration magnetic field/s
- animal movement electric field/s
- marine animal electromagnetic field/s
- aquatic EMF
- magnetic field effects on animals
- electric field effects on animals

Once these search terms had been inputted into the databases, links to other relevant publications, suggested by the software, were also followed.

### **2.2 Current methods for measuring and modeling EMF**

When considering EMF levels emitted by cables, the standard approach is to estimate the fields using models that take the cable characteristics to parameterize the model and then the outputs are 2D plots of peak EM emission and propagation loss with distance from the axis of the cable (see Normandeau et al., 2011). Individual cables have their own EM signatures associated with their specific characteristics. However, in general, there is a peak near to the axis of the cable and there is a symmetrical degradation in the intensity of the field on either side of the cable axis.

In terms of actual measurements of EMF to confirm or validate model estimations, there is a paucity of data (Gill et al., 2012b). The EU MaRVEN project specifically set out to address this lack of field data by detecting and quantifying EMFs emitted by the subsea cable of an Offshore Wind Farm in the Belgian North Sea (Thomsen et al., 2015). The approach taken was to use a custom-built device, the SEMLA (Swedish ElectroMagnetic Low-noise Apparatus provided by the Swedish Defense Agency), which simultaneously measured magnetic and electric fields associated with a wind turbine, inter-array cables, export cables, and a transformer station. Both electric and magnetic fields were measured over several 10's of meters via drifting and sledging methods. EMFs from cables were the dominant source of EMFs associated with generating electricity and the cables transmitting higher power emitted higher EMFs. The EMF directly associated with a wind turbine was negligible (Thomsen et al., 2015).

In Florida coastal waters, the EMF emissions from a set of subsea cables owned and operated by the US Navy were measured and characterized using an AUV by Dhanak et al., (2015). The AUV was custom built and included a 3-axis electric field sensor and a commercially available magnetometer towed behind the AUV. The AUV also had on board upward and downward facing Acoustic Doppler Current Profilers (ADCP) and a Conductivity, Temperature, and Depth (CTD) sensor for contextualizing the hydrographic and water quality environment. The AUV was programmed to follow a lawnmower survey path, whereby the AUV moved forward along a path perpendicular to the cable with 180° turns at set intervals to cover segments of the cable without repetition (i.e. similar to the path of a lawnmower). These surveys determined that the EMF emitted reached peak levels along the cable axis. The magnetic field was measured in the  $\mu\text{T}$  to nT range and electric fields that were in excess of 200  $\mu\text{V}/\text{m}$ . The EMF decayed within 10's of meters to background in line with model estimations. This study confirmed that EMF emitted by subsea cables in the range of detectability by EM-sensitive species is present within the marine environment adjacent to a subsea cable when it is turned on.

In the period considered, Snyder et al., (2012) presented the case for a substantive lack of knowledge worldwide on the impacts of power cables on marine species from the EMF. The resultant uncertainty is proving to be a concern for stakeholders, and is delaying renewable energy developments and other activities that use subsea power cables. There have been some concerted efforts across the globe to understand the environmental interactions between anthropogenic EMF and marine organisms and they suggest that species are responding to EMFs, but whether these responses manifest themselves as either biologically, or ecologically significant impacts is still unknown. All studies highlight the need for research looking at the effects, and then consideration of the possible impacts that may result. The other important area of uncertainty is that assessing the actual EMFs is complex, the models used to predict them are limited in availability, and the validation of models with in-situ measurements is uncommon.

## **2.3 Knowledge of interactions of EMF with marine organisms**

### **2.3.1 Interactions of EMF with organisms in general**

Research on the effects of low-frequency magnetic fields on animals has been focused toward continuous exposure and the effects on humans, mammals and fish (Li et al., 2016). The literature tends to cover changes to animal behavior (e.g. Krylov et al., (2014)), immunological effects (e.g. Loghmannia et al.,(2015)), cell growth physiology (e.g. Kantserova et al., (2013, 2013)), and embryonic development (e.g. Lee and Yang (2014)). The behavioral studies have primarily looked at fish, birds or turtles and their migration, feeding, locomotion, and stress. The conclusion is that a risk assessment approach may be advisable for understanding low-frequency and low-intensity magnetic field effects on animals.

In a review of the effects of extremely low-frequency alternating magnetic fields on animal behavior, Belova et al., (2015) propose a biochemically mediated mechanism that leads to changes in animal behavior and magnetic sensitivity in the presence of an anthropogenic magnetic field. Postlethwaite et al., (2014) presented a theoretical model that takes into account the navigational errors of animals moving

over large distances to be corrected during transit. Engels et al., (2014) showed how anthropogenic magnetic fields in an urban environment directly affect the magnetic compass of migratory birds and similar effects may occur in other species that orient to magnetic fields.

Three plausible mechanisms by which animals detect magnetic fields have been proposed by Nordmann et al., (2017); a mechanical, magnetite based magnetoreceptor, a chemical based mechanism associated with light sensitivity, and electromagnetic induction in accessory structures. To understand which, if any, of these mechanisms is at work will require an interdisciplinary approach to help understand how the evident response to magnetic fields occurs.

In their review of biological effects of exposure to static electric (E) fields associated with high voltage direct current (HVDC) electricity cables on vertebrates, Petri et al., (2017) found good evidence that animals perceive the presence of static electric fields. The effects have been seen predominantly in terms of altered metabolism, and either immunologic, or developmental effects. Although the studies are deemed variable in quality, there is little clear evidence of adverse biological effects, hence the static electric fields can be perceived, but they are not considered as adverse.

Similarly with invertebrates, Schmiedchen et al., (2018) reviewed the biological effects of exposure to static electric fields associated with HVDC electricity cables. The evidence to date, while variable in quality, shows that electric fields can be perceived by invertebrates and that physiological functions are affected, such as altered metabolism, and either delayed reproduction, or developmental stages. Again there is little evidence of any adverse effects.

Panagopoulos et al., (2015) provided an analysis of natural and anthropogenic EMFs that showed that the latter are polarized (i.e. non-ionized), whereas natural EMFs are not. Polarization can cause increased biological activity at the cellular and molecular level of organization that could disrupt the electrochemical balance. The resultant biological effects could have a higher probability of occurrence owing to polarization.

## **2.3.2 Interactions of EMF with marine organisms**

### **2.3.2.1 Field studies**

Klimley et al., (2017) undertook acoustic tracking studies of Chinook salmon (*Oncorhynchus tshawytscha*) and green sturgeon (*Acipenser medirostris*) migrating through the San Francisco Bay, where there are several noted EM-emitting features. Bridges were shown to influence the local magnetic field by distorting them to a greater degree than the main electricity power cables running through the Bay. The bridges and the cable do not appear to have created a barrier to the seasonal migrations of the two species of fish. The field produced by the cable is parallel to the movement of the fish, whereas those produced by the bridges are perpendicular to the fish migration. The same team modeled the magnetic fields of the HVDC power cable following a series of transect measurements of the magnetic field with Geometrics magnetometers (Kavet et al., 2016). The modeling showed that the subsea cable emissions were minor relative to magnetic field distortions caused by either nearby bridge structures, or other submerged objects.

Much of what is known about animal response to the earth's magnetic field comes from studies of turtle migration. Putman et al., (2015) studied the magnetic navigation of the oceanic life stages of loggerhead turtles using a combination of field and lab studies. The study conclusion was that the navigation behavior of sea turtles is closely tied to the interplay between ocean circulation and the dynamics in the geomagnetic field. Fuxjager et al., (2014) further showed how the geomagnetic environment within which turtle eggs are incubated influences their magnetic orientation behavior during ontogeny.

From the perspective of biological communities, the effects on glass sponge reefs and megafaunal assemblages associated with subsea power cables were researched by Dunham et al., (2015) using *in situ* video and photography over a four year period. The cover of the glass sponge was observed to be lower along cable transects as was the number of megafauna.

Kilfoyle et al., (2017) assessed whether EMF from subsea power cables affected coral reef fish assemblages using diver surveys of fish species occurrence and abundance associated with different cables and noted any fish reaction when EMF changed. No difference was apparent between power states; however, there were indications of higher fish abundance at sites when the power was off. For this reason, further study was suggested.

To specifically address potential effects on the catch of commercially important Dungeness crab (*Metacarcinus magister*) and rock crab (*Cancer productus*), Love et al., (2017) investigated catchability based on whether the crabs would cross over an energized subsea cable to a baited trap. No difference was found in the catchability of these two species in relation to an energized cable. In previous studies, Love et al., (2015) compared caged rock crabs exposed to energized and unenergized cables and found no difference in their response.

While field studies are important to provide context to the response of marine organisms to EMFs, there are limitations in relation to the repeatability of studies and the methodologies used to assess these responses. Therefore, much of the advancement in knowledge has come from controlled laboratory studies, some of which are supplemented by or are part of a research project that incorporates field research elements.

### **2.3.2.2 Laboratory and enclosure studies**

In laboratory studies, Kimber et al., (2011) showed that a benthic electroreceptive elasmobranch was unable to discriminate between biological electric fields from a typical crustacean prey (the shore crab *Carcinus maenus*) and an artificially produced electric field. While this study did not use an electric field emitted by an electrical cable, the fact that electric fields of similar intensity were not discriminated was important when considering how elasmobranchs may hunt for electric field stimuli and potentially be confused by the artificial fields. However, in a subsequent study, Kimber et al., (2014) clearly demonstrated how the same elasmobranch species has a clear, innate ability to learn that an electric field that does not return any food will be ignored after a few encounters.

For the early life stages of electroreceptive species, Kempster et al., (2013) demonstrated that shark embryos within their egg capsule detect artificially produced predator type electric fields and cease respiratory gill movement to avoid predation. Ball et al., (2016) found that embryonic benthic skates within the egg case can also respond to artificial electric fields that are similar to predator emitted electric fields. Intriguingly, this ability was shown in embryos only one third into their ontogenetic development, which indicates how advanced the electroreception sense can be.

In free-swimming elasmobranchs, Anderson et al., (2017) studied how they obtain positional and navigational information via geomagnetic fields. In behavioral conditioning studies they showed that magnetic field perception is not just associated with the electrosensory system but they also appear to have a putative magnetoreceptor within the naso-olfactory apparatus. Juvenile lemon sharks have been recorded avoiding magnetic fields associated with a net on first encounter by O'Connell et al., (2011), however, some of them became less sensitive to the field through repeated exposure to the same stimulus. Furthermore, O'Connell et al., (2014) indicated that the lemon sharks appear to increase their reliance on the electrosensory system when visual range is reduced, such as when water is more turbid.

In studies of whether adult blue sharks would be less likely to be caught on longlines with magnets associated with hooks, Porsmoguer et al., (2015) tested two different magnetic intensities. They found there was no reduction in blue shark catch and there was a suggestion of an attraction effect particularly for the larger magnetic field intensity of 0.885 Tesla. This result would suggest that either the magnetic field produced, or the induced electric field was within the range of prey type electric fields attractive to blue sharks. In another shark species, the Galapagos shark, some magnet configurations could be used to reduce the catch of individuals on long-lines (Robbins et al., 2011). Siegenthaler et al., (2016) came to a similar conclusion in a study of magnets as a deterrent to Sandbar sharks.

When considering the response to electric fields directly, electroreception appears to be active over a short range with little evidence of species being able to use the sense over longer distances (Caputi et al., 2013). These findings indicate that the electrosense is part of a series of sensory abilities that are used in close proximity to the electric field source.

A topic of considerable interest is whether highly migratory species of conservation importance may be affected in their movements when encountering subsea cables along their migratory routes, particularly in shallow coastal waters of <20 m (Gill et al., 2012a). These species could encounter EMF from power cables either during their freshwater to seawater movement (as juveniles in the case of salmonids, or adults for anguillid eels) or marine phase to freshwater (juveniles for eels and adults returning to spawning rivers for salmonids; Gill et al., (2012a)).

Armstrong et al., (2015) set up laboratory studies to assess how both salmonid and eel movements (in separate studies) are affected by a magnetic field produced by a magnetic coil. The salmonid studies did not show any statistically significant effects for adult or juvenile salmon to a 95  $\mu$ T magnetic field generated via a Helmholtz coil. However, there were some potential trends and the sample size used for the studies may have limited the power and effect size of the study. For the eels there was not any significant response, although the authors highlight that the small sample size, lack of night-time studies and the low magnetic field strengths of 9.6  $\mu$ T limit the conclusions from the study (Orpwood et al., 2015).

Durif et al., (2013) showed that anguillid eels have a magnetic compass that enables adaptive behavior such as when encountering different water temperatures during migration or if displacement occurs. The eels appear to have the ability to resume the direction of movement along a previous compass bearing when they move away from either changed environmental conditions, or barriers. At the juvenile glass eel stage a magnetic compass is used for orientation and the orientation system appears to be linked to a circatidal rhythm (Cresci et al., 2017). Such an adaptive nature is important when considering the potential impact of changes to the magnetic/EMF environment.

The use of a magnetic map to actively find oceanic feeding habitat has been demonstrated in juvenile pacific salmon to be inherited (Putman et al 2014). This finding supports the possession of magnetic maps demonstrated in sea turtles (Putman et al 2015) and suggests that such maps could be widespread across a variety of taxa. Baltazar-Soares and Eizaguirre (2017) have also shown that during the juvenile dispersal phase across the oceans, eels use the geomagnetic fields to navigate. These findings are extended by Naisbett-Jones et al., (2017) where eels appear to have an adaptive magnetic map linked to ocean circulation that is used throughout the different life history stages of the eel.

Putman et al., (2014) conducted displacement studies of the magnetic field and assessed the orientation preferences of reared juvenile steelhead trout focused on the boundaries of their north and south oceanic range. The fish reared in the distorted field were unable to distinguish between experimental fields meaning they were not able to orient to the right direction to take them to marine foraging grounds. The importance of this study is that rearing of the fish in unnatural or distorted fields could affect the survival

and homing ability of the fish. In Pacific salmon magnetic imprinting of their natal rivers has been shown to improve the likelihood of returning from oceanic feeding areas (Hays, 2013).

Fish larvae have been recently noted as consistently orienting within their pelagic environment to coral reefs via geomagnetic cues (O'Connor et al., 2017). Field manipulations of the magnetic field using a Helmholtz coil showed that coral fish larvae orient using a magnetic compass in the absence of visual cues. Therefore, the presence of man-made EMF is suggested as important to consider as a potential influence on fish larvae orientation for swimming.

In swim tunnel studies of zebrafish shoals, Cresci et al., (2017) investigated how rheotactic (orientation response of facing toward or away from a flow direction) response is affected by a static earth-strength magnetic field. The horizontal component of the magnetic field in relation to water flow had an influence on the threshold response when fish were in a shoal, but not when they were on their own. Zebrafish have also been the focus of several research projects to determine the effects of low frequency (50 Hz) EMF (Li et al., 2014). Embryonic development was affected in terms of delayed hatching, decreased heart rate, and induced cell death (apoptosis), although none of these effects appeared to increase mortality rate. The same team of researchers found that digestion and growth of juvenile tilapia, *Oreochromis niloticus*, were affected by exposure to 50 Hz EMF at intensities of up to 200  $\mu$ T, with the indicators measured returning to normal levels once the EMF was removed (Li et al., 2015).

While most laboratory studies appear to be focused on fish, Tomanova et al., (2016) recently provided evidence of magnetic orientation of Antarctic amphipods (krill, *Gondogeneia antarctica*), that is disrupted by magnetic fields of around 20 nT down to 2 nT. The krill appear to be highly sensitive and become disoriented even at low fields.

Even marine biofilms have been shown to be affected by EMF and Trueba et al., (2016) have suggested using EMF as a mitigation measure for marine biofouling of a heat exchange system. The biofilm on the surface of the rib-tube surfaces was much thinner owing to a weakening of the biofilm matrix by the EMF, and the subsequent action of flowing seawater eroding the biofouling film thickness.

Recent studies in the field of aquaculture have begun to assess how magnetic fields may potentially enhance growth, immune response, and digestive enzymes in sea cucumbers (Tang et al., 2015) and fish (Nofouzi et al., 2017). These applied studies provide evidence that low frequency artificial magnetic fields have acknowledged physiological and biochemical effects that may be positive, in terms of increasing aquaculture production.

### **2.3.3 Freshwater organisms**

The main interest in potential effects of EMF generated by submerged cables has been within marine waters. This focus is expected as the marine environment is conductive, hence EMF will propagate to a further distance compared to a relatively low conductive freshwater environment. However, studies have also been undertaken in freshwater and low salinity environments, such as estuaries.

Bevelhimer et al., (2013) and Cada et al.,(2012) studied EMFs from river and tidal current energy generation and their potential effects on aquatic organisms. They used replicated small scale laboratory experiments with permanent magnets to produce static (DC) and variable (AC) EMFs to represent the intensities of EMFs associated with power cables. The locations of different species of freshwater fish in relation to the position of the magnet were recorded over short periods of exposure to the magnetic field. Some species, most notably the juvenile lake sturgeon (*Acipenser fulvescens*), responded in terms of distribution and behavioral activity, whereas other species showed no response. The electric field component of EMF in freshwater is attenuated more abruptly than in sea water owing to the low

conductivity of the freshwater. However, the fact that some species responded indicates that EMFs are an important real environmental stimuli that can cause some effect on species.

In the Great Lakes of North America, a study was conducted by Dunlop et al.,(2016), which concluded that the EMF from a wind farm transmission cable had no effect on the fish community at different distances from the cable. The researchers used electrofishing and acoustic fish surveys to determine the freshwater fish community present. Local habitat features explained the variation in fish density rather than proximity to the cable. One important aspect noted by the authors is that the fish community present prior to the cable installation should be determined as an appropriate baseline to determine if there are any subsequent fish community changes.

## **2.4 Consideration of scaling and cumulative effects and knowledge gaps**

Very little research has been conducted on how the potential effects of EMFs on animals scale in terms of spatial and temporal extent and in terms of the scale of biological effect on a receptive species. This paucity is likely a result of the poor information base at any scale. Thus far, systematic studies taking either the scale, or intensity aspect into account have not been undertaken. There has been some attempt to look at scale of effect in terms of the environmental impact assessment process in relation to oil and gas hydrocarbon prospecting (Tsoflias et al., 2012). Environmental Impact Assessments (EIAs) of techniques used in oil and gas exploration show that surveys use EMF transmitted by an antenna towed behind survey vessels to identify differences in resistivity of subsurface geology and hydrocarbons. While these EMFs are directly emitted into the marine environment, the assessment concluded that with current methods and observed EM intensities that there is no potential for significant effects on animals groups. The cumulative effects are regarded as negligible compared to natural EM anomalies and other anthropogenic sources of EMF.

At the scale of offshore structures, such as either offshore wind farm, or existing subsea cables, some studies have compared the fish community present with some reference site(s). Bergström et al., (2013) did not find any evidence of differences between an offshore wind farm community and reference sites, it appeared that habitat features were the best predictor of fish presence. Love et al., (2016) came to a similar conclusion when comparing powered and unpowered cables in Californian waters. Overall the main variable affecting fish and invertebrate presence and abundance appeared to be habitat related. The basis of the research is that if EMF has an effect at the level of the fish community, then it should be detectable. This line of reasoning assumes that those species present will be affected. Whether the species seen are likely to be affected by EMF is currently unknown, and these community-based studies tend to focus on the resident species. However the interpretation is that the EMF does not appear to be a factor in the fish community differences observed at structures that emit EMFs. The obvious follow up question is which transient species or highly mobile species are present, and are they affected or not? This question remains unanswered.

### **2.4.1 Current status of knowledge and remaining gaps**

The knowledge of EMF and the interactions with marine (and to a lesser extent freshwater) organisms has been added to, however there remain significant gaps in the knowledge base. In a State of the Science (SoS) report, Copping et al., (2016) conducted a thorough review and highlighted the knowledge status for EMF and environmental interactions. Many animals are potentially receptors (but most studies have focused on fish). In terms of the EMF from subsea cables, very few data exist on the effects of the EMF on species. Behavioral responses have been observed, but these studies do not allow impacts of biological significance to be determined. Benthic and demersal species are more likely to be exposed to higher field strengths from buried cables than pelagic species. Both field and laboratory studies have been undertaken,

but the results are generally equivocal. In some studies, there are indications of developmental, physiological, and/or behavioral responses to EMFs which may be species or context dependent and all require more research (e.g. Woodruff et al., (2013, 2012)). Consequences of exposure to EMF for sensitive species are most likely to be associated with multiple encounters with a short timescale between encounters.

To date, there is no demonstrable impact (negative or positive) of EMF related to subsea cable energy emissions on EM-sensitive species. Importantly, there is a need for a greater evidence base to improve assessment confidence. To evaluate potential effects, EMFs need to be measured as well as modeled and contextualized through comparison with both natural fields and other anthropogenic EMFs in the area.

It is clear that according to current knowledge, EMFs can cause some species specific responses. However, there is not enough evidence to date to determine if there are significant negative or positive impacts on the receptor species. Furthermore, it cannot be ruled out if there are any longer term physiological, biochemical or behavioral effects as a consequence of interaction between organisms and EMF at different developmental stages of life. Snyder et al., (2012) highlighted the need for specific experiments to better understand the biological processes that are affected when electro and magneto-receptive species respond to EMF. They suggest that it will be necessary: (1) to determine how responsive species behave in the longer term following exposure to an EMF source; (2) to identify EMF characteristics (frequencies and intensities) to which different species respond and are impacted; and (3) improve EMF modeling through validated predictive tools. Finally, the uncertainties will only be addressed by collaborative studies by engineers and marine scientists to understand the environmental impact of subsea EMFs.

In terms of sources of EMF, there is a need to determine the characteristics of the EMF, the strength and type of fields produced by different cables, cable networks, number of devices, and associated hardware in different locations. These aspects then need to be considered in relation to the types of sensitive organisms that may be exposed to the EMFs. This approach will require specific assessments of the EMF that marine animals may be exposed to in relation to source EMFs associated with power cables. Furthermore, dose-response studies would be useful to understand the level of response/effect on EM sensitive species in relation to their range of detection of different EMF sources and intensities.

These knowledge gaps can be addressed in part by targeted research studies with the appropriate level of statistical power and effect size considered. Furthermore, operators and developers can facilitate data collection by monitoring power transmission characteristics and the linked EMF emitted to help validate models and understand how local conditions can affect the EMF.

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## **3.0 Field Surveys of the Cross Sound, Neptune, and Sea2shore Cables**

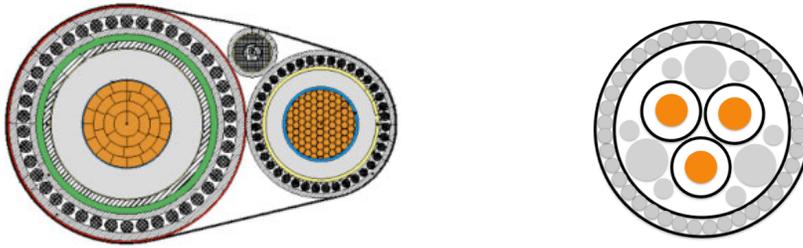
### **3.1 Electromagnetic fields generated by cables**

The propagation of electromagnetic waves in the marine environment is described by Maxwell's equations (Panowsky and Philips, 2001). These equations state that a constant current in a conductor generates a constant magnetic field, and an alternating current generates an alternating magnetic field, which in turn induces electric fields and eddy currents. For alternating currents both magnetic and electric fields co-exist and are related. Electric fields are also induced in the marine environment around a cable when an animal swims through the magnetic field or water moves over it, such as during tidal streams. In the literature, a constant current is also known as a Direct Current, abbreviated by DC, whereas a current that fluctuates symmetrically at a known frequency is an Alternating Current and is abbreviated by AC. These acronyms are colloquially used with entities such as current, power, voltage and transmission. In this report, magnetic field is used interchangeably with magnetic flux density, and the field strengths are given as zero-to-peak values. An inherent property of electric devices is that they emit electromagnetic fields. In this study, the focus was on the magnetic and electric fields emitted by three submarine cables; the Cross Sound Cable the Neptune Cable, and the sea2shore cable. The investigation of the latter cable was not part of this project. The sea2shore cable was surveyed for National Grid, and included herein for comparison.

### **3.2 The Cross Sound Cable**

The Cross Sound Cable (CSC) power system is based on a bipolar High Voltage Direct Current transmission technique (HVDC), in which the DC-current is fed into one cable and the neutral current is returned in a second parallel cable. The DC-transmission technique is often employed due to lower power loss compared to AC-systems, but initial infrastructure costs are usually higher. The CSC is a 24 mile (40 km) long submarine cable buried in Long Island Sound. The cable connects the electric grid of New England with that of Long Island, New York. The converter stations and the cables were constructed by the ABB Group. Commercial operation started in 2003. The transmission design consists of two power cables and a fiber-optic cable. The cable enters New Haven Harbor (Connecticut), runs to the Halvarssons Converter station in New Haven, crosses Long Island Sound, and enters the Tomson Converter station in Shoreham, New York. The CSC transmits a maximum of 330 megawatt (MW) at a voltage difference of 300 kilovolt (kV). The maximum rated current is 1175 A. Generally, the New England grid exports power to Long Island. The power is kept constant and adjusted hourly, on the hour. The AC power is rectified to DC at the converter station and transferred through the cable as a DC-current. At the opposite end the DC-current is converted back to AC-power, and fed into the power grid. Besides DC-currents, this technique generates DC side harmonics (Railing et al. 2004), which appear as multiples of the basic feeding frequency of the grid, i.e. 60 Hz. From an environmental point of view this technique, in addition to the DC-field, will also generate an AC-field. The manufacturer characterized the side harmonics for the CSC where the dominating AC harmonic was found to be the second harmonic (120 Hz) followed by the first (60 Hz) (Railing et al. 2004). Harmonics up to the 80<sup>th</sup> harmonic were observed.

The CSC consists of two cables that are bundled with a fiber-optic cable as shown in Figure 3.1. The cable was deployed in the sediment with a target burial depth of 2 m (6 feet).



**Figure 3.1. Cross-section of the submarine cables.**

The left sketch shows the principle of a bundled cable pair for the Cross Sound Cable and the Neptune Cable. The thicker cable (left) is the main high voltage cable. The right cable is the medium voltage return cable. The top conductor is a fiber-optic cable for system control. The right sketch shows the design of the sea2shore AC-power cable. The three copper-colored circles show the three inner conductors of the cable. The sea2shore cable also contains a fiber-optic cable that is not shown.

### 3.3 The Neptune Cable

The Neptune Regional Transmission System is a 65-mile (105 km) undersea and underground High Voltage Direct Current (HVDC) transmission line that connects New Jersey to Nassau County on Long Island. The cable provides up to 660 MW of power to Long Island via a 500 kV cable. The DC cable runs approximately 50 miles under the Raritan River in New Jersey and the Atlantic Ocean. The cable interconnects two converter stations, one on Long Island at Duffy Avenue, and the other in Sayerville, New Jersey. The current (AC to DC) converters were built by the Siemens Corporation, and the DC cable was installed by the Prysmian Group. The cable project was completed in 2007. The cable was buried to 1.2 to 1.8 m (4-6 feet) depth in the seabed and the submarine part of the cable is bundled in the same way as the Cross Sound Cable (Figure 3.1).

### 3.4 The sea2shore Cable

The sea2shore cable is a 20-mile (32 km) long submarine cable that is used to export the power produced by five wind turbines south of Block Island. The sea2shore cable connects Block Island with the Rhode Island mainland grid. The core of the cable consists of three concentric inner conductors carrying 3-phase AC-currents (Figure 3.1). The three conductors are helically twisted, which reduces the generated magnetic field compared to three straight concentric conductors (Pettersson and Schönberg, 1997). The maximal rated electric current is 502 A per conductor. The Block Island wind park was taken into operation in 2016.

### 3.5 Electromagnetic fields from a bundled cable pair

Two bundled cables with equal but opposing currents constitute a dipole line source for which the corresponding levels will be linearly dependent on the electric current and inversely proportional to the square of the distance. An infinite straight pair of bundled cables will generate an azimuthal magnetic field (rotating around the cables) and a radial electric field (perpendicular to the cable direction). A hypothetical survey undertaken on an infinite flat plane elevated above and perpendicular to the cables will result in two magnetic field components in that infinite plane, and the vertical direction. Their relative amplitudes will change as a function of distance to the cable pair. The electric field will only show up in the cross component, provided that the survey is made perpendicular to the cable pair and if there is an AC-current. The cable geometry, cable material and burial depth affect the levels of the cable-generated magnetic field. The geometry is described by the separation of the two conductors and the angular tilt, here defined as the angle between the vertical direction and the line that connects to the centers of the two cables. The burial depth and the tilt of the Cross Sound and Neptune Cables were

unknown and have to be estimated. The dipole field of the cable will be superimposed on the Earth's magnetic field. The total magnetic field will in general not be symmetrical since the dipole field changes direction on the two sides of the cable pair.

### **3.6 Electromagnetic fields from a helically twisted three-core cable**

High power AC-power transmission is based on the three-phase technique where the currents are phase shifted 120 degrees relative to each other. The sum of the three currents is always zero provided that the AC-transmission is in balance. There is still an electromagnetic field generated due to the concentric geometry of the conductors, and as a result the AC-cable will produce both magnetic and electric fields. The dominating frequency of the AC-fields in the USA is 60 Hz, but higher harmonics are also produced. The fields from three straight conductors placed in the corners of a triangle will produce fields that are proportional to the currents and inversely proportional to the square of the distance to the cables. The difference between DC-transmission and AC-transmission is that the AC-system will, by the laws of physics, generate both magnetic and electric AC-fields. It was observed that the DC-system in the AC/DC conversion stage produces AC-fields. This phenomenon will be discussed in detail in sections 3.12 and 3.13 of this report. The submarine cable used for the sea2shore cable consists of three concentric conductors that are helically twisted. This twisting technique will increase the attenuation of the field in comparison to three straight conductors. The attenuation of a twisted cable will be exponential under certain circumstances (Pettersson and Schönborg, 1997).

The fields generated by a high-power AC-cable are generated not only by the balanced currents but also by unbalanced currents, which have different propagation characteristics. The balanced currents will attenuate quickly as a function of distance, whereas the unbalanced currents will not. The observed fields will be dependent on the strength of the unbalanced and balanced currents and the distance to the AC-cable.

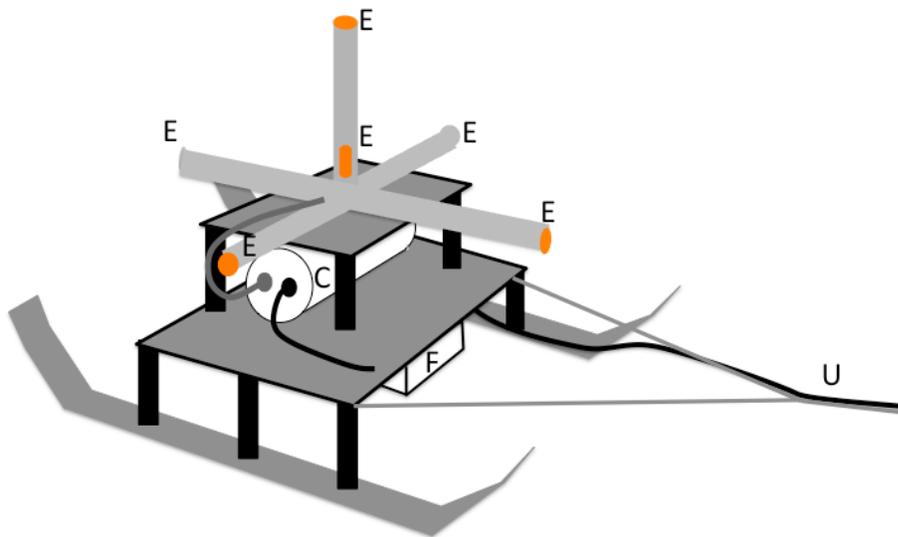
The AC-transmission from wind turbines is associated with relatively large power variations. The current in the three conductors will in general not be in balance, which implies that the sum of the currents will not cancel. In addition, due to the voltage difference between the earth groundings of the two end points of the cable, current will flow in the armoring of the cable. The sum of these two effects will result in a net current flowing in the cable. The unbalanced current can be modeled as a current flowing in a single straight conductor. The corresponding field strength will be proportional to the current (unbalanced current) and inversely proportional to the distance.

### **3.7 The sensor platform**

Two sensor platforms were used for the initial survey of the Cross Sound Cable (CSC). The first platform was a Saab Seaeye Falcon Remotely Operated Vehicle (ROV) with an Innovatum Smartrak magnetometer sensor array mounted on the ROV. The ROV was piloted on April 28, 2016 by personnel from Meridian LLC onboard the University of Rhode Island's RV Shanna Rose research vessel. Strong tidal currents resulted in difficulty piloting the ROV accurately over the cable. In addition, the Innovatum sensor was only able to provide an indication of high or low magnetic field values, rather than provide quantitative field values. The ROV could track the cable route, but the resulting data were not satisfactory. Field work ended approximately seven hours after deployment, when the ROV became entangled with additional instrumentation in the water (the other sensor package) due to pilot error. Cables associated with both instruments were damaged and required repair. After the disappointing and expensive results obtained from the Innovatum Smartrak, use of the ROV-mounted survey tool was abandoned for the duration of the project.

The second platform, the Swedish ElectroMagnetic Low-noise Apparatus (SEMLA) is an instrument specially designed to measure electromagnetic fields generated by submarine cables (Figure 3.2). The

SEMLA was equipped with skis to place the sledge as close as possible to the seabed surface. This design makes it possible to measure maximum magnetic and electric fields that are emitted from a buried cable. Furthermore, the positioning on the seabed stabilizes the platform and thereby reduces the motion-induced noise. The platform was equipped with a low-noise three-axial fluxgate magnetometer (Bartington MAG-03) with a sensitivity of  $6 \text{ pT}/\sqrt{\text{Hz}}$  at 1 Hz and a frequency response from DC to 3 kHz. The three axial electric sensors were manufactured by the Swedish Defense Research Agency (FOI) with a sensitivity of  $5 \text{ nV}/\sqrt{\text{Hz}}$  at 1 Hz (Crona et al., 2001). On a flat seabed the fluxgate was located at 0.15 m in height, the two electric sensors in the horizontal plane were located at 0.52 m in height, and the center of the electric sensors in the vertical plane was located at 1.04 m above the seabed. In this study all surveys were done almost perpendicular to the cable. This approach implies that the magnetic field components were observed in the cross and vertical direction relative to the cable and the electric field along the cable direction. The fluxgate and electrode signals were directly fed to line drivers where the electric fields had to be amplified 80 dB. The line drivers were placed in an underwater casing on the SEMLA close to the sensors to minimize electronic interference. The outputs of the line drivers were connected to the umbilical cord, which connected the SEMLA with the electronics on the surface where the signals were low-pass filtered at 1 kHz to avoid aliasing before being sampled with a 24-bit Analog-to-Digital converter (DEWE-43) at 5 kHz. The AD-converter was connected to an ordinary laptop presenting the measured fields on the laptop screen. This arrangement allowed for real-time monitoring of the survey, both the crossing of the cable was observable as well as the motion of the SEMLA.



**Figure 3.2. Diagram of the SEMLA.**

The E's mark the location of the six electrodes, the F indicates the location of the fluxgate sensor, the C the cylindrical casing and U the umbilical cord. The amplifiers for the electrodes and the line drivers were placed in the cylindrical casing.

### 3.8 Survey Methodology

The SEMLA was designed to be suspended in the water column from the side of a boat, or towed on the seabed. The suspended mode was used when towing was not possible due to obstructions on the seabed that could damage the SEMLA. Both modes were tested extensively before surveying the cable. The SEMLA was deployed on the seabed and then raised 0.5 m and kept suspended during the survey. In the first test the boat was kept on minimum speed in a direction crossing the cable. The drag of the SEMLA was too large resulting in it lagging behind the boat and neither the actual depth, nor the stability of the SEMLA was possible to control. To overcome the lag, the boat was left drifting with propulsion shut off.

The drift direction of the boat became dependent on wind and tides, which seldom favored a perpendicular crossing of the power cable. It also took a very long time to finish one transect. The suspended mode was never used after the initial trials.

The towed mode was successful. Towing commenced after deploying the SEMLA on the seabed from the A-frame of the boat. The boat was slowly steaming forward and about 150 m umbilical cable was unreeled, before the SEMLA was towed. It was observed that the SEMLA was stable when sliding on the seabed by monitoring the components of the magnetic field.

The three axial magnetic and electric fields were measured separately in the long, cross and vertical directions of the cable. The initial analysis of the magnetic data showed that the three orthogonal magnetic components were sensitive to the fluxgate motion relative to Earth's magnetic field. The observed variations in the signal levels were caused by motion-induced projection of the Earth's vector magnetic field into the reference frame of the fluxgate. The result was that the crossing of the cable was barely visible in any of the individual magnetic components. This result was the reason for investigating the total magnetic field, for which Earth's magnetic field is invariant. The electric field does not suffer from influence of strong external fields since there was no electric DC-field in the area. Throughout this study, total fields were used in the analysis.

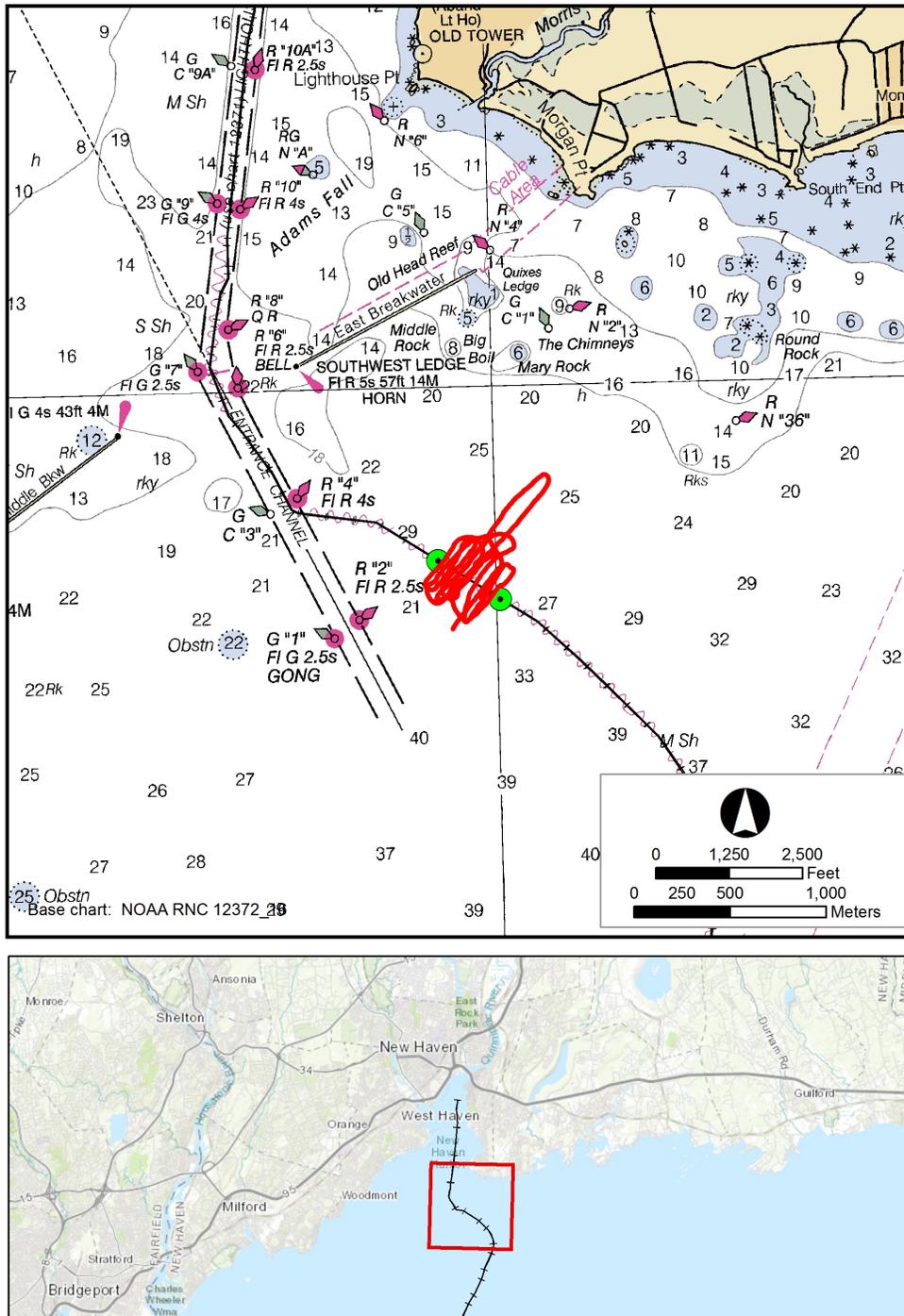
The total magnetic and electric AC-fields were derived in three consecutive steps. First, the three components of each field were high-pass filtered at 10 Hz to reduce the effect of low-frequency influence. In the second step, a moving maximum filter of 1 sec length was employed to extract the envelope. The fields were finally adjusted for background levels.

Power Spectral Densities (PSD) were calculated to estimate spectral content. The PSD were first estimated for the three orthogonal field components and then added to give the spectrum for the total fields. In this study, the segment length of the transform was chosen to be 5000 samples (corresponding to 1 second time intervals) to agree with the sampling frequency. This choice of interval makes the PSD-level and the amplitude of a tone (tonal amplitude) approximately equal, provided that the tones are sharp and do not spill over into neighboring bins. The total time length of the signal was 10 seconds, which spans the main part of the peak measurement of the field. It should be stressed that the PSD can only be used as an indicator of spectral content since the signal amplitude varied considerably during the 10-second time intervals.

### **3.9 Results from Cross Sound Cable**

The choice of a test area for the enclosure experiments was dictated by three logistical conditions: 1) the area should not be too deep; 2) the area should be close to New Haven but outside the breakwater; and 3) and the distance from the shipping lane entering the harbor had to comply with the US Coast Guard safety mandates. These conditions led to a test site being selected east of the entrance to the New Haven harbor (see Figure 3.3). The SEMLA was towed on April 28, May 3, and May 9, 2016. The objective was to make an extensive mapping of *in situ* fields generated by the cable and to find locations for the two enclosures. The surveys performed on 3 May are shown in Figure 3.3. All surveys took place between the two green circles shown in Figure 3.3. During these three survey days, the Cross Sound Cable was operated in three different modes. On the first survey day, the cable was not transferring power, on the second survey day the power transmission was feeding 345 A, and on the third survey day the cable transmission was shut down. On the first day when the power system was not transferring power, there was still maintenance current in the cable on the order of 16 A, while on the third day, when the cable was shut down, there was no current in the cable. The three survey days resulted in a total of 23 km of sledging and with 32 cable crossings. The larger loops on the northeast part of the test site were surveyed to establish background levels from an area unaffected by the cable (see Figure 3.3). This survey was undertaken on 3 May when the current in the cable was 345 A, using the same methodology as for the

other transects to make all measurements comparable. The background measurement was done at 358 m distance from the cable, about half way to the northeast end of the largest loop. The background levels were found to be considerably lower than what was observed when current was present in the cable. The spectrum of the magnetic background field contained only 50 Hz components and its overtones. These frequencies emanate from the surface electronics that used a 50 Hz DC/AC converter. It was observed that the cable-induced electric field was still present, but the amplitude was relatively low compared to the fields obtained near to the cable (Figures 3.6, 3.9 and 3.12).

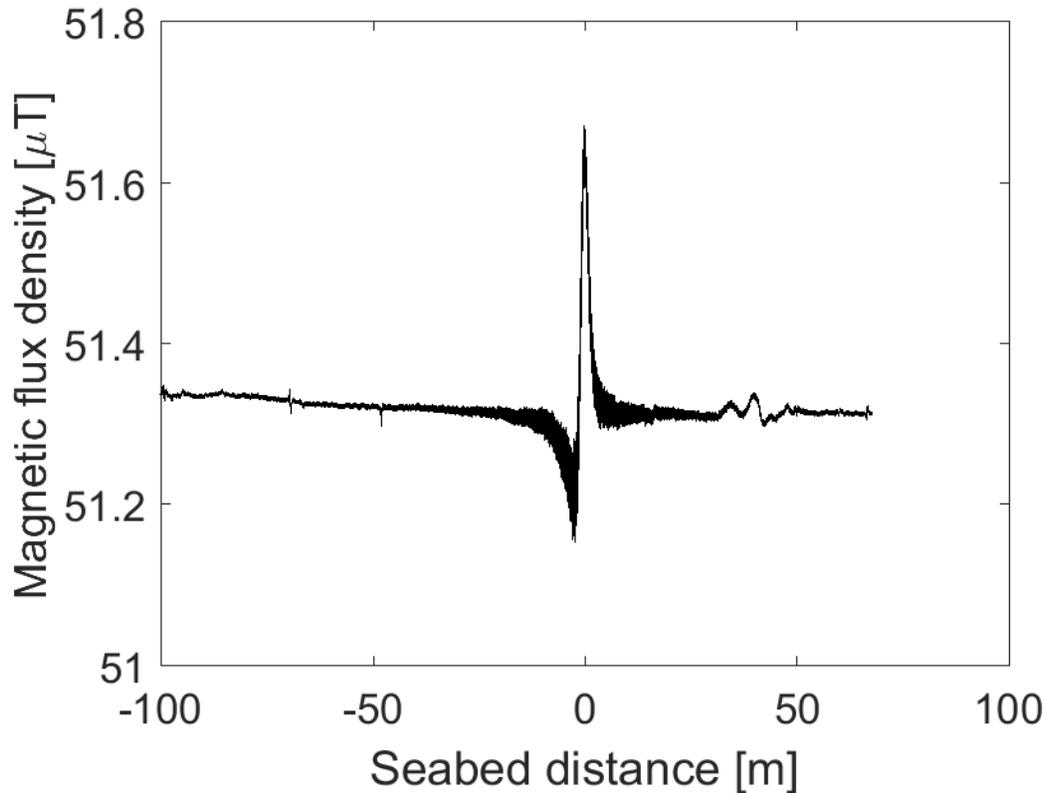


**Figure 3.3. Survey map of the Cross Sound Cable outside New Haven.**

The upper panel shows the survey made on May 3, 2016. The two green dots mark the border points, inside which the enclosure was deployed. The lower panel shows the cable route outside New Haven and the red square, the area magnified in the upper panel.

### 3.10 Results obtained when the Cross Sound Cable was in operation, but not transmitting power

The cable was in operation but not transferring power on April 28, 2016. There was still a minimum maintenance current applied, which was 16 A according to the cable operator. The SEMLA crossed the cable almost perpendicularly ten times during the April 28, 2016.



**Figure 3.4.** The total magnetic field observed at transect 5 obtained on April 28, 2016. The deviation from the Earth's magnetic field is clearly observable. The magnetic AC-field shows up as a black widening close to the crossing point.

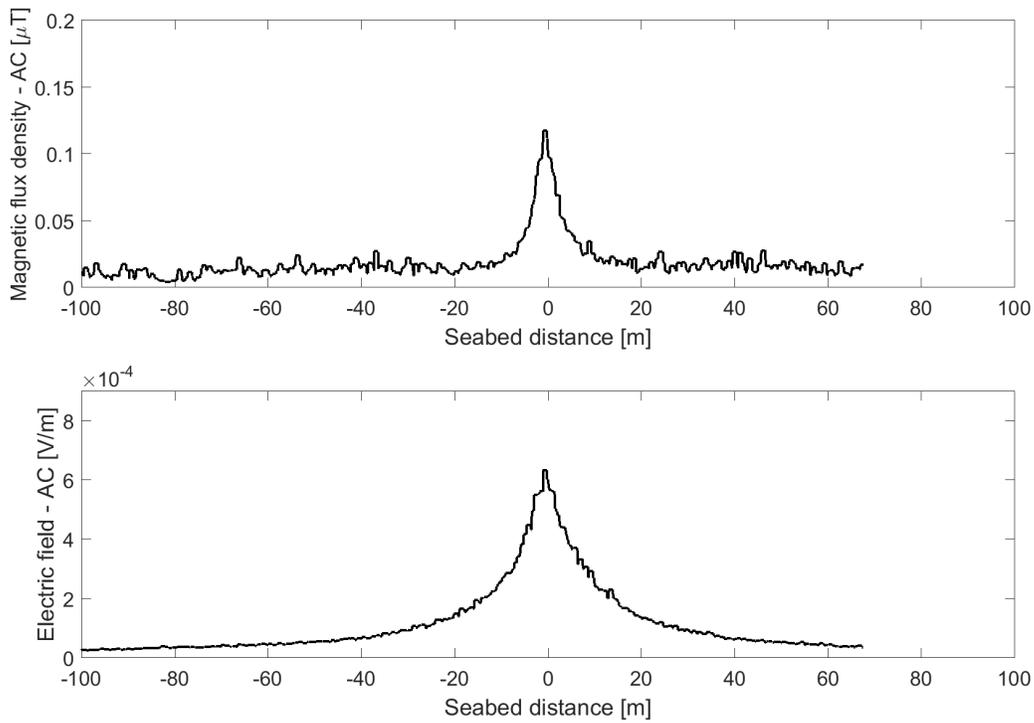
The observed total magnetic field from transect number 5 is shown in Figure 3.4. Zero seabed distance in the Figure 5 and all consecutive figures correspond to the closest point of approach, e.g. the SEMLA was on top of the cable where the distance was equal to the burial depth of the cable. The magnetic field was dominated by the DC-field. The deviations of the magnetic DC-field for the ten transects are presented in Table 3.1. The average deviation of the total magnetic DC-field was  $0.38 \mu\text{T}$  (positive) and  $0.26 \mu\text{T}$  (negative). Maximal deviation was found to be  $0.64 \mu\text{T}$ . The current in the cable contained AC-currents presumably produced in the AC/DC-conversion process at the stations.

**Table 3.1. Measured magnetic and electric fields obtained on 28 April 2016 when the Cross Sound Cable was not transferring power. A maintenance current of about 16 A was applied.**

Transect	Positive deviation of total magnetic field	Negative deviation of total magnetic field	Amplitude of total magnetic field	Amplitude of total electric field	Current
	DC $\mu\text{T}$	DC $\mu\text{T}$	AC $\mu\text{T}$	AC V/m	
1	0.64	0.37	0.17	7.70E-04	16
2	0.23	0.31	0.14	6.90E-04	16
3	0.56	0.31	0.16	6.70E-04	16
4	0.26	0.15	0.1	6.10E-04	16
5	0.36	0.16	0.12	6.30E-04	16
6	0.33	0.43	0.17	7.60E-04	16
7	0.57	0.28	0.17	8.30E-04	16
8	0.23	0.2	0.11	8.10E-04	16
9	0.32	0.18	0.11	8.40E-04	16
10	0.27	0.17	0.1	8.10E-04	16
<b>Average value</b>	0.38	0.26	0.14	7.42E-04	
<b>Maximal value</b>	0.64	0.43	0.17	8.40E-04	
<b>Median value</b>			0.13	7.65E-04	

The AC components of the field for transect number 5 are shown in Figure 3.5. The average amplitude of the magnetic AC-field was 0.14  $\mu\text{T}$  and of the electric AC-field was 0.7 mV/m. The maximal AC-fields were observed to be 0.17  $\mu\text{T}$  and 0.8 mV/m for the magnetic and electric fields, respectively.

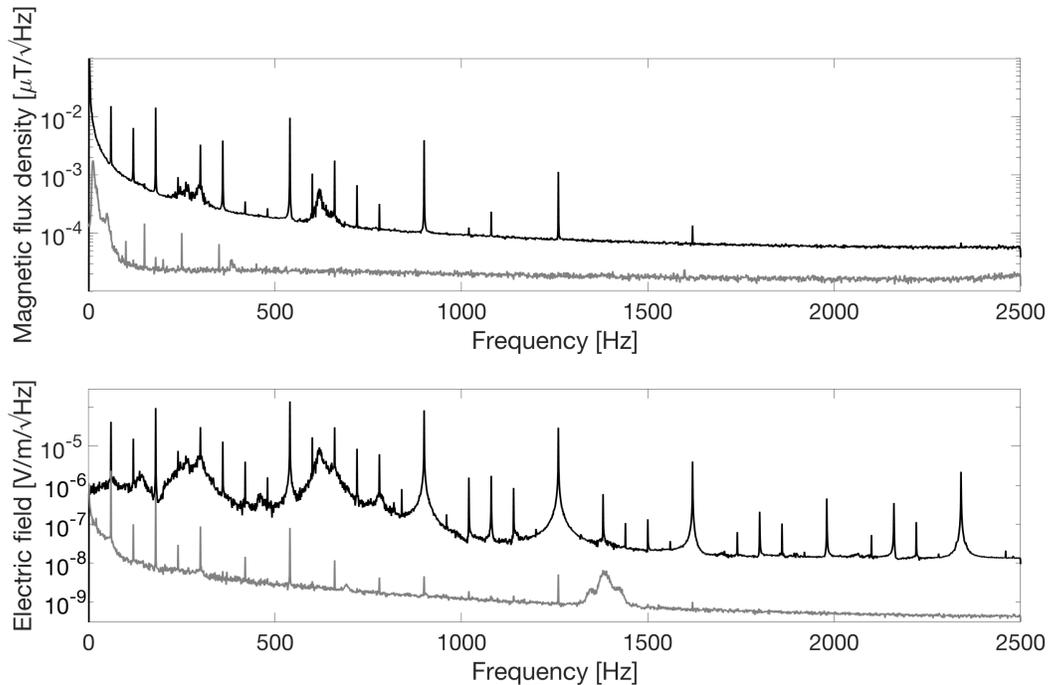
Power Spectral Densities (PSD) for transect number 5 are shown in Figure 3.6. The dominating frequency for the magnetic AC-field was 60 Hz, followed by 180, 540 and 120 Hz harmonics and for the electric AC-field 540 Hz followed by 180, 900 and 60 Hz harmonics. There were no significant differences observed between the PSD amplitude and the tonal amplitude of the 60 Hz tone. The PSD derived amplitude of the 540 Hz in Figure 3.6 was, however, underestimated by 8% for both the magnetic and electric fields. The reason for the underestimate was that at higher frequencies the tones started to spill energy into neighboring bins. The overall results show that the observed levels at 16 A were considerably higher than the background levels obtained on May 3 (Figure 3.6, grey graphs).



**Figure 3.5. The AC-fields of transect 5 obtained April 28, 2016.**

The upper panel shows the total magnetic AC-field and the lower panel the total electric AC-field.

Comparing DC- and AC-signals, it can be concluded that the average amplitude of the magnetic AC-field was about 3 times weaker than the average magnetic DC-field (positive deviation). This ratio can be visually observed in Figure 3.4 where the AC-field appears as an increased broadening in close vicinity to the cable crossing.



**Figure 3.6. Estimated spectra for transect 5 of the Cross Sound Cable obtained on April 28, 2016.**

The upper panel shows the magnetic AC-field (black) and the lower panel the electric AC-field (black). The electric current was 16 A. The grey graphs shows the background levels obtained at a 358 m distance from the cable on the May 3.

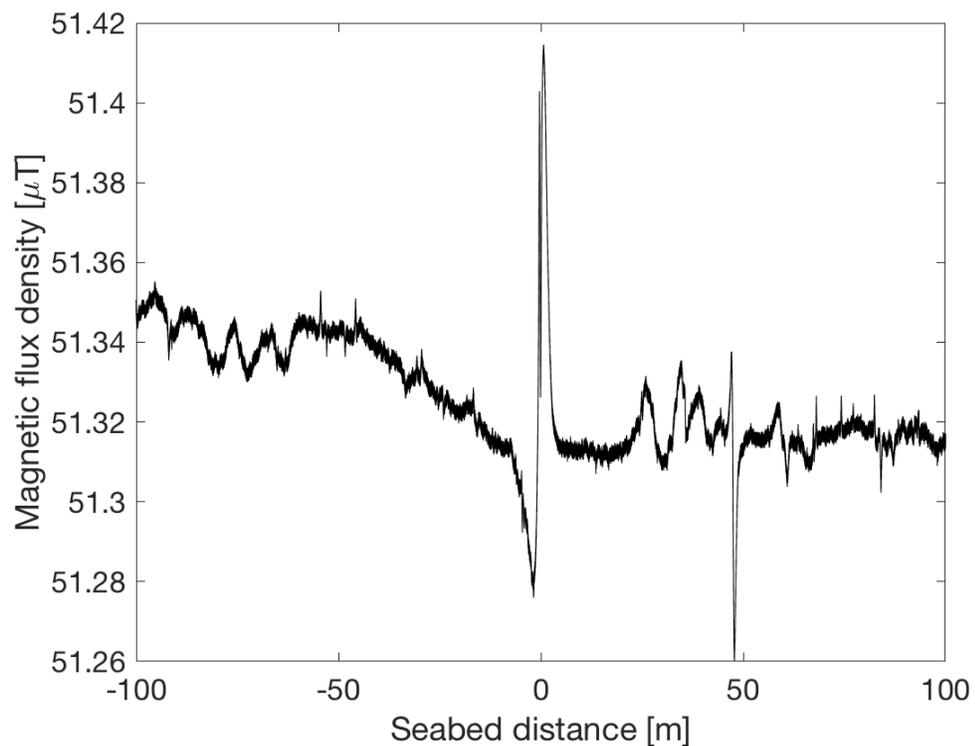
It should be emphasized that the presence of the AC-fields strongly indicates that there was current in the cable even though it was low.

### 3.11 Results from Cross Sound Cable with no electric current

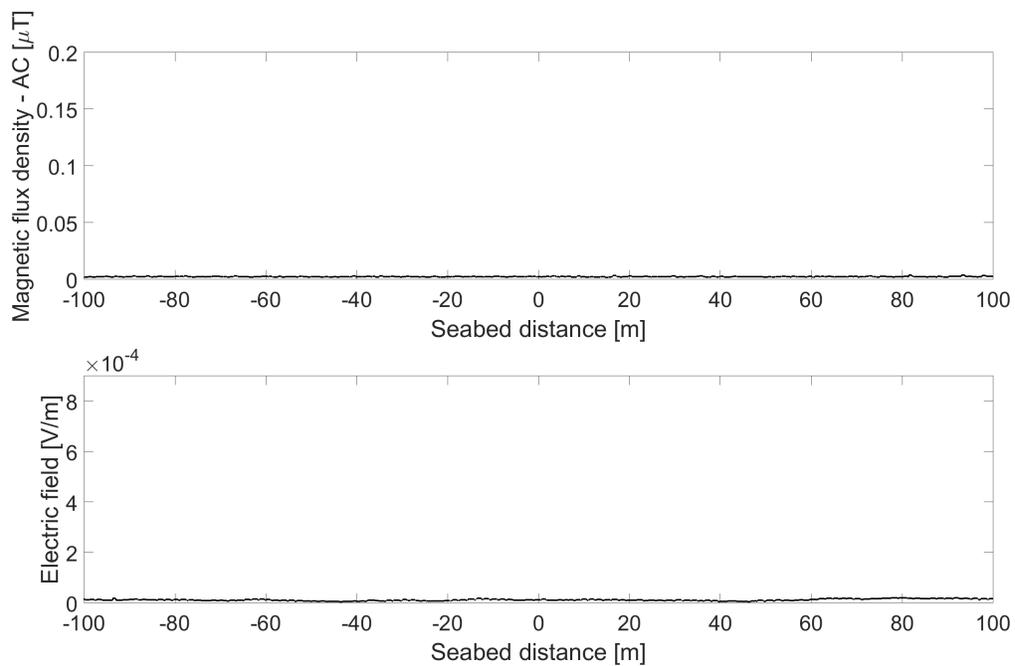
On the May 9, 2016 survey day, the Cross Sound Cable was out of operation and no electric current was transmitted in the cable. Nine surveys were performed with almost perpendicular crossings over the cable. The observed magnetic field is shown in Figure 3.7. The average DC-field with no electric current in the cable was twice as weak as when the electric current was 16 A. Nevertheless, a DC-deviation was discernable at the crossing point, probably due to the magnetization of cable material. The most prominent indication of the “no current in the cable” status and the result thereof is shown in Figure 3.8, which was plotted at the same scale as Figure 3.5. There is no sign of any AC-fields in the measurement; none of the nine crossings on May 9, 2017 indicated any presence of AC-fields. The Power Spectral Density for transect 4 is shown in Figure 3.9. Comparing the graphs in Figure 3.6 and 3.9 it is noted that the amplitudes of the AC-fields were much lower on May 9. It was further observed that the spectrum did not change as a function of distance from the cable, supporting the statement that the cable did not generate the observed AC-fields, which is further corroborated by the measured background levels obtained on 3 May (Figure 3.9, grey graphs). A broad peak of unknown origin is also observed at 1400 Hz.

**Table 3.2. Measured magnetic and electric fields obtained on May 9, 2016 when the Cross Sound Cable was off line. No current was flowing in the cable. NO designates No values.**

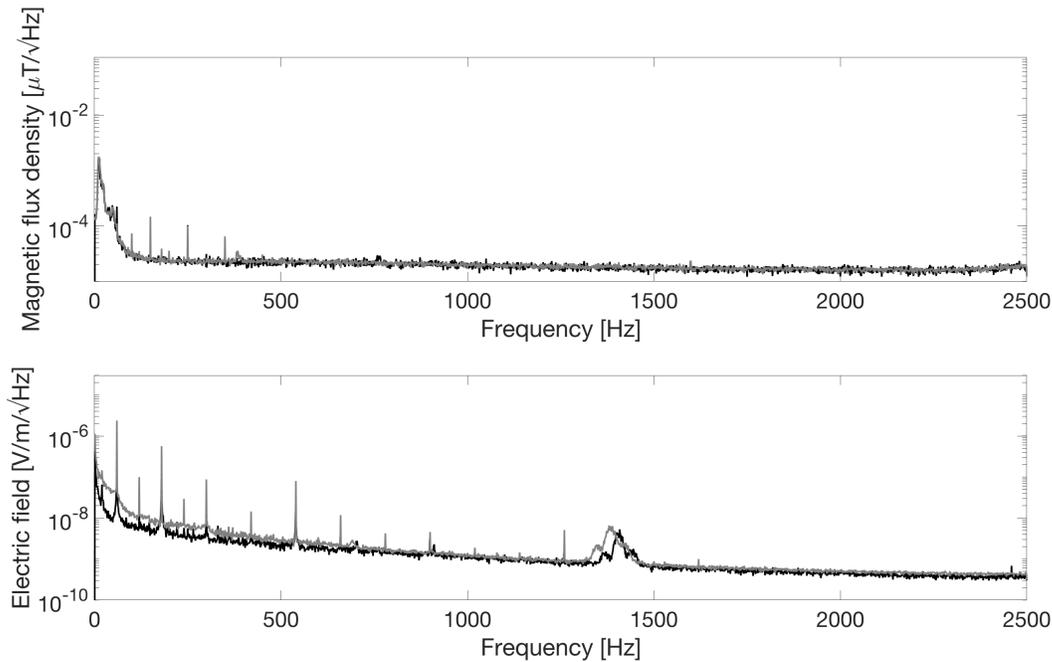
<b>Transect</b>	<b>Positive deviation of total magnetic field</b>	<b>Negative deviation of total magnetic field</b>	<b>Amplitude of total magnetic field</b>	<b>Amplitude of total electric field</b>	<b>Current</b>
	DC	DC	AC	AC	
	$\mu\text{T}$	$\mu\text{T}$	$\mu\text{T}$	V/m	A
<b>1</b>	0.46	0.66	NO	NO	0
<b>2</b>	0.02	0.04	NO	NO	0
<b>3</b>	0.08	0.06	NO	NO	0
<b>4</b>	0.1	0.04	NO	NO	0
<b>5</b>	0.11	0.04	NO	NO	0
<b>6</b>	0.2	0.03	NO	NO	0
<b>7</b>	0.19	0.07	NO	NO	0
<b>8</b>	0.18	0.11	NO	NO	0
<b>9</b>	0.26	0.07	NO	NO	0
<b>Average value</b>	0.18	0.12			
<b>Maximal value</b>	0.46	0.66			
<b>Median value</b>	0.18	0.06			



**Figure 3.7.** The total magnetic field observed at transect 4 obtained on May 9, 2016. The deviation from the Earth's magnetic field is observable.



**Figure 3.8.** The AC-fields of transect 4 obtained May 9, 2016. The upper panel shows the total magnetic AC-field and the lower panel the total electric AC-field. No obvious signal was detected at the crossing point.



**Figure 3.9. Estimated spectra for transect 4 of the Cross Sound Cable obtained May 9, 2016.** The upper panel shows the spectrum for the magnetic field (black) and the lower panel for the electric field (black). There was no electric current in the cable. The grey graphs show the background levels obtained at 358 m distance from the cable obtained on May 3.

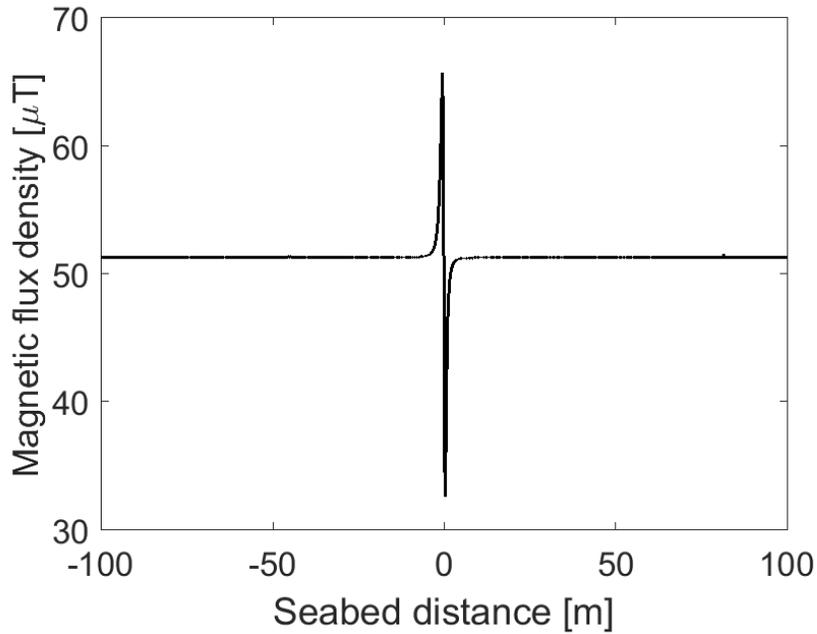
### 3.12 Results from an operational Cross Sound Cable

On May 3, 2016 the Cross Sound Cable was in operation transmitting 345 A (maximum current corresponds to 1175 A). Thirteen surveys were performed with crossings almost perpendicular to the cable. The levels of the observed magnetic DC-field increased considerably compared to the field strength observed on April 28, 2016. The results are summarized in Table 3.3. Relatively high levels of magnetic DC-fields were observed at transect 7, where the maximal deviation was found to be 18.7  $\mu\text{T}$  (Figure 3.10). Consequently, this hot spot area was chosen for the deployment of the treatment enclosure. The average magnetic DC-field for all transects was 3.8 and 2.8  $\mu\text{T}$  with medians values of 2.3 and 1.2  $\mu\text{T}$ . An important result is that these observations show that electric current in the cable generate deviations comparable to strength of the Earth's magnetic field.

The median magnetic levels of the AC-field at 345 A were 0.11  $\mu\text{T}$  and 0.67 mV/m. These values were comparable to levels obtained at a 16 A electric current (Table 3.1), which were 0.13  $\mu\text{T}$  and 0.76 mV/m. This observation suggests that the magnetic and electric AC-fields do not scale. However, the manner in which the converter stations are run when in maintenance mode has not been investigated. Validity of scaling should be tested with different levels of power transmission. Figure 3.11 indicates that the width of the electric AC-field peak was broader than the corresponding magnetic AC-field peak. This relationship was observed for all surveys with electric current running in the cable.

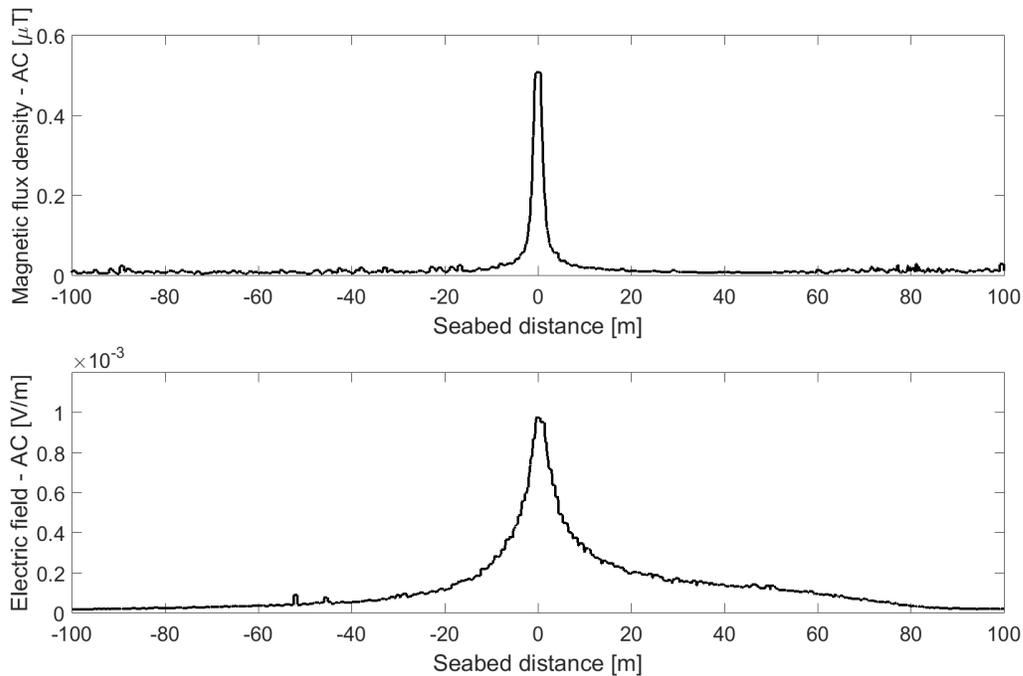
**Table 3.3. Measured magnetic and electric fields obtained on May 3, 2016. In the morning the cable was run with a maintenance current of 16 A then increased to 345 A.**

Transect	Positive deviation of total magnetic field	Negative deviation of total magnetic field	Amplitude of total magnetic field	Amplitude of total electric field	Current	Estimated burial depth
	DC	DC	AC	AC		
	μT	μT	μT	V/m	A	feet
<b>1</b>	0.49	0.38	0.18	7.00E-04	16	
<b>2</b>	0.53	0.37	0.09	7.00E-04	16	
<b>3</b>	2.23	1.15	0.11	6.10E-04	345	5.5
<b>4</b>	1.49	1.11	0.1	6.70E-04	345	No fit
<b>5</b>	2.33	1.1	0.1	6.70E-04	345	5.5
<b>6</b>	1.41	0.97	0.08	6.10E-04	345	No fit
<b>7</b>	14.3	18.7	0.51	9.70E-04	345	1.9
<b>8</b>	3.85	1.2	0.13	8.20E-04	345	4.4
<b>9</b>	5.27	1.48	0.14	7.40E-04	345	3.8
<b>10</b>	2.3	1.41	0.09	6.70E-04	345	5.5
<b>11</b>	2.11	0.87	0.09	6.70E-04	345	5.7
<b>12</b>	3.48	1.85	0.14	7.80E-04	345	4.3
<b>13</b>	2.95	1.25	0.12	7.30E-04	345	4.9
<b>Average value (3-13)</b>	3.79	2.83	0.15	7.22E-04		
<b>Maximal value (3-13)</b>	14.3	18.7	0.51	9.70E-04		
<b>Median value (3-13)</b>	2.33	1.2	0.11	6.70E-04		



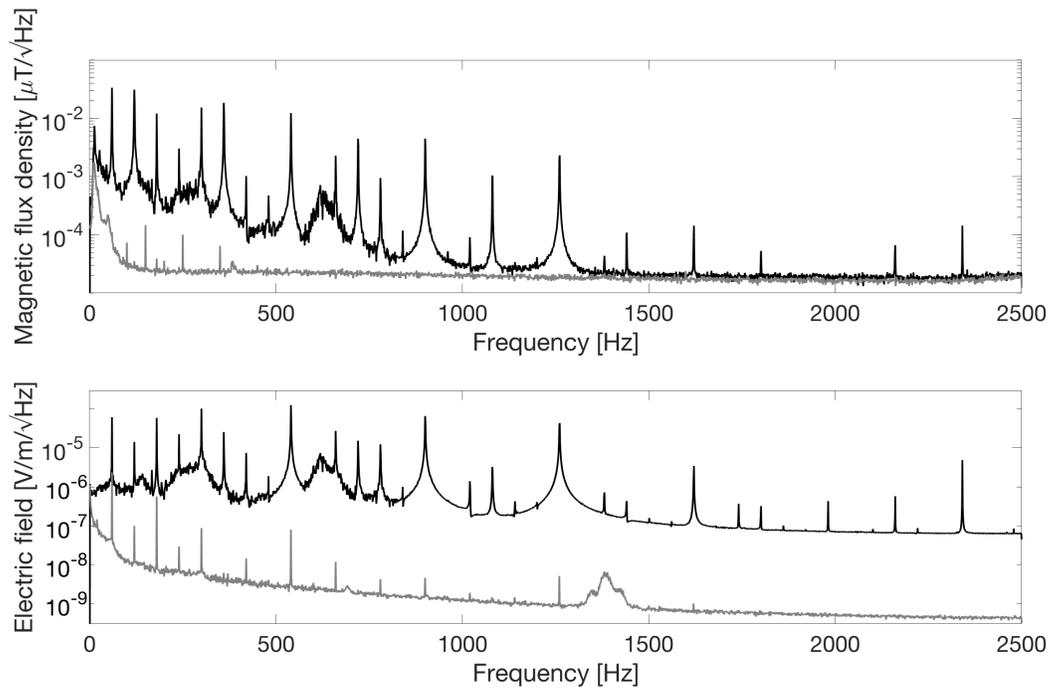
**Figure 3.10. The measured magnetic field observed at transect 7 on 3 May 2016.**  
 The deviation of the Earth's magnetic field is in the order of 20  $\mu\text{T}$ . The electric current in the cable was 345 A.

The main frequency harmonic of transect 7 was 60 Hz followed by 120 and 300 Hz harmonics for the magnetic field. The electric field was dominated by 540 Hz followed by 300, 60 and 180 Hz harmonics. The observed levels were considerable higher than the background levels obtained on May 3 (Figure 3.12, grey graphs).



**Figure 3.11. The measured magnetic and electric AC-fields at crossing 7 obtained on May 3, 2016.**

The upper panel shows the total magnetic AC-field and the lower panel the total electric AC-field.

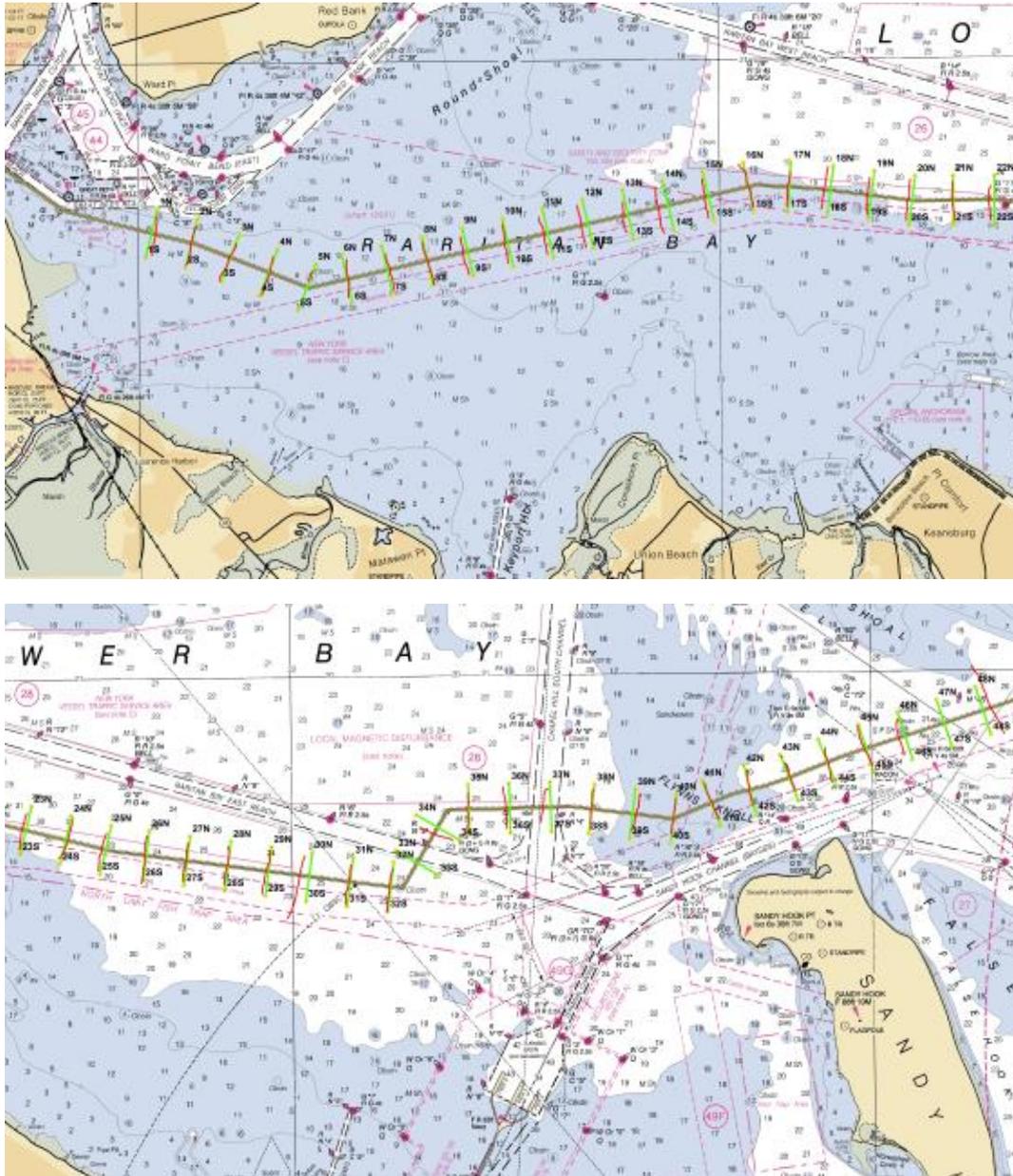


**Figure 3.12. Estimated spectra for transect 7 obtained on May 3, 2016.**

The upper panel shows the magnetic field (black) and the lower panel the electric field (black). The electric current was 345 A. The grey graphs shows the background levels obtained at 358 m distance from the cable obtained on 3 May 2016.

### 3.13 Results for the Neptune Cable

The survey was performed in Raritan Bay offshore of New Jersey on August 16 and 17, 2017 (Figure 3.13). The SEMLA was towed on the seabed using the same experimental methodology as for the Cross Sound Cable. In total 45 transects were made almost perpendicular to the cable direction. The current in the cable was 660 A and 1320 A on August 16 and 1320 A on August 17.

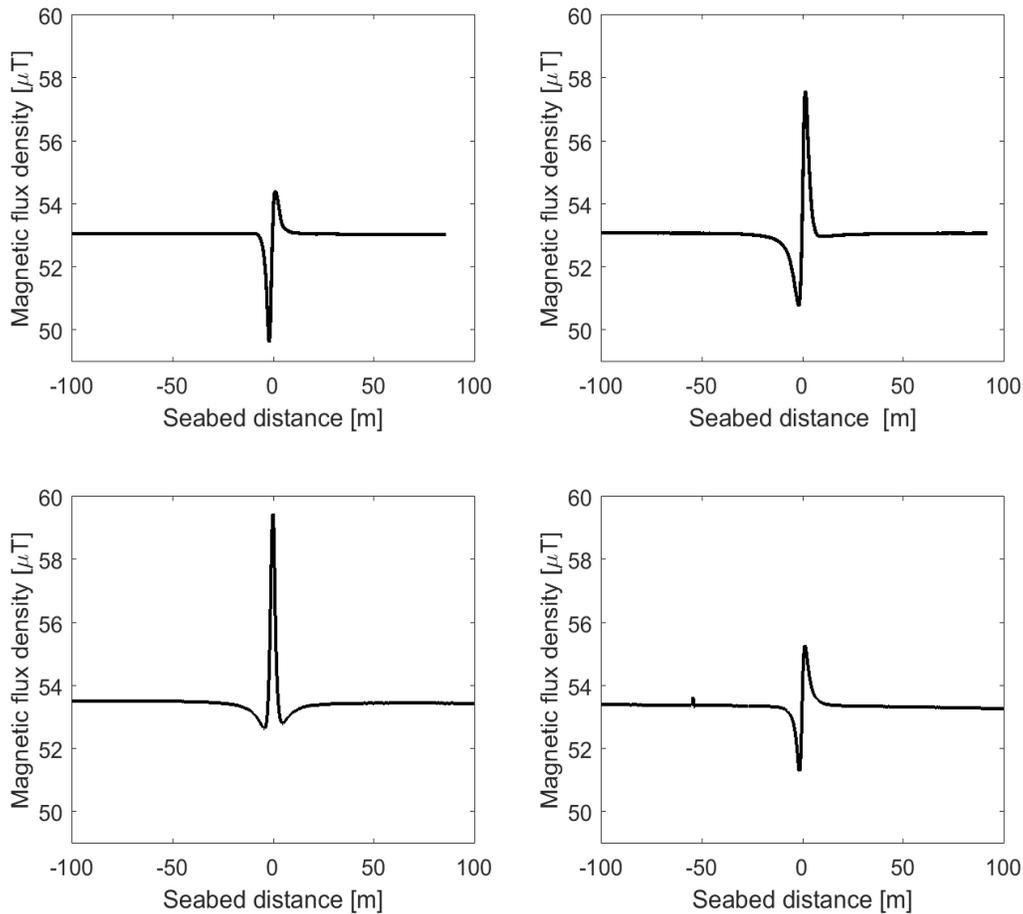


**Figure 3.13. The Neptune Cable survey.**

The black and yellow line marks the Neptune Cable, the green line the planned transects and the red graph the actual transects. In total 45 transects were surveyed. The upper panel shows the western part of the survey and the right panel the eastern part.

All transects resulted in both magnetic and electric field measurements. In general, different shapes of the total magnetic field were observed. Four transects are shown in Figure 3.14 to exemplify the variety of

observed shapes of the total magnetic DC-field. The shapes are the result of the two bundled cables having different angles relative to the vertical direction, i.e. the bundled cables were laid rotated in the sediment along the cable path.



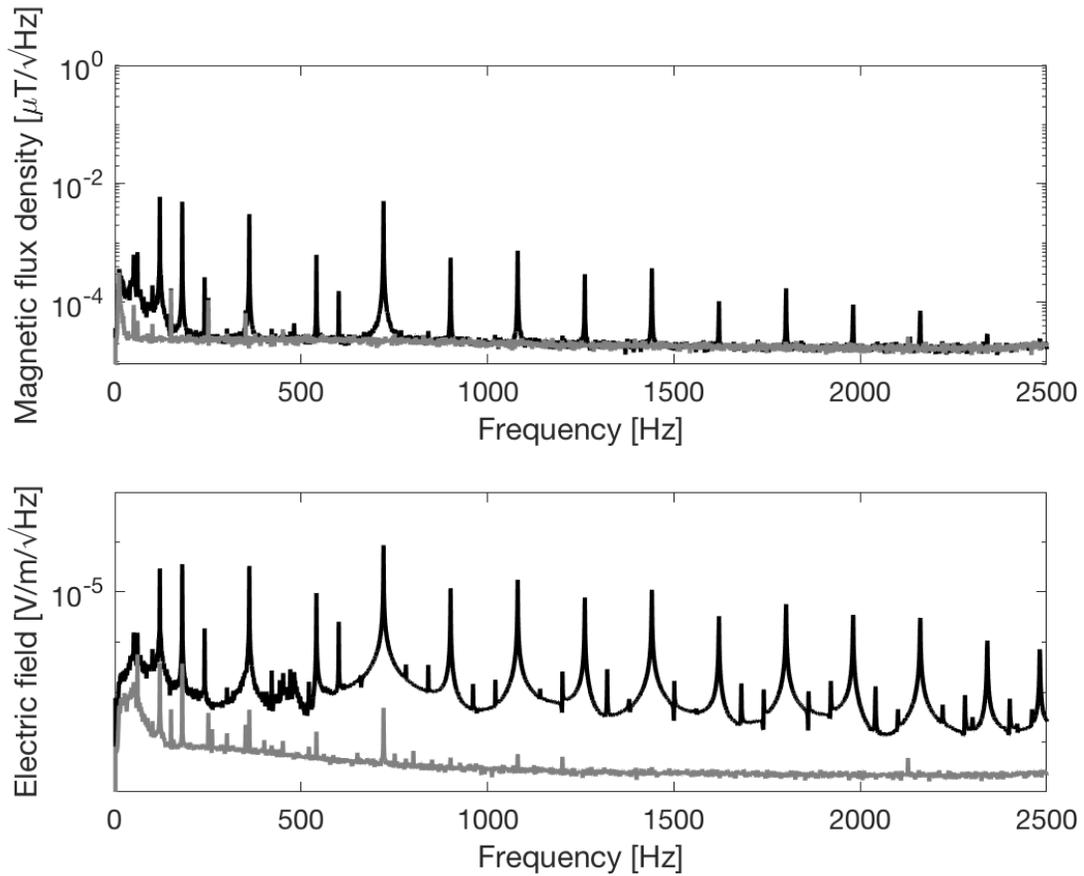
**Figure 3.14. Magnetic DC-field obtained at four different transects along the Neptune Cable.**

The two cables were rotated relative to the vertical direction, which accounts for the shapes. Upper left panel transect 23 (1320 A) upper right panel transect 25 (1320 A), lower left panel transect 26 (1320 A) and lower right panel transect 16 (660 A).

Magnetic and electric fields were obtained at full power, corresponding to 1320 A, for 33 transects. The average positive deviation of the magnetic DC-field relative to Earth’s magnetic field was 6.8  $\mu\text{T}$  and the average negative deviation of the magnetic DC-field was 2.2  $\mu\text{T}$ . Maximum observed deviation was 21  $\mu\text{T}$ . The results of the Neptune survey for an electric current of 1320 A are compiled in Table 3.4.

The AC-fields at 1320 A were estimated using the same processing techniques as for the Cross Sound Cable. The average magnetic AC-field was 0.04  $\mu\text{T}$  and the average electric AC-field was 0.4 mV/m. The

dominating frequency for both the magnetic and electric field was 720 Hz, followed by 120, 180 and 360 Hz harmonics (Figure 3.15).



**Figure 3.15. Estimated spectra for transect 26 of the Neptune Cable.**

The upper panel shows the spectrum for the magnetic field (black) and the lower panel for the electric field (black). The current was 1320 A in the cable. The grey graph shows the fields obtained on the same transect at 180 m distance from the cable.

The results of the Neptune survey are compiled in Table 3.4.

**Table 3.4. Survey results from the Neptune Cable. The electric current was 1320 A.**

Transect number	Positive deviation of total magnetic field	Negative deviation of total magnetic field	Amplitude of total magnetic field	Amplitude of total electric field	Current	Estimated burial depth
	DC μT	DC μT	AC μT	AC V/m		
48	20.7	3.3	0.08	4.03E-04	1320	3.8
46	9.2	5.5	0.09	4.93E-04	1320	5.7
44	10.2	6.9	0.09	6.51E-04	1320	4.8
42	5.3	0.77	0.034	3.37E-04	1320	7.6
40	10.5	2.4	0.064	5.46E-04	1320	5.4
38	5	0.8	0.028	3.32E-04	1320	7.8
36	6.9	0.87	0.044	4.04E-04	1320	6.6
34	4.7	2.3	0.046	5.08E-04	1320	7.2
32	5.5	0.8	0.037	4.38E-04	1320	7.4
30	4.4	1.9	0.04	4.17E-04	1320	7.8
28	5.9	0.7	0.037	3.93E-04	1320	7.2
26	5.8	0.8	0.036	3.80E-04	1320	7.2
24	4.9	1.4	0.035	3.31E-04	1320	7.6
22	4.5	0.8	0.03	3.40E-04	1320	8.3
20	10.3	6	0.06	5.25E-04	1320	5.1
45	8.4	1	0.02	4.11E-04	1320	GPS error
43	8	1.4	0.029	3.92E-04	1320	6.2
41	5.4	2.4	0.017	3.87E-04	1320	7.3
39	5.7	8.3	0.04	4.62E-04	1320	5.5
37	1.3	0.3	0.0066	2.05E-04	1320	No fit
35	7.5	1	0.02	3.87E-04	1320	6.5
31	5.8	0.8	0.03	3.96E-04	1320	7.2
29	5.4	1	0.037	4.59E-04	1320	7.4
27	5.1	1.4	0.015	3.98E-04	1320	7.6
25	4.4	2.2	0.023	3.82E-04	1320	7.6
23	1.3	3.3	0.024	3.61E-04	1320	8.6
21	4.7	0.6	0.011	4.35E-04	1320	8.0
19	11.4	6.5	0.041	6.39E-04	1320	5.0
17	5.2	1.4	0.025	4.75E-04	1320	7.4
15	5.7	0.8	0.02	4.06E-04	1320	7.3
13	7.2	1.5	0.035	4.26E-04	1320	6.5
11	4.9	1	0.03	3.64E-04	1320	7.8
09	5.3	1.1	0.037	3.69E-04	1320	7.4
<b>Maximal value</b>	20.7	8.3	0.09	6.5E-04		
<b>Average value</b>	6.8	2.2	0.04	4.2E-04		
<b>Median value</b>	5.5	1.4	0.035	4.0E-04		

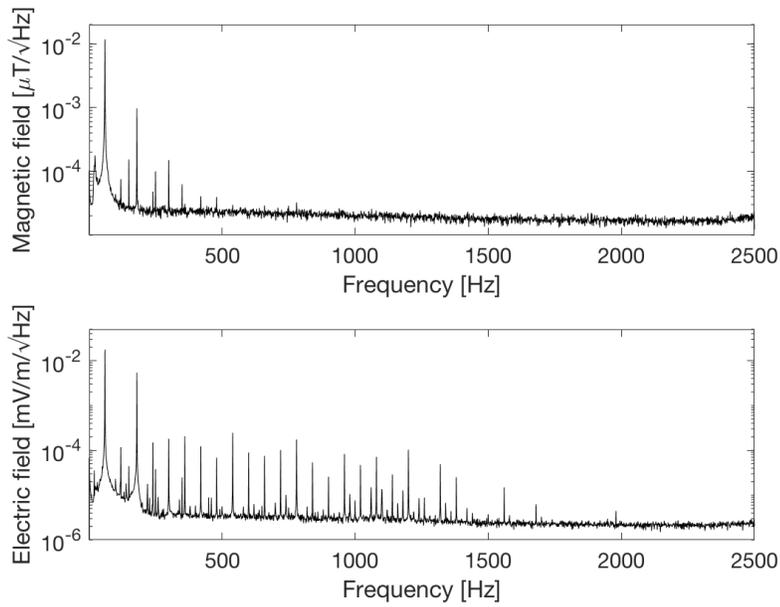
Twelve transects were measured when the current was 660 A. The average positive magnetic deviation of the DC-field relative to Earth's magnetic field was 3.0  $\mu\text{T}$  and the average negative deviation of the magnetic DC-field was 0.9  $\mu\text{T}$ . The results confirm that the DC-fields behave as expected, i.e. the DC-level (deviation) increases when the electric current increases. The corresponding AC-fields at 660 A were 0.023  $\mu\text{T}$  and 0.24 mV/m. Comparing the AC-results obtained at 660 and 1320 A, it can be concluded that the AC-fields are scalable with the applied electric current.

The end of transect 26 located at 180 m distance from the cable were used to estimate the background levels. The spectrum for the magnetic field was dominated by 50 Hz and its harmonics. Just like the Cross Sound Cable, these harmonics were generated by the onboard electronics that were powered by a 50 Hz power supply. The electric field at 180 m distance was still present but was considerably lower than what was observed at the crossing point (Figure 3.15). Both the magnetic and electric backgrounds were comparable to the levels obtained for the Cross Sound Cable.

### **3.14 Results from the sea2shore cable**

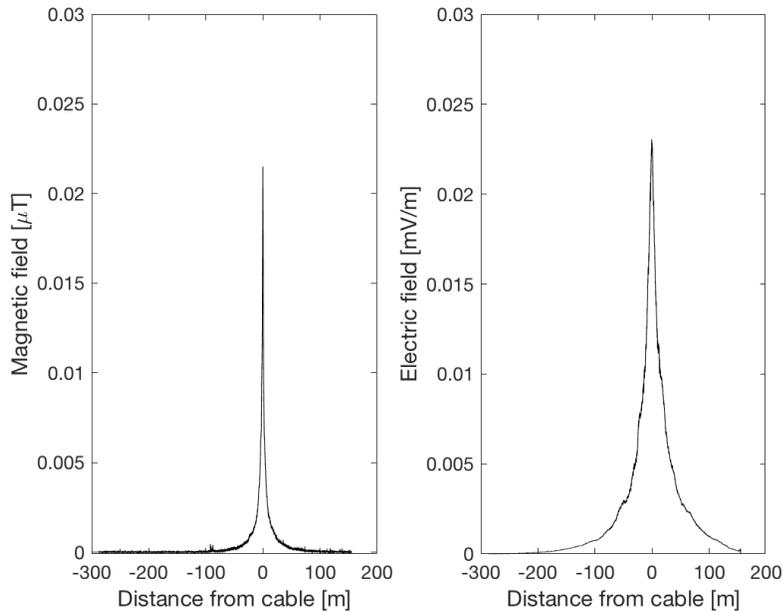
The sea2shore cable was surveyed in July, 2017. This survey was done for National Grid, the cable operator. The survey was intended to address concerns expressed by Rhode Island environmental managers from the Department of Environmental Management and the Coastal resources Management Council that in areas where the cable was not buried to full project depth, it might generate high enough EMFs to impact marine organisms. The survey did not find high enough EMFs to be of concern. Measurements of electric and magnetic fields were obtained along transects almost perpendicular to the cable at nominal 1-km line intervals and were evenly distributed over the full cable length. In total, 44 transects were surveyed. The 60 Hz harmonic dominated the fields (Figure 3.16). Higher harmonics were present but relatively lower in strength compared to 60 Hz. The shape of the crossings (strength as a function of distance from the cable) indicates the presence of both balanced and unbalanced currents. The presence of the latter is noticeable as wings in Figure 3.17. The unbalanced current can, however, not explain the field strength observed at the crossing point. In this region the field strength from the unbalanced currents is too weak to account for the observed peak value. Inferring the balanced currents into the equation will make up for the "missing" contribution.

The measured magnetic field levels were extracted and scaled to full power, which corresponds to an electric AC-current of 502 A per conductor. The scaled magnetic fields were in the range 0.005 to 3.1  $\mu\text{T}$  and the electric fields were 0.02 to 0.25 mV/m. The upper limits were the strongest levels observed during the sea2shore cable survey.



**Figure 3.16. Estimated spectra for the sea2shore cable.**

The upper panel shows the spectrum for the magnetic field and the lower panel for the electric field. The current in the cable was 95 A.



**Figure 3.17. The observed AC-fields from the sea2shore cable.**

The left panel shows the magnetic field and the right panel the electric field. The electric field is observed to be broader than the magnetic field.

### 3.15 The fields at the reference enclosure near the CSC

The reference enclosure was deployed 358 m from the cable. The southern branch of the large loop in Figure 3.3 passed this location. The measured fields were extracted at 358 m and the Power Spectral Density was estimated for both the electric and magnetic fields. Even if the current was 345 A on this occasion and not 1175 A (corresponding to full power), the spectra are representative for the fields that the species were exposed to in the reference enclosure. The measured background fields at 358 m are shown in Figure 3.6, 3.9 and 3.12 where they are compared to levels at 16, 0 and 345 A. The spectra in Figure 3.9 strongly indicate that the species in the reference enclosure were exposed to ambient background levels.

### 3.16 The fields at the treatment enclosure on the CSC

The result of the Cross Sound Cable survey on May 3, 2016 showed that there was a magnetic “hotspot” area at transect number 7 where the deviation of the field was exceptionally strong. The treatment enclosure was deployed in this area for this reason. The long-sides of the enclosure were marked with 20 equidistant marks, corresponding to 0.25 m steps, covering the full length of the enclosure’s long-side. To map out the magnetic field, a diver stopped at each mark and placed the fluxgate sensor on the mark, the magnetic field levels were measured for about 12 seconds, thereafter the diver moved the fluxgate to the next mark. This procedure was repeated for both sides of the enclosure and for the fluxgate sensor placed at the seabed, mid depth (1.25 m height above seabed) and top of the enclosure (2.5 m height above the seabed). During the survey the electric current was 1175 A, which corresponds to full power transmission. The fluxgate mounted on the SEMLA was detached and used in standalone mode in this survey. The results from the diver-based survey are presented in Figure 3.18. The magnetic field at the seabed was strong as expected and a clear deviation from the Earth’s magnetic field was observed. However, the measured fields at mid and top levels of the enclosure were weaker and affected by noise. The maximum deviation at seabed level were found at 1 m and 1.25 m horizontal distance from the short side of the enclosure, indicating that the long-side of the enclosure was positioned at a 94 degree angle relative to the cable direction.

The observed levels suggest that the magnetic field generated by a bundled cable pair is complex. The resulting field is the result of a superposition of the Earth’s magnetic field and the cable-generated field, which introduces an asymmetry between the two sides of the cable. The reason is that the cable-induced magnetic field will enhance on one side and oppose the Earth’s magnetic field on the other side. The survey shows that the field inside the enclosure had both a maximum and a minimum at seabed level, whereas at mid level and higher only maxima occurred.

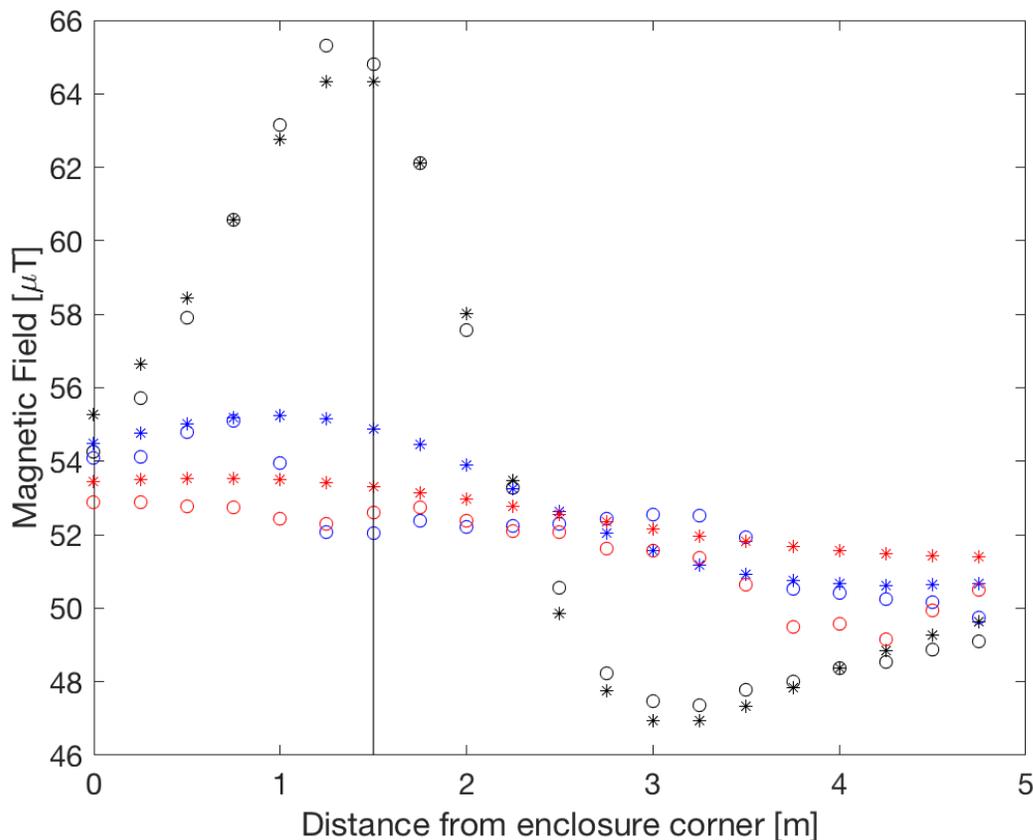
The diver survey not only gave detailed information on the field inside the enclosure volume but was used for modeling of the cable configuration. A fast numerical model of the two bundled cables was developed and used for optimization of the cable configuration. The model was employed since it can be iteratively used for predicting the optimal parameters, whereas the COMSOL model discussed in Section 4 of this report is too slow to be used in this application. The "fast" model estimated the magnetic DC-field generated by two bundled cables placed in a non-magnetic and non-conductive media at a specific height above the cable pair. In contrast to the COMSOL model, the fast model did not account for the magnetic properties of the cable. The current was kept fixed at 1175 A in accordance with the reading made by the power company, but the angle between the cables relative to the vertical direction, the separation of cable centers and burial depth were selected as free parameters. Only the measured magnetic fields at the seabed were used in the optimization. The objective function,  $L$ , was defined as:

$$L = \sum_{n=1}^{20} \|B_{measured} - B_{modeled}\|^2$$

where  $B$  corresponds to magnetic flux density of the DC-field. The error per fitted point ( $L/20$ ), was  $0.28 (\mu\text{T})^2$ , which is reflected in the visual agreement between the two black graphs in Figure 3.18. The model predicts that the maximum magnetic DC-field at seabed was  $65 \mu\text{T}$ , the field at mid level was  $55 \mu\text{T}$  and at the top of the enclosure even lower. Note that the model was used to derive the levels at mid and top levels, based on the fitted parameters from the optimization made on magnetic fields at the seabed.

The model results show a good agreement with the measurement at seabed level and a principle agreement with the mid and top levels. The mid and top levels are not only weaker but the spatial shape of the field was different compared to the field at seabed level. Both the measured and modeled magnetic field at seabed level had both a maximum and a minimum, while the model predicts that there was only a maximum at the mid and top level in the enclosure, which seems to agree with the observations.

The model results also indicate that the two bundled cables were placed at 120 degrees relative to the vertical direction, the separation between the two cables was 0.1 m and the burial depth 1.3 m (4.4 feet). Even if the model is not validated, it demonstrates that it can be used both for deriving burial depth and for modeling the expected field as a function of angle, depth and electric current. It further agrees with the modeling result presented in Section 4.2.5.



**Figure 3.18. Measured and modeled magnetic fields inside the treatment enclosure area.** The measured fields are plotted with stars and the modeled with open circles. The optimization was done on the magnetic field measured at the seabed. The black marks show the measured and modeled result for the seabed, the blue for mid-level and the red for top level. The long side of the enclosure starts a 0 m and ends at 5 m.

The model reveals that the cable was positioned 0.25 m off relative to the magnetic peak level towards the center of the enclosure; the black vertical line in Figure 3.18 indicates the position of the cables according to the model result.

Running the model with 345 A and a burial depth of 2 m (target burial depth) gives a deviation on the order of 2  $\mu$ T, which seems consistent with the observation of average deviations made on May 3, 2017 when the cable was transferring a current of 345 A, see Table 3.3. The actual burial depth was not known but the hydraulic jet plow had the capacity to bury the cable up to 2 m depth in to the seabed (Power Engineering, Improved reliability).

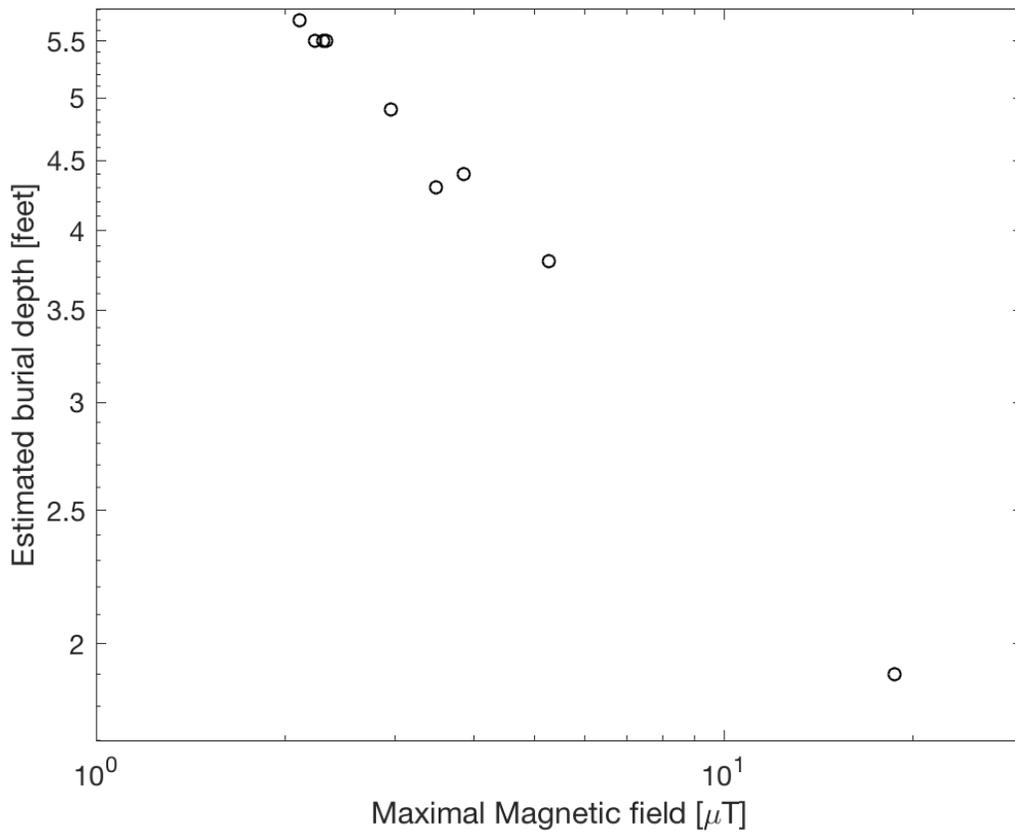
### 3.17 Estimated burial depth of the Cross Sound Cable and the Neptune Cable

The model outlined in section 3.16 was used to estimate the burial depth of the cables. The distance between the cables was set to be fixed at 0.106 m, while the angle and the burial depth were used as free parameters. The modeled results are summarized in Table 3.3 and 3.4 in the last column. A comparison between target depths and estimated depths obtained from models is summarized in Table 3.5.

**Table 3.5. Comparison between target design burial depths and model estimated burial depths.**

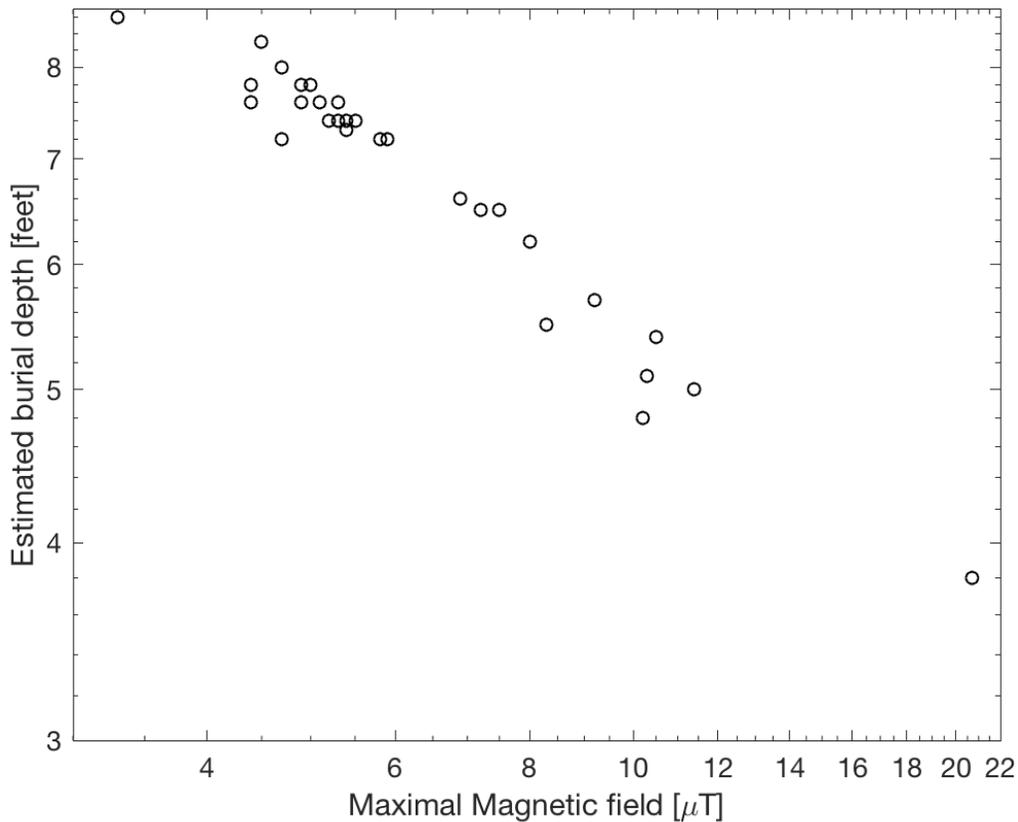
Cable Name	Target Depth ft (m)	Estimated Depth ft (m)
Cross Sound	6.6 (2.01)	1.9 - 5.7 (0.58 - 1.74)
Neptune	4 (1.22)	3.8 - 8.6 (1.16 - 2.62)

It should be stressed that the model does not take into account the magnetic properties of the cable and that numbers of the estimated burial depths should be regarded as relative but inter-comparable. Test runs with the COMSOL model showed that the permeability of the cables will increase the strength of the magnetic DC-field compared to a cable without armor. The target burial depth of the Cross Sound Cable was up to 6 feet and for the Neptune Cable 4 to 6 feet. The model results are consistent with the hypothesis that the magnetic field strength is related to the burial depth. Logarithmic plots of the results are shown in Figure 3.19 and 3.20.



**Figure 3.19. Estimated burial depth and measured maximal deviation of the magnetic field for the Cross Sound Cable.**

The estimated burial depths as a function of maximal magnetic fields are plotted with open circles. The measured field of transect 7 for 345 A was observed to be exceptionally strong (18.7  $\mu\text{T}$ ). The targeted burial depth was up to 6 feet.



**Figure 3.20. Estimated burial depth and measured maximal deviation of the magnetic field for the Neptune Cable.**

The estimated burial depths as a function of maximal magnetic fields are plotted with open circles. The magnetic fields were obtained at 1320 A. The measured field of transect 48 was observed to be exceptionally strong (20.7  $\mu\text{T}$ ). The target burial depths were between 4 and 6 feet.

### 3.18 Comparison between the Cross Sound Cable, Neptune Cable and Sea2shore Cable

The Cross Sound Cable and the Neptune Cable are two DC-current carrying cables based on the HVDC-technique, where both utilize a pair of bundled cables. The maximum rated electric currents are 1175 and 1320 A. It was observed that both cables produced magnetic DC-fields that were comparable to the Earth's magnetic field strength. The observations show that the levels increased with increased electric current, which was expected. The average deviation of the magnetic DC-field for the Cross Sound Cable was 4  $\mu\text{T}$  (345 A) and for the Neptune Cable 7  $\mu\text{T}$  (1320 A). The strength of the magnetic DC-field at the crossing points were observed to vary for different locations along the cable route even if the electric current was constant. This effect is most probably explained by variation in the burial depth of the cable. The strongest observed deviation from the Earth's magnetic field for the Cross Sound Cable was 18.7  $\mu\text{T}$  (345 A) and for the Neptune Cable 20.7  $\mu\text{T}$  (1320 A). The minimum deviations were observed to be 0.4  $\mu\text{T}$  (345 A) for the Cross Sound Cable and 0.3  $\mu\text{T}$  (1320 A) for the Neptune Cable.

The Cross Sound Cable and Neptune Cable were observed to generate magnetic AC-fields, which in turn induced electric AC-fields. As expected, the sea2shore cable generated only AC-fields. The profile of the electric AC-fields were observed to extend over a larger area than the corresponding magnetic AC-fields for all transects and for the three cables. The analysis showed that the AC-levels of the Neptune Cable scale with the electric current, while the same dependence was not clearly observed for the Cross Sound Cable.

The average magnetic AC-fields were observed to be 0.04  $\mu\text{T}$  for the Neptune Cable (1320 A), 0.15  $\mu\text{T}$  for the Cross Sound Cable (345 A) and in the range 0.005 to 3.1  $\mu\text{T}$  for the sea2shore cable (scaled to 502 A). The average electric AC-fields were observed to be 0.4 mV/m for the Neptune Cable (1320 A), 0.7 mV/m for the Cross Sound Cable (345 A) and in the range 0.02 to 0.25 mV/m for the sea2shore cable (scaled to 502 A).

The strongest magnetic AC-fields were observed to be 0.09  $\mu\text{T}$  for the Neptune Cable (1320 A), 0.51  $\mu\text{T}$  for the Cross Sound Cable (345 A) and 3.1  $\mu\text{T}$  for the sea2shore cable (scaled to 502 A). The strongest AC-fields were observed to be 0.65 mV/m for the Neptune Cable (1320 A), 0.97 mV/m for the Cross Sound Cable (345 A) and 0.25 mV/m for the sea2shore cable (scaled to 502 A).

### **3.19 Conclusions**

Three subsea power cables, two DC (Cross Sound and Neptune) and one AC (sea2shore) were surveyed during this study. The following conclusions can be made:

- The towed SEMLA is a sensitive, reliable, accurate and cost-effective method for conducting EMF surveys of subsea power cables in water depths of less than 50 meters.
- The cross section of EMF peaks exhibited by DC subsea power cables were broader than anticipated at both the Cross Sound and the Neptune Cables. The broader than anticipated character of the EMF peaks may have implications for biological effects.
- Significant AC electric fields were observed to be associated with both DC power cables. The AC fields reached background levels on a scale of hundreds of meters from the cables. This result was not anticipated and may have implications for biological effects.
- The AC electric fields associated with the sea2shore cable were higher than the unanticipated AC electrical fields produced by the DC cables. The magnetic and electric fields produced by the sea2shore cable were significantly lower than modeled values commissioned by the grid operator, indicating that the three-conductor twisted design achieves significant self-cancellation.
- Based on the project's field surveys, AC cables are likely to mitigate possible biological effects.

### 3.20 References

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## 4.0 Electromagnetic Fields Simulation of the Cross-sound Cable

### 4.1 Introduction

The High Voltage Direct Current (HVDC) technique is often employed for long distance electric power transmissions to achieve low power loss. The Cross Sound Cable (CSC) is a 40 km long bipolar HVDC submarine power transmission cable between New Haven and Long Island. In the power transmission process, the DC-current is fed in one cable and the neutral current is returned in the other. According to the Electromagnetic Induction Principle, these two currents will generate a stationary electromagnetic field (EMF), which could have effects on electro- and magneto-sensitive marine organisms. Within the CSC bundle, the current-carrying cables are each shielded by a metallic screen. The metallic screen is connected to the ground and could effectively confine the electric field within the cable. However, the screen cannot shield the magnetic fields. As a result, the currents will have an influence on the surrounding environment. To estimate the EMF quantity outside the cable, this chapter will specifically focus on the EMF modeling and statistical analysis of the EMF generated by the Cross Sound Cable.

An EMF simulation of the CSC is an application of computational electromagnetics. Generally, an EMF can be described by the corresponding Maxwell equations. To calculate the EMF value of a certain domain, Maxwell equations must be solved based on the specific source value and the boundary conditions. Basically, the analytical solution of the Maxwell equations could be found only if the geometries of the source and the domain are regular. For complex environments, the Maxwell equations are almost unsolvable due to the various constitutive relations of media, and complex boundary conditions. To deal with these situations, several numerical methods are developed to approximate the solution of the Maxwell equations. The Finite Element Method (FEM), also referred to as Finite Element Analysis (FEA), is a popular numerical method for solving partial differential equations over complex domains. When the EMF of a certain domain is simulated with the FEM, the problem is formulated as a set of algebraic equations. To find the solutions of the problem, the entire domain is divided into smaller parts, which are called finite elements. The EMF of the finite elements can be modeled by simple equations. Assembling these equations together, an equation system that models the entire problem can be obtained. Variational methods can then be applied to approximate a solution by minimizing an associated error function.

Computerized EMF simulation packages have been developed based on the finite element method, such as ANSYS, Maxwell, and COMSOL Multiphysics. In this work, we choose COMSOL Multiphysics (COMSOL) as our simulation platform. COMSOL is cross-platform finite element analysis, solver and multiphysics simulation software. It offers conventional physics-based user interfaces and coupled systems of partial differential equations. COMSOL provides an integrated development environment and unified workflow for electrical, mechanical, fluid, and chemical applications. The AC/DC Module is designed for EMF simulation in static and low-frequency applications. Typical applications include capacitors, inductors, coils, and motors. Moreover, in this module the materials and constitutive relations are defined in terms of permittivity, permeability, and conductivity. Material properties are allowed to be spatially varying, time-dependent, and have losses. Both electric and magnetic media can include nonlinearities, such as B-H curves, or even be described by implicitly given equations. In general, the procedures to simulate EMF using COMSOL software are as follows:

1. *Geometry definitions*: The geometry information is supplied to the Model Builder window, where the shape and the size of the objects are specified.
2. *Materials definitions*: After the geometry of the objects is defined, the materials of each part in the objects are specified.

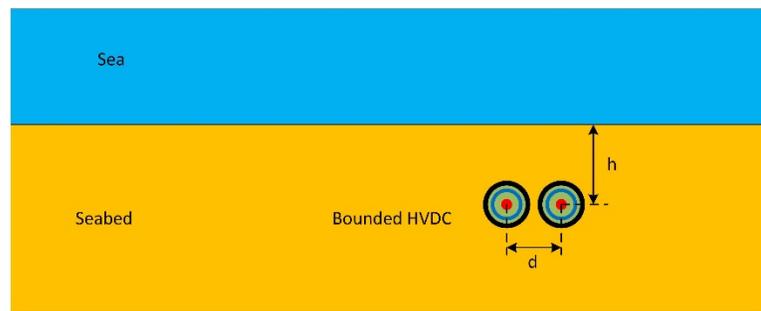
3. *Mesh definitions*: FEA requires the users to mesh the whole objects, such as specifying the distribution and the number of the elements.
4. *Study and results output*: The post-process of the results.

The simulation process in COMSOL is straightforward. Simulation results using COMSOL are discussed below.

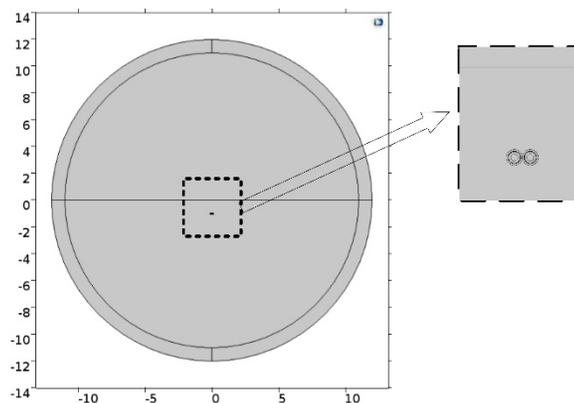
## 4.2 EMF Simulation

### 4.2.1 Geometric model

In the real power transmission scenario, two HVDC cables (a bundled cable pair) are buried under the seabed with a depth of  $h$  and distance of  $d$ , which is illustrated in Figure 4.1. To implement the EMF simulation, an effective model of the real-world cable has to be constructed. Since the cables are of a large length, it can be modelled as a straight cylinder with infinite length. Furthermore, the EMF can be studied in a cross-section with a 2D model instead of a 3D model of the entire cable. The simplified 2D geometric model is shown in Figure 4.2.



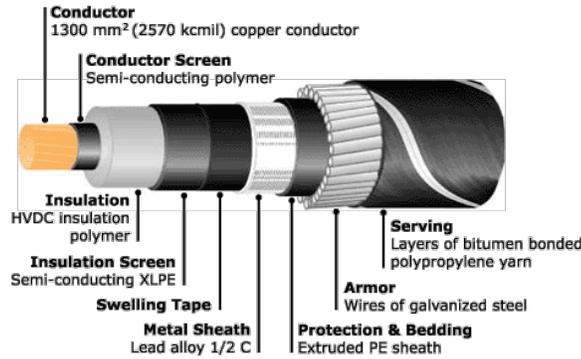
**Figure 4.1.** Cabling scenario of the subsea cable.



**Figure 4.2.** The geometric model of the undersea cross-sound cable.

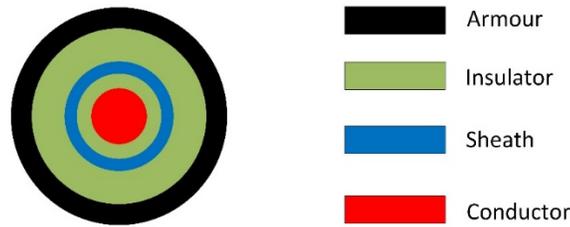
The whole analysis domain is a circle, which is divided into two main parts. The upper and lower parts represent the sea and the seabed, respectively. The outer layer of the circle is set as the infinite domain. In

the middle of the model, two cables are located in the seabed domain. The structure of the real CSC is shown in Figure 4.3.



**Figure 4.3. Inner structure of the cross-sound cable.**

The real cable contains several layers, which are made of different materials and have different functionality. However, in the EMF simulation, some layers can be either combined together, or omitted according to their electromagnetic properties. After a detailed survey of the material properties of these layers, in the simulation, the cross-section of the cable is simplified as shown in Figure 4.4.



**Figure 4.4. The cross-section of the CSC model.**

In the model, each cable is bundled by a lead sheath, which serves as an electrostatic shield. The cable is filled with polyethylene XLPE, which is an insulator. At the outermost extent, the cable is covered by a layer of steel armor, which provides stronger mechanical strength and added protection to the cable. The geometric parameters of the model are listed in Table 4.1.

**Table 4.1. Geometric parameters of the model.**

Parameters	Values
Burial depth	1.5 m
Distance between two cables	0.106 m
Cable radius	0.053m
Armour thickness	0.01m
Lead sheath radius	0.041m
Lead sheath thickness	0.04m
Conductor radius	0.0235 m

### 4.2.2 Electromagnetic properties of the materials.

The CSC contains two HVDC cables that carry a pair of opposite-directed currents. In this simulation, the absolute value of each current was set to 1175 A, which is the maximum value of the transmission current of the CSC. According to the Electromagnetic Induction Principle, each current will generate a stationary magnetic field. The two magnetic fields should cancel each other if the cables are perfectly overlapped. However, there is a distance between the two conductors resulting in a magnetic field. To simulate the EMF generated by the currents, the electromagnetic properties of the material are defined as shown in Table 4.2. The permittivity  $\varepsilon$  (F/m) and the permeability  $\mu$  (H/m) of each material are given in terms of their relative values  $\varepsilon_r$  and  $\mu_r$ , respectively. The permittivity and permeability are derived by

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0$$

$$\mu = \mu_r \cdot \mu_0,$$

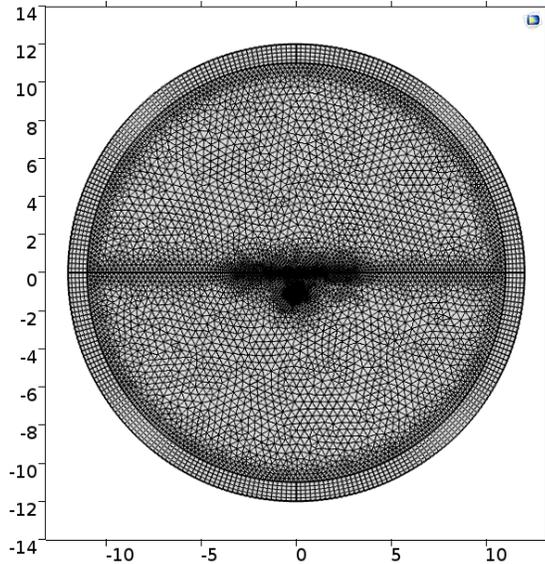
where  $\varepsilon_0$  and  $\mu_0$  are the permittivity and the permeability of vacuum, and the values of them are  $8.8542 \times 10^{-12}$  F/m and  $4\pi \times 10^{-7}$  H/m, respectively.

**Table 4.2. Electromagnetic properties of different materials.**

Name	Electrical conductivity $\sigma$ (s/m)	Relative permittivity $\varepsilon_r$	Relative permeability $\mu_r$
Conductor (Copper)	5.8e7	1.0	1.0
Sheath (lead)	1e6	1.0	1.0
Insulator (XLPE)	0	2.3	1.0
Armour (Steel wire)	1.1e6	1.0	1000
Seawater	1.0	81.0	1.0
Seabed	0.25	25.0	1.0

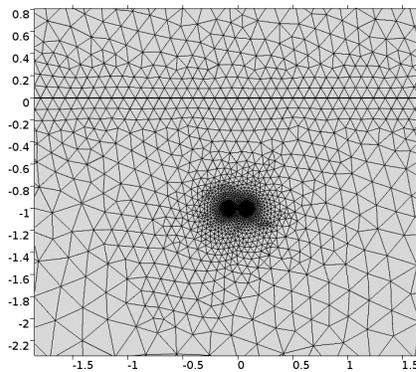
### 4.2.3 Mesh

When applying the FEM to solve the EMF of a certain domain, a necessary step is to use a mesh generation technique to divide the complex domain into small finite elements. The mesh quality will decide the accuracy of the simulation results. Generally, the finer the mesh used, the more accurate the simulation results will be. However, a finer mesh also comes with more finite elements and will increase the computational burden, which means there is a trade-off between the simulation accuracy and the computation time/memory. To improve the computational speed and guarantee accuracy, the domain where the EMF changes rapidly must be meshed with high density and other parts could use a coarse mesh. In COMSOL, there is a built-in mesh program, which enables the user to control the mesh quality conveniently. With different mesh settings on different domains, the overall mesh of our model is generated as shown in Figure 4.5.



**Figure 4.5. The mesh of the COMSOL model.**

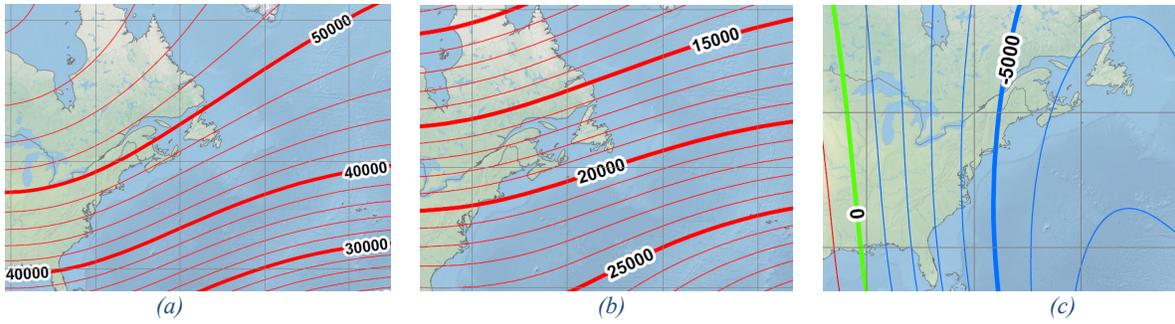
For the project the Free Tetrahedral mesh was applied for the whole analysis domain. A quadrilateral mesh is used on the infinite domain. It should be noted that the cable dimension is much smaller in comparison to the whole model and the EMF nearby varies quickly. Therefore, the mesh density around the cables was increased, which can be observed in Figure 4.6. The complete mesh of the model consists of 17952 domain elements and 1499 boundary elements.



**Figure 4.6. Mesh distribution around the cables.**

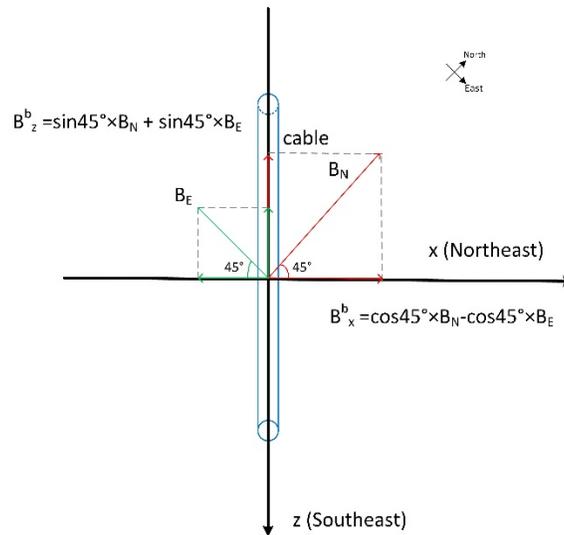
#### **4.2.4 Background magnetic field**

Since the EMF generated by the cable will superimpose on the local geomagnetic field, geomagnetic information also needs to be considered. The local geomagnetic field at the enclosure location (Figure 3.3) can be estimated based on geomagnetic maps provided by the National Centers for Environmental Information (Figure 4.7).



**Figure 4.7. Contour of geomagnetic flux density (nT).**  
 (a) Vertical component; (b) North component; (c) East component.

Using the geomagnetic flux density distribution shown in Figure 4.7, the local vertical component is about  $47 \mu\text{T}$ , the local north component is about  $20 \mu\text{T}$  and the local east component is about  $-5 \mu\text{T}$ . Build a local Cartesian coordinate system where the cable lays on the z-axis, the x-axis points to northeast, and the y-axis points to the vertical direction of the earth. In this local coordinate system, the y component of the geomagnetic field is  $-47 \mu\text{T}$ . The x component and the z component can be obtained by the vector decomposition in Figure 4.8.



**Figure 4.8. The vector decomposition of the geomagnetic flux density in the local Cartesian coordinate system.**  
 $B_E$  and  $B_N$  are the east component and the north component of the geomagnetic flux density, respectively.

Calculating as shown in Figure 4.8, in this coordinate system, the x component and the z component of the background magnetic field should be  $10.6 \mu\text{T}$  and  $-17.7 \mu\text{T}$ . Therefore, the corresponding local geomagnetic flux density could be written as  $(B_x^b, B_y^b, B_z^b) = (10.6, -47, -17.7) \mu\text{T}$ , and the magnetic intensity of the background B-field is around  $51.3 \mu\text{T}$ . The magnitude of the total B-field can be calculated by

$$\|B_{tot}\| = \sqrt{(B_x^b + B_x)^2 + (B_y^b + B_y)^2 + (B_z^b)^2} .$$

### 4.2.5 Simulation Results

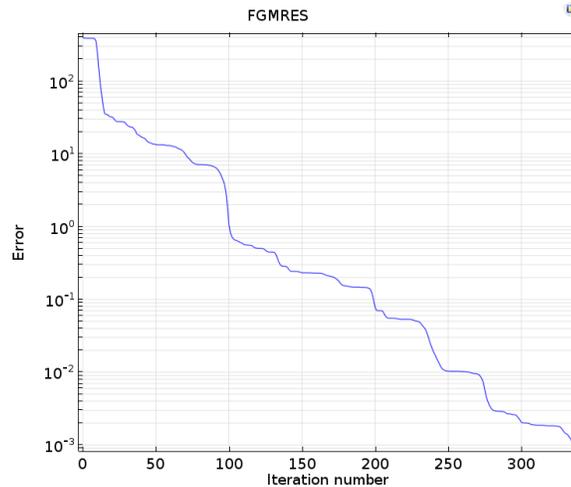
In COMSOL, the 2D AC/DC module describes the EMF with the following equations:

$$\nabla \times H = J$$

$$B = \nabla \times A$$

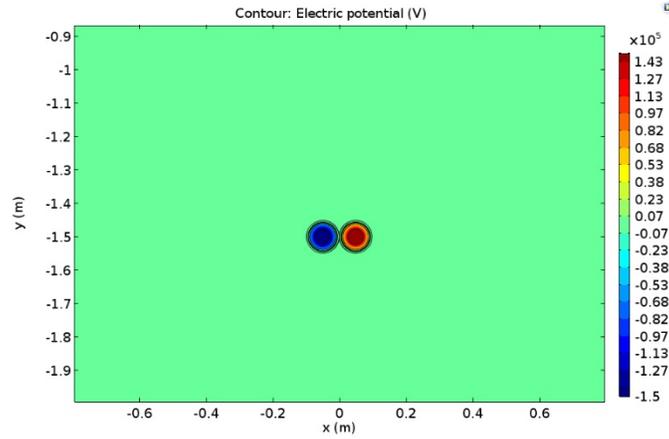
$$J = \sigma E + \sigma v \times B + J_e,$$

H is the magnetic field intensity, J is the current density, B is the magnetic flux density, A is the magnetic vector potential, E is electric field intensity,  $v$  is the velocity of the conductor, and  $J_e$  is the externally generated current density. Among these variables, the magnetic vector potential A is the dependent variable. These equations will be solved with numerical iteration algorithm. For the model presented above, FGMRES (flexible generalized minimal residual method) was chosen as the solver and the relative error tolerance was set to 0.001. Moreover, the initial value of A is set to 0. With these settings, the simulation did successfully converge, which is shown in Figure 4.9.



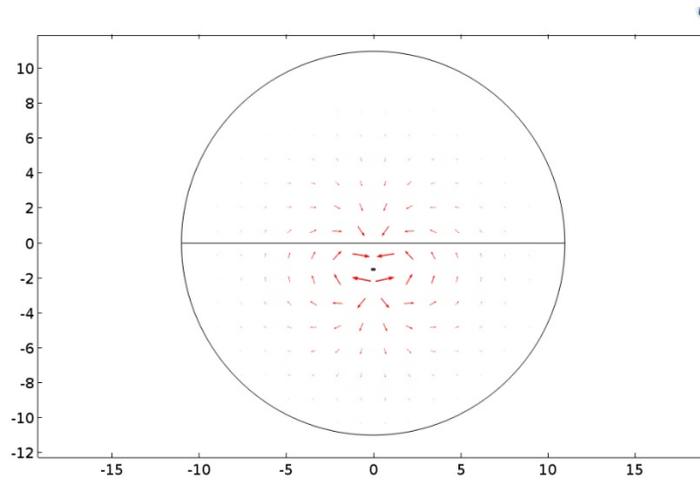
**Figure 4.9. Convergence process of the EMF simulation.**

As was stated before, the electric field should be strictly confined in each cable due to shielding effect of the grounded lead sheath. To demonstrate this shielding, a plot of the electric potential distribution around the cables is shown in Figure 4.10. It is clear that the electric potential is a constant value outside the cable, which implies that the corresponding E-field is zero.



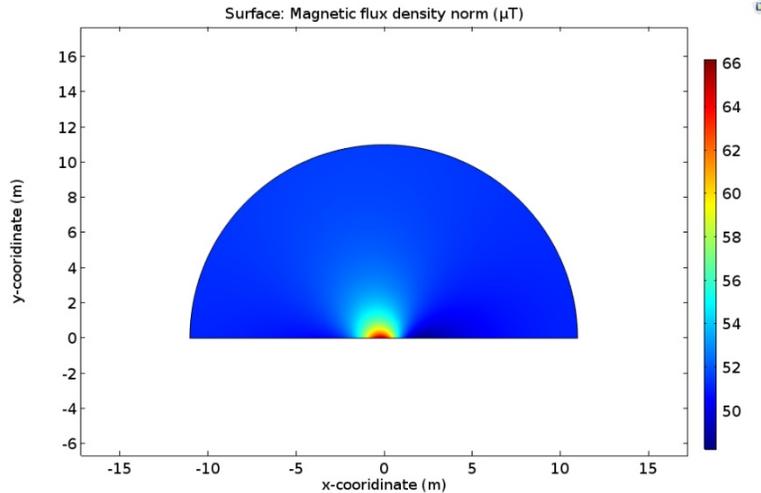
**Figure 4.10. Electric potential distribution around the cables.**

Figure 4.11 provides a visualization of the magnetic field. In this figure, the arrow direction denotes the direction of the magnetic field and the arrow length is the logarithmic of the magnitude of the magnetic field. It is clear that the CSC is the source of the EMF.



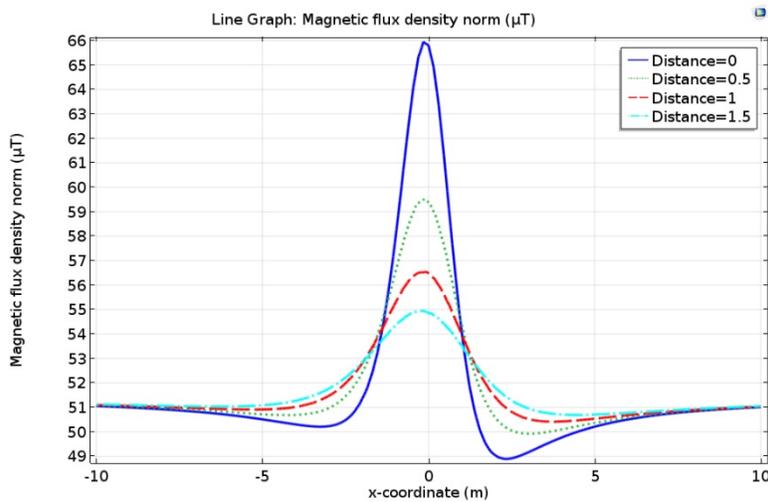
**Figure 4.11. Magnetic flux density in the analysis domain.**

The total magnetic flux density distribution in the ocean domain is shown in Figure 4.12. As noted, the magnitude of the magnetic field decreases to a value that is close to that of the background magnetic field.



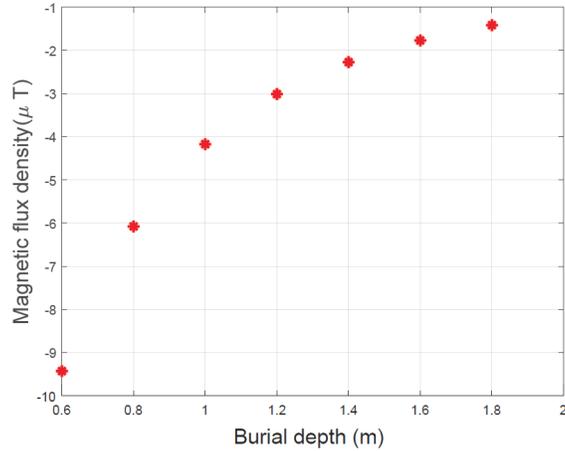
**Figure 4.12. Total magnetic flux density distribution in the ocean.**

To show the magnetic field more clearly, a plot of the magnitude of the total magnetic field along several parallel routes, corresponding to transects, was made (Figure 4.13). The first route is located on the boundary between the seabed and ocean. The remaining routes are elevated above the seabed with a spacing of 0.5 m. The results are shown in Figure 4.13. The blue line is the total magnitude of the magnetic field on the seabed, which has a peak value of about 66  $\mu\text{T}$ . The maximum value of elevated routes decreases as the height over the seabed increases. It can be noted that the graph of the magnetic field on these routes is similar to the measured field in the treatment enclosure (Figure 3.18).

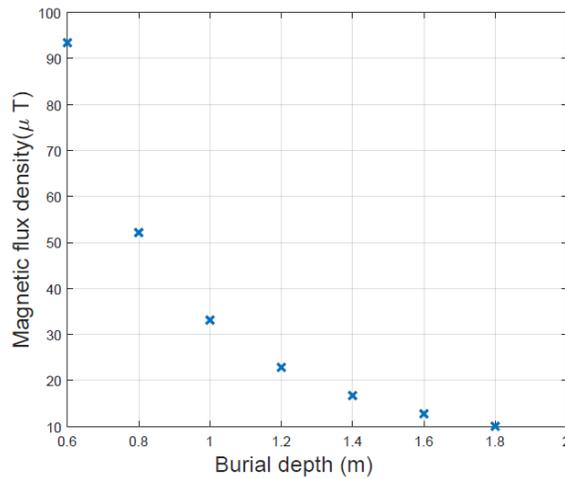


**Figure 4.13. Magnetic flux density at different level above the seabed.**

Since the burial depth of the cable is not constant at different locations, it was changed in the model as well. The burial depth was varied from 1.8 m to 0.6 m with a step of 0.2 m. For each burial depth, the positive and negative deviation of the geomagnetic field in the ocean domain was calculated. The results are shown in Figure 4.14 and Figure 4.15.

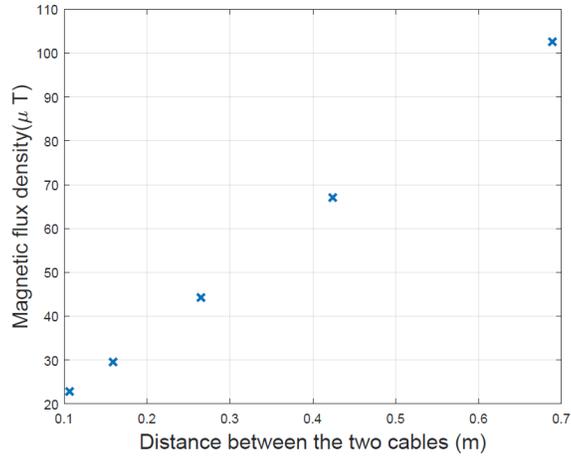


**Figure 4.14. The negative deviation from the geomagnetic field of different burial depths.**

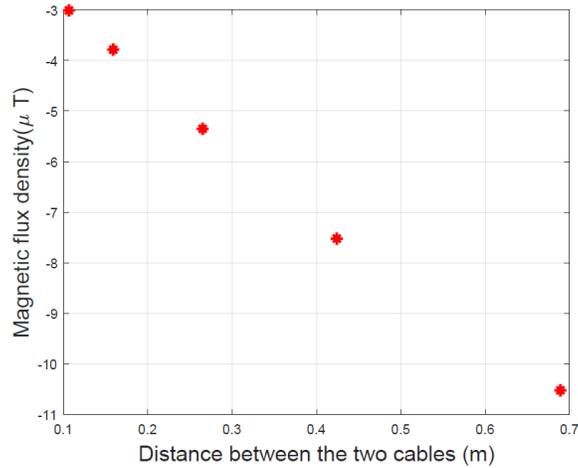


**Figure 4.15. The positive deviation from the geomagnetic field of different burial depths.**

The absolute value of both the positive and negative deviation increases as the burial depth decreases. Similarly, the distance between the two cables may also vary. To study the influence of the distance between the two cables, the corresponding positive and negative deviation of the geomagnetic field in the ocean was modeled for distances ranging from 0.106 m to 0.689 m. The results are shown in Figure 4.16 and Figure 4.17. It can be clearly observed that the deviations are proportional to the distance between the two cables.



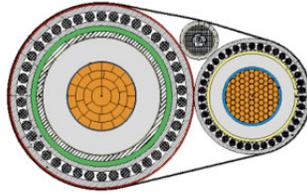
**Figure 4.16.** The positive deviation from the geomagnetic field of different burial depth.



**Figure 4.17.** The negative deviation from the geomagnetic field of different burial depth.

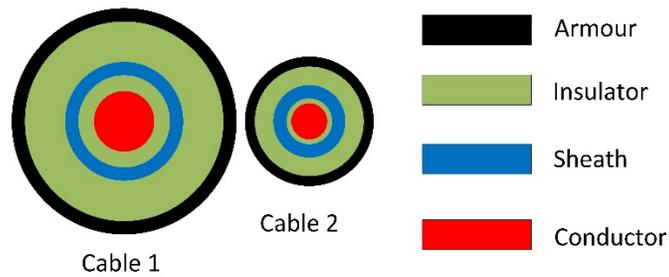
### 4.3 Simulation results of the Neptune cable

The EMF simulation of the Neptune cable is also carried out. As shown in Figure 4.18, the real cable contains several layers, which are made of different materials and have different functionality.



**Figure 4.18. The cross-section of the Neptune Cable.**

In our simulation, the cross-section of the cable is simplified as Figure 4.19.

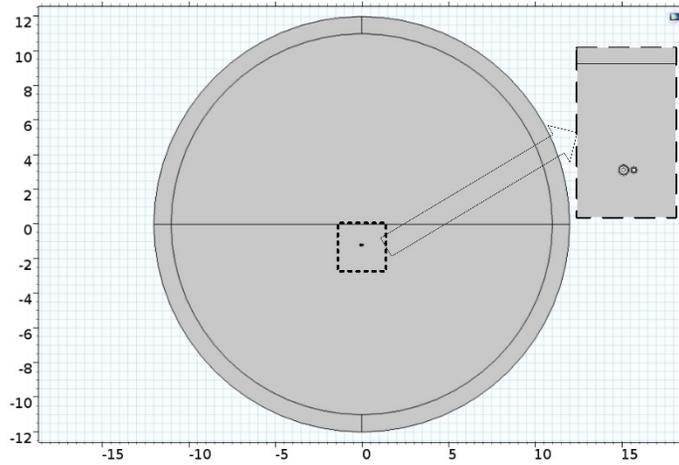


**Figure 4.19. The cross-section of Neptune cable model.**

The geometric parameters of the model are listed in Table 4.3.

<b>Table 4.3. Geometric parameters of the model.</b>	
<b>Parameters</b>	<b>Values</b>
<b>Burial depth</b>	1.4 m
<b>Distance between two cables</b>	0.1155 m
<b>Radius of cable 1</b>	0.063m
<b>Radius of cable 2</b>	0.042m
<b>Armour thickness</b>	0.01m
<b>Lead sheath radius of cable 1</b>	0.041m
<b>Lead sheath radius of cable 2</b>	0.03m
<b>Lead sheath thickness</b>	0.04m
<b>Conductor radius</b>	0.0235 m

With these parameters, we build the COMSOL model as Figure 4.20.



**Figure 4.20. COMSOL model of the Neptune cable.**

The electromagnetic properties of the material are defined as shown in Table 4.4.

**Table 4.4. Electromagnetic properties of the cable materials.**

Name	Electrical conductivity $\sigma$ (s/m)	Relative permittivity $\epsilon_r$	Relative permeability $\mu_r$
Conductor (Copper)	5.8e7	1.0	1.0
Sheath (lead)	1e6	1.0	1.0
Insulator (XLPE)	0	2.3	1.0
Armour (Steel wire)	1.1e6	1.0	1000
Seawater	1.0	81.0	1.0
Seabed	0.25	25.0	1.0

Since the EMF generated by the cable will superimpose on the local geomagnetic field, we should also take the geomagnetic information into consideration. We can estimate the local geomagnetic field based on the geomagnetic maps (Figure 4.7) provided by the ‘National Centers for Environmental Information’.

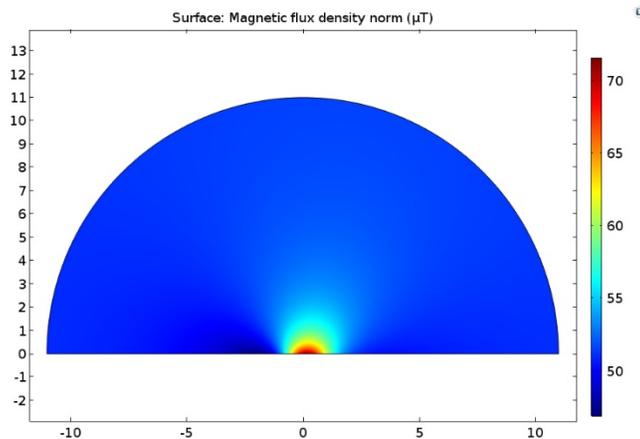


**Figure 4.21. Geographical position of Neptune cable.**

Considering the cable in the red rectangle of Figure 4.21, the local vertical component is about  $-47 \mu\text{T}$ , the local North component is about  $20 \mu\text{T}$  and the local east component is about  $-5 \mu\text{T}$ . Let's build a local coordinate system where z-axis points to east, x-axis points to south and y-axis points to the vertical direction of the earth. In this coordinate system, the cable should be parallel to the z-axis and the corresponding local geomagnetic flux density could be written as  $(B_x^b, B_y^b, B_z^b) = (-20, -47, -5)\mu\text{T}$ . Thus, the magnitude of the background B-field is around  $51.3 \mu\text{T}$ . The magnitude of the total B-field can be calculated by

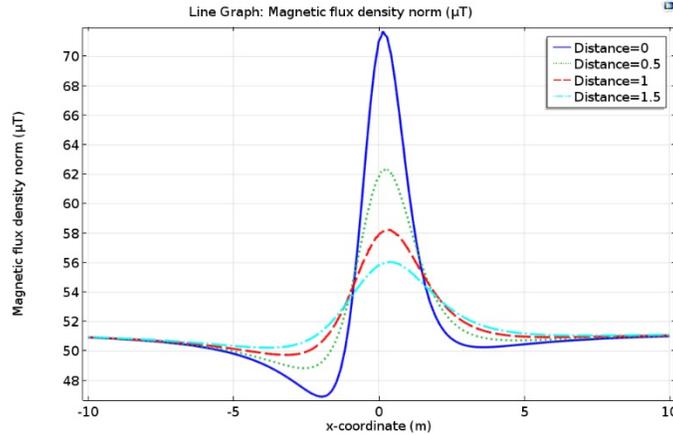
$$\|B_{tot}\| = \sqrt{(B_x^b + B_x)^2 + (B_y^b + B_y)^2 + (B_z^b)^2}.$$

When the current in the cable is 1320 Amps, the EMF simulation result is shown below. The total magnetic flux density distribution in the sea domain is shown in Figure 4.22. As we can see, the magnitude of the B-field vanishes to a value that is close to that of the background B-field.



**Figure 4.22. Total magnetic flux density distribution in the sea.**

To show the B-field more clearly, we plot the magnitude of the total B-field along several parallel routes. The first route is located on the boundary between the seabed and sea. The remaining routes lift right above the first route with a distance of 0.5 m to each other. The results are shown in Figure 4.23. The blue line is the total B magnitude on the first route, which has a peak value about 72  $\mu\text{T}$ . The maximum value of different routes decreases as the route get further from the seabed.



**Figure 4.23. Magnetic flux density norm at different level above the sea bed.**

## 4.4 Conclusions

The magnetic field of the HVDC bipolar Cross Sound Cable was modeled using the AC/DC module of COMSOL. The cable was modeled with a metallic screen connected to the ground, which resulted in an electric field perfectly confined in the cable. However, the magnetic field generated by the cable will occur outside the cable and cause a deviation of the surrounding geomagnetic field. This deviation depends on the burial depth, the distance between the two cables, and environment parameters. This influence will decrease when the measurement location gets further from the cables. By comparing Figure 4.13 and Figure 3.18, it can be observed that the simulation results and the measurement results are fairly consistent, with similar maximum/minimum values and shape. Furthermore, simulations of the Neptune cable also verified that the model can scale up to a large capacity HVDC cable. These results demonstrate that the COMSOL model can be an effective tool in modeling and simulating the EMF for underwater HVDC cables.

## 5.0 Field Study to Detect the Effects of EMF on Marine Species

### 5.1 Introduction

The findings from the field surveys of the two HVDC and the single HVAC subsea cables (Section 3.0) and the modeling of the Cross-Sound cable provide clear evidence that the passage of electrical current (either in DC, or AC form) produces magnetic fields and associated electric fields. These electromagnetic field (EMF) levels are within the potentially detectable range of both magneto- and electro-sensitive animals. The fields detected were in the  $\mu\text{T}$  range for the magnetic fields and  $\mu\text{V}/\text{m}$  to  $\text{mV}/\text{m}$  for electric fields, and reach a very low frequency range (10's Hz). The HVDC cables produced the greatest deviation in EMF from the background geomagnetic field compared to the HVAC cables (Section 3.0). Therefore, it was expected that the EMF from the HVDC cables were most likely to be detected by animals that use changes in either magnetic, or electric field levels for orientation, foraging, and/or migration; all vital aspects of the life history of many species. A number of these species have fisheries and conservation importance, which has led to a perceived potential impact on the ability of these species to naturally move around if their electromagnetic (EM) environment is altered through emissions from subsea cables.

A field study was developed to determine if the electromagnetic field (EMF), emitted from a buried subsea HVDC cable, can cause biologically relevant effects in important benthic animals. Animals chosen for the study belong to taxa known to respond to either magnetic or electric fields. The animals of interest were the commercially important and potentially magneto-receptive crustacean, the American lobster, *Homarus americanus* (Section 5.1.1) and the elasmobranch, Little skate, *Leucoraja erinacea*, which is a good model organism for electro-sensitive species (Section 5.1.2). The effects deemed biologically relevant were linked to movement and orientation within the marine environment, therefore the focus of the field study was to quantify the behavioral movements of animals when encountering the EMF emitted by an HVDC subsea power cable. The behavioral parameters chosen to quantify the effect on animals were; the total distance traveled, the speed of movement, the height from the seabed, change in the direction of movement (the turn angle) and their spatial distribution within the enclosures. These behavioral parameters were used to assess differences in animal movements when exposed to EMF (treatment) and when held under control conditions (no EMF) thereby determining if they moved differently in response to the EMF.

Section 5.1.1 sets the context for the project by highlighting some reported concerns of decapod fishers with regard to the development of offshore renewable energy and associated subsea cables, and also highlights the commercial value of *H. americanus*. The distribution and migration of *H. americanus* is explained before reviewing the current knowledge base for the potential of decapods to respond to EMFs. Similarly, Section 5.1.2 introduces the rationale for researching elasmobranch response to EMFs and specifically *L. erinacea* as a model species. An overview of elasmobranch sensory mechanism and biological function is provided before reviewing the evidence for responses to subsea electricity cables. Finally, the experimental approach for determining if the EMF from a subsea HVDC cable elicits a behavioral response in *H. americanus* and *L. erinacea* is explained in Section 5.1.3.

#### 5.1.1 American lobsters

It has been suggested that it may be possible to co-locate decapod fisheries and offshore windfarms (OWF), which have seen much expansion in European seas. It is possible that OWFs may enhance coastal habitat for *Homarus sp.*, however it was acknowledged that there is little understanding of decapod response to other influences such as electromagnetic fields (Hooper et al., 2014). Despite the potential for mutual benefits to developers and fisheries, the risk of displacement to fishing industries and

practicalities of co-benefits need to be addressed (Hooper et al., 2015). These concerns have also arisen during the planning for OWFs in the USA, specifically for *H. americanus* (RFP No. M14PS00026). A first step to resolving potential conflict is determining if there is a risk of lobsters changing their behavior in response to EMFs from cables associated with marine renewable energy.

American lobsters were one of nine priority invertebrate species in US waters that could potentially be affected by exposure to EMF (Normandeau et al., 2011). The perceivable risk for lobsters is the potential delay or alteration to migration patterns/paths and homing behaviors. Lobsters (and other benthic decapods) were perceived to be a moderate risk group since their epibenthic habitat and relatively low mobility exposes them to the highest EMF from cables (Normandeau et al., 2011). *Homarus americanus* occurs within three of the geographic regions within BOEM planning areas; North Atlantic, Mid Atlantic and South Atlantic (Normandeau et al., 2011).

This introduction provides background information on the *H. americanus* fishery in the USA (Section 5.1.1), their distribution and migration (Section 5.1.2) together with a review of the current knowledge of the evidence for decapods responding to electromagnetic fields (Section 5.1.3).

#### **5.1.1.1 Commercial fishery**

The American lobster has been an important commercial fishery in the USA since the 1950s (ASMFC, 2017). There are three main fisheries; the Gulf of Maine, predominantly inshore, the Georges Bank, predominantly offshore and the South New England (ASMFC, 2015). Historically the South New England fishery was focused inshore and was the second largest fishery but due to a combination of overfishing and ecological pressures resulting in population declines, it is now predominantly offshore (ASMFC, 2015, Wahle et al., 2013). The South New England stock remains severely depleted, fishery restrictions are in place and landings are very low (ASMFC, 2015). The most recent stock assessment in 2015 reported that the Gulf of Maine fishery accounted for over 90% of all US lobster landings (ASMFC, 2015). In 2016, the total landings of American lobster were 158 million pounds with a value of \$666.7 million making it one of the most valuable fisheries on the Atlantic coast (ASMFC, 2017).

#### **5.1.1.2 Distribution and Migration**

The American lobster occupies rocky habitats taking shelter in crevices but is also known to burrow in soft sands and mud (Wahle et al., 2013). They are regarded as scavengers but are also opportunists, feeding on benthic fish and crustaceans (Gendron et al., 2001). American lobsters inhabit shallow intertidal habitats up to 50 m but are also known to occupy the continental shelf and have been found as deep as 700 m (Cooper et al., 1980). They have been described as inshore and offshore populations, and as residents or migrants defined by their dispersal behavior (Bowlby et al., 2007, Cooper et al., 1971, Haakonsen et al., 1994), however, it is now accepted that these are the same population (Hoenig et al., 2015, Pezzack et al., 1986). Horizontal movements are recorded in inshore and offshore lobsters although this is not considered migration (Haakonsen et al., 1994, Hoenig et al., 2015). Lobsters typically have a 'home range' although the core area for 'home' is flexible and may be largely dependent on the competition for shelter; in this sense they can be considered to fluctuate between nomadic and resident states (Scopel et al., 2009). Migratory lobsters move from inshore waters to offshore waters which is linked with the season (Haakonsen et al., 1994, Hoenig et al., 2015). Multiple studies have recorded the inshore migration to be in spring/early summer and the offshore migration to be in the fall/early winter (Bowlby et al., 2007, Cooper et al., 1980, Haakonsen et al., 1994, Hoenig et al., 2015). Migration is reported to be positively correlated with the change in temperature although turbulence, salinity and storm frequency may also contribute (Campbell, 1986, Haakonsen et al., 1994, Jury et al., 1995). Some studies have reported that the migration is to optimize temperature for the purposes of reproduction and/or egg development however food availability, molting or growth may also contribute (Campbell, 1986, Campbell et al., 1986). Berried females from an offshore site displaced to an inshore site showed limited

activity while carrying eggs but increased after the eggs had hatched and subsequently the lobsters found their way back to their offshore capture site (Saila et al., 1968). Cowan et al., (2007) have shown that ovigerous female lobsters modify their migratory behavior to reduce the variability in their thermal regime however laboratory studies have shown that behavioral thermoregulation is not specific to females (Crossin et al., 1998). The most recent stock assessment reported a higher number of females in offshore areas in the fall that were not present in the spring (Hoenig et al., 2015).

Migrations can be short ranging or can exceed hundreds of kilometers at speeds ranging from 1.8 to 11 km/day (Cooper et al., 1980, Pezzack et al., 1986). While some migratory lobsters have shown homing tendency's others have not, although this may be an influence of the data collection techniques/length of study (Bowlby et al., 2007, Pezzack et al., 1986). Although there is a large body of literature on lobster movements linked to understanding migration, there are no studies to date that assess if American lobsters make use of the Earth's magnetic fields for navigation during migration. However, the ability to 'home' suggests that this could be possible and therefore presents a potential risk that EMF from cables could disrupt orientation and/or navigation (Normandeau et al., 2011).

### 5.1.1.3 Potential for response to EMF

Some animals are able to use the Earth's magnetic field as a source of information to aid their navigation (e.g. migration and/or homing) and are said to have a 'magnetic map' or a 'magnetic compass' and may have both (Lohmann et al., 2007). In this way, magnetoreception aids an animal in determining its position (map sense) and/or for determining a direction (compass sense). For true navigation such as that required by homing behavior, an animal must be able to determine its position in relation to a goal (Boles et al., 2003). The best evidence to date of a magnetic map sense in decapods is from the studies of the western Atlantic spiny lobster, *Panulirus argus* which undergoes an annual migration and is capable of 'homing' to coral reef dens (Lohmann et al., 1995 and references therein).

Firstly, ferromagnetic material was discovered in *P. argus* with the highest concentrations in the cephalothorax but also present in the abdomen and a positive correlation of each with thorax length (Lohmann, 1984). Subsequent laboratory studies suggested that they could preferentially orientate to a reversed geomagnetic orientation of N-S indicating they were capable of deriving directional information from the magnetic field (Lohmann, 1985). Later work confirmed that *P. argus* responded to a reversal in the horizontal geomagnetic component suggestive of a polarity compass, different to that of birds and turtles (Lohmann et al., 1995). Field studies assessed the homing ability of *P. argus* by displacements to unfamiliar territory (12-37 km) when deprived of sensory cues during displacement; vision and then vision plus magnetic field disruption. The study showed that *P. argus* was capable of reliable orientation to their original capture site and was the first evidence of magnetic map sense in a marine invertebrate (Boles et al., 2003). There is however no evidence on the influence of anthropogenic magnetic fields such as those from cables on the magnetic map sense of *P. argus*.

Although *P. argus* is one of the better studied decapods in terms of the magnetic map, thresholds of detection of magnetic fields have not been determined for *P. argus*. Normandeau et al., (2011) speculated that based on a magnetite detection system and an AC EMF,  $>5 \mu\text{T}$  at 60 Hz frequency may be detected by *P. argus* that would be within a 100 m range of an AC cable (1000 A). However, there have been few studies investigating decapod responses to this level of magnetic field. The closest was a study of single mechanoreceptor neurons in crayfish which showed weak and variable neuron impulse activity in response to weak and extremely low frequency magnetic fields (1-400  $\mu\text{T}$ ), found to be maximal at 0.001-60Hz (Uzdensky et al., 1997). Neural responses were also studied in the giant axon of the European lobster *Homarus vulgaris* but no response was observed to a  $2 \times 10^5 \mu\text{T}$  (500 Hz) or  $8 \times 10^5 \mu\text{T}$  (50 Hz) magnetic field (Ueno et al., 1986). It is however of note that this field strength is five orders of magnitude higher than that of an average buried cable (Normandeau et al., 2011). Whole organism studies are few. A study which exposed the North Sea prawn *Cragon cragon* to  $3.4 \times 10^3 \mu\text{T}$  (DC) for

three weeks reported no differences in mortality compared with those under control conditions (Bochert et al., 2004) but there were no observations of behaviors reported. Behavioral assessments of decapod responses to magnetic fields have started to emerge. There is evidence of the motor activity of the red king crab, *Paralithodes camtschaticus*, peaking in response to geomagnetic fields of 0.15  $\mu\text{T}$  (Muraveiko et al., 2013). There are now behavioral studies of the Dungeness crab, *Metacarcinus magister* and American lobster, *H. americanus* (Woodruff et al., 2013, Woodruff et al., 2012) to magnetic fields but these were reported as ‘screening level studies’.

Controlled aquarium experiments of *M. magister* showed a non-significant decrease in antennular flicking rate when exposed to  $3 \times 10^3 \mu\text{T}$  EMF (Woodruff et al., 2012). During the attraction/repulsion study there was evidence of a significant decrease in time buried and increase in changes in activity when exposed to an EMF with a peak of  $1.1 \times 10^3 \mu\text{T}$  (compared to control a of  $0.12 \times 10^3 \mu\text{T}$ ), particularly in the first two days of exposure (Woodruff et al., 2012). In contrast, there was no obvious detection of EMF in the antennular flicking rate and no obvious difference in the detection of food in the presence of EMF compared to the control conditions (Woodruff et al., 2012). Love et al., (2015) also reported no changes in behavior in response to powered (40-80  $\mu\text{T}$ ) and unpowered (0.2  $\mu\text{T}$ ) cables however behavioral responses were only measured at 1 and 24 hours. Further studies by Woodruff et al., (2013) again identified changes in behavior in response to EMF but they were confounded by other properties of the study e.g. tank, water flow direction, and individual variability. Similar studies were completed on *H. americanus* where the control tank had a stable magnetic field of 50  $\mu\text{T}$  and the treatment peaked at  $1.1 \times 10^3 \mu\text{T}$  with boundary levels of  $0.5 \times 10^3 \mu\text{T}$ . Unfortunately there were difficulties in assessing behavioral changes due to high individual variability and the fact that lobsters spent 76% of their time either burrowed, or in shelters (Woodruff et al., 2013). Lobsters that burrowed chose to do so in the low zones of EMF; however, the only shelter available was placed in the high zone of EMF and may have influenced this behavior. There was significantly more time spent in the area of high EMF than the downstream low EMF zone but this did not hold true for the other tank and may have been either a tank effect, or could be attributed to individual variability. The results were somewhat inconclusive.

### **5.1.2 Little skates**

Normandeau et al., (2011) highlighted elasmobranchs as being sensitive to electric and magnetic fields based on a selection of behavioral, anatomical, physiological and theoretical evidence. The potential effects identified related to feeding, predator or conspecific detection and in some cases, navigation. Due to their electrosensory abilities, the elasmobranchs are considered one of the most likely groups to respond to EMF from underwater cables (Normandeau et al., 2011). Normandeau et al., (2011) stated that all elasmobranchs in US waters (127 species) were priority species. Despite this fact, there is little robust evidence to determine how elasmobranchs may respond to electromagnetic fields from cables (Copping et al., 2016). Furthermore benthic species are likely to be more exposed to EMF than pelagic species (Gill et al., 2014). For these reasons, the benthic *Leucoraja erinacea*, which is found along the eastern coast of the USA was used as a model elasmobranch to quantify the behavioral response to the EMF emitted by an HVDC cable. Section 5.3.1 provides background information on the ecology of *L. erinacea*, before describing the relevant sensory mechanisms of elasmobranchs (Section 5.3.2) and the evidence base of responses to cables (Section 5.3.3).

#### **5.1.2.1 *Leucoraja erinacea***

The life history and habitat characteristics of the little skate, *L. erinacea* are best reviewed by Packer et al., (2003). Little skate are common in the western Atlantic, from Nova Scotia down to North Carolina and although they are not considered long distance migratory elasmobranchs, they do however undergo onshore/offshore and north-south movements related to temperature; these can be considered short distance migrations. They are typically found in coastal waters up to 100 m however have been found in much deeper waters, for example >300m in Georges Bank. *Leucoraja erinacea* are typically found in

gravelly habitats and sometimes in mud, often found buried in depressions during the day and more active at night. They typically feed on crustaceans, amphipods, polychaetes, squid and fish. Little skates are not an important fishery, but they are collected for bait, particularly for lobster and eel traps (Cicia et al., 2009). Importantly *L. erinacea* is a good model organism for studies of electro-sensitive elasmobranchs (Bodznick et al., 1992, Duman et al., 1996, Gillis et al., 2012, Lu et al., 1994, New, 1990) and are Rajiformes which were reported to exist in thirteen of the BOEM Planning Areas (Normandeau et al., 2011).

### 5.1.2.2 Elasmobranch sensory mechanisms

The electrosensory system in elasmobranchs (sharks, skates, rays) is ubiquitous across the taxa (Murray, 1974). There is a network of pores and receptors that are typically situated on the head and pectoral fins in skates and rays. The pores on the surface of the skin are connected via electrically conductive mucopolysaccharide gel filled canals (~1 mm diameter, 1-10's cm long) to the ampullae of Lorenzini, a bundle of sensory cells, which are connected to nerve fibers. The neurological structure associated electrosensory system ensures that detection of electric fields on the dorso-ventral and left-right sides can be distinguished. There are multiple roles of this electrosensory system that are now briefly introduced.

One of the primary uses of electroreception is to locate prey. Multiple studies have shown that prey that have odors and visual cues concealed can be detected (Blonder et al., 1988, Kalmijn, 1971, 1988) and can be artificially simulated (Kajiura et al., 2002, Kimber et al., 2011). Prey are detected by their bioelectric fields produced from a heart beating, muscular contraction, nerve impulses and ionic pumps (Kalmijn, 1988), although cleverly elasmobranchs are able to distinguish between the fields from prey and their own electric fields through neural compensation (Bodznick et al., 2003).

Bioelectric fields of predators can also be detected by elasmobranchs when they are the prey. It has been shown in embryos that when predators are detected they initiate a 'freeze response' which may help conceal their location (Ball et al., 2016, Kempster et al., 2013, Peters et al., 1985, Sisneros et al., 1998). Experimental studies have shown that electroreception of this kind is active very early in development (Ball et al., 2016).

Electroreception also presents as a form of communication. Some elasmobranchs have an electric discharge organ which produces a weak electric field that can be used to stun prey, protect against predators and/or is used in social interactions among and between species (Bratton et al., 1987, Kalmijn, 1988, New, 1994, Sisneros et al., 1998). In skates it was shown that the frequency is variable between species, discharges were recorded more regularly in groups of skates than in individuals and could be provoked by tactile stimuli (Bratton et al., 1987).

Electroreception is also used to help find conspecifics and reproductive mates where in skates they may be buried in depressions during the day (Sisneros et al., 1998, Tricas et al., 1995). Sexual dimorphism in the electrosensory system of *Taeniura lymma* (stingray) has been found, which may be related to mate selection and the need for females to distinguish between a potential mate and a predator (Kempster et al., 2013).

Aside from biologically important electroreception, there are also environmental cues that are important. These cues arise from the movement of tides/currents and the animal itself through the Earth's magnetic field which produces an induced electric field (Kalmijn, 1988, Normandeau et al., 2011). In this way, the ampullae of Lorenzini are generally accepted to be magneto-receptors and have been suggested to play a navigational role in long ranging migrations in elasmobranchs, although other senses may also contribute (Bonfil et al., 2005, Klimley, 1993, Molteno et al., 2009, Montgomery et al., 2001).

It was proposed by Kalmijn (1981, 1971) that elasmobranchs were capable of navigation via induced electric fields from geomagnetic fields. This ability was later shown experimentally with the stingray, *Urolophus halleri* (Kalmijn, 1978). Further studies of the ampullae of Lorenzini, nerve and neural responses to magnetic stimulus in skates (*Tyron pastinaca*, *Raja clavata*) and confirmed that the responses depended on position of the receptor and the direction of the magnetic field, intensity of the field as well as the rate of change in magnetic field (Akoev et al., 1976, Andrianov et al., 1974, Brown et al., 1978). These studies reported no responses to a constant magnetic field (Akoev et al., 1976, Andrianov et al., 1974), unless the fish either moved in the water, or the water moved in relation to the fish (Brown et al., 1978).

Conditioning experiments have been used to determine if elasmobranchs can differentiate changes in the magnetic field (Kalmijn, 1981, Kalmijn, 1982, Meyer et al., 2005). For example, juvenile sandbar sharks, *Carcharhinus plumbeus*, were conditioned to the pairing of food and a magnetic field of 25 to 100  $\mu\text{T}$  (Meyer et al., 2005). Subsequently, in the absence of food, the sharks immediately responded to the magnetic field being turned on confirming the ability to detect the change in magnetic fields at thresholds similar to the change of the Earth's geomagnetic field (Meyer et al., 2005). Studies of the same species have found strong responses to small variations in the magnetic field, 0.03 to 2.89  $\mu\text{T}$  (Anderson et al., 2017). The same study found that the response to 0.03  $\mu\text{T}$  was strongly impaired by magnets, which the authors suggest is evidence of a magneto-receptor over and above that of the detection of the induced electric field by the ampullae of Lorenzini (Anderson et al., 2017). The same authors also reported a repulsion to higher magnetic fields that is also being explored as a deterrent to reduce shark bycatch (O'Connell et al., 2014, Porsmoguer et al., 2015, Siegenthaler et al., 2016).

The exact mechanism(s) of the magneto-reception and its contribution to navigation is still debated in elasmobranchs and in other species, as is the methodology for deciphering the mechanism experimentally (Anderson et al., 2017, Johnsen et al., 2005, Molteno et al., 2009, Montgomery et al., 2001, Nordmann et al., 2017). It is plausible that more than one mechanism has evolved in multiple species. Despite not knowing the intrinsic details of magneto-reception in elasmobranchs, there is evidence that elasmobranchs are electro- and magneto-sensitive and the influence of electromagnetic fields from cables must be considered.

### 5.1.2.3 Evidence for responses to cables

Elasmobranchs are capable of detecting and discerning important bioelectric signals from other biological noise (Bodznick et al., 2003), but it is not known if they can use the same approach to distinguish these signals from anthropogenic EMF 'noise'.

Laboratory studies of electroreception in bamboo shark embryos have shown that the 'freeze response' was longer for frequencies that are similar to bioelectric signals of predators. Additionally, there was evidence of habituation to the same signal over time (Kempster et al., 2013). The small spotted catshark, *Scyliorhinus canicula*, was unable to differentiate between the bioelectric field from prey (crab, *Carcinus maenus*) and an artificial DC field. When presented with two artificial EMF, there was a preference for stronger DC fields over weaker ones and a preference for AC rather than DC fields (Kimber et al., 2011). Later studies showed that catsharks, *S. canicula*, were however able to learn that artificial electrical fields were not associated with food, which was memorized for up to three weeks (Kimber et al., 2014).

Through controlled mesocosm studies, Gill et al., (2009) assessed the responses of *S. canicula*, *R. clavata* and *Squalus acanthias* (spurdog) to a powered AC cable (100A, 7 volts), which emitted a magnetic field of 8  $\mu\text{T}$  and an induced electric field of 2.2  $\mu\text{V}/\text{m}$ . A significantly higher number of *S. canicula* were found in the EMF area of the powered cable in both trials and they were found to move significantly less, which is consistent with feeding behavior. The study demonstrated an attraction to the zone around the powered cable in *S. canicula* however the response was highly variable amongst individuals. There was

also a significantly increased movement between acoustic tag positions in three of five *R. clavata* when the cable was powered. Overall, this study demonstrated a response in some elasmobranchs, but the response was highly variable amongst individuals and not easily predictable.

As reported by Normandeau et al., (2011), the perception of an EMF by an electro- and/or magneto-sensitive species is complex and dependent upon several factors such as; cable characteristics, electric current, cable configuration, cable orientation relative to geomagnetic field, the swimming direction of the animal, local tidal movements and characteristics of the species life history and developmental stage. In order to address the primary objectives of the research, these parameters had to be carefully considered.

### **5.1.3 Experimental approach**

To determine the behavioral responses of *H. americanus* and *L. erinacea* to the EMF emitted into the marine environment by an operational HVDC subsea cable, a field experiment using enclosures was developed (Appendix 1). The cable used in the study was the Cross Sound Cable, which is a 330 MW HVDC electrical transmission cable that connects the grids of Connecticut, New England and Long Island, New York. The subsea cable is buried and runs from New Haven, CT to Shoreham, NY. The electromagnetic field from this cable was surveyed prior to the field experiment (Section 3.9-3.12) and informed the development of the enclosure study.

Two enclosures were deployed; one onto the buried cable, which emitted an EMF (treatment), and one at a reference site (control) for comparison. The most up to date acoustic telemetry technology was used to detect the three dimensional movements of individually identifiable specimens within the enclosures. This approach allowed the behavioral movements of animals to be monitored in relation to the EMF of the cable and compared with their movements in the control enclosure. To allow for individual variability, the movement of each individual was assessed at both enclosures. Animals were released at each enclosure for 12-24 hours and their movements recorded continuously.

The high frequency, three-dimensional data were analyzed for differences in relevant behavioral parameters at the enclosure exposed to the powered cable (treatment) compared to the reference site (control). The behavioral parameters chosen were ecologically relevant in terms of their relative influence on energy or time expenditure. The behavioral parameters were compared between enclosures to determine whether a significant change in movement behavior/activity occurred when exposed to the EMF which could be associated with a potential attraction or avoidance to the EMF emitted by the cable. For example, it is plausible that an animal attracted to the EMF may be in closer proximity to the seabed where the EMF is strongest or that an animal trying to avoid an EMF would try to swim/climb over the EMF or turn away from it. The parameters assessed were: the total distance traveled per day, the speed of movement, the height from the seabed, changes in the direction of movement (the turning angle) and the spatial distribution of the animals within the enclosures. These parameters were used to determine whether *H. americanus* and *L. erinacea* responded to the EMF from an active subsea HVDC cable.

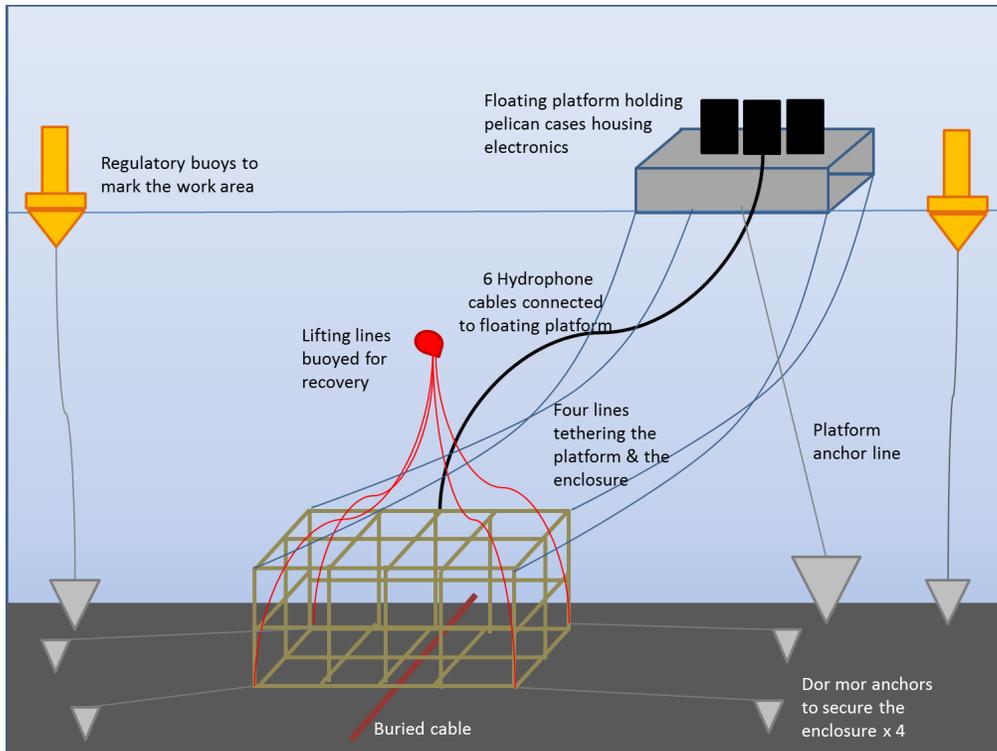
## **5.2 Methods**

### **5.2.1 Overview**

Two enclosures (mesocosms) were built to house the animals during the *in situ* experiment. One enclosure was placed on top of the buried cable (HVDC Cross Sound Cable), the treatment site, and one at a similar site with no cable, the control site. A hydrophone array within each enclosure triangulated the three dimensional positions of acoustically tagged animals. This design provided high frequency tracking data to determine if there were differences in the behavior of individuals at the control site verses the treatment site. The array of Hydroacoustic Technology Inc. (HTI) hydrophones were connected to electronics housed on a platform at the sea surface. Figure 5.1 shows an overview of the experimental set

up at the treatment enclosure. To allow for individual variability in behavior, all specimens went to both enclosures (control and treatment). Exposure to both enclosures is referred to as one full trial. Each animal studied was only used for one full trial. Any potential bias in the behaviors at each enclosure due to the order of exposure (naive versus non-naive), was avoided by alternating the sequence of exposure between trials.

The methods employed are presented in the following sections as: field site and preparations, acoustic telemetry, monitoring the magnetic field, enclosure field deployment, specimen handling, specimen field deployment, data collection, data processing, and statistical analyses.



**Figure 5.1. Experimental overview of the treatment site.**

## **5.2.2 Field Site and Preparations**

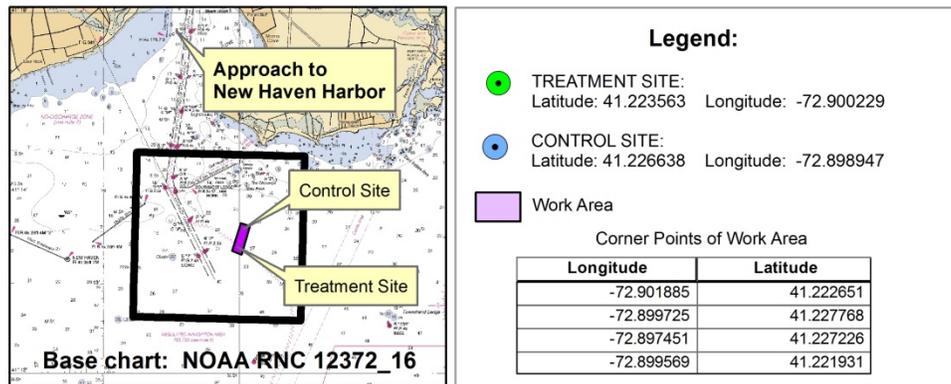
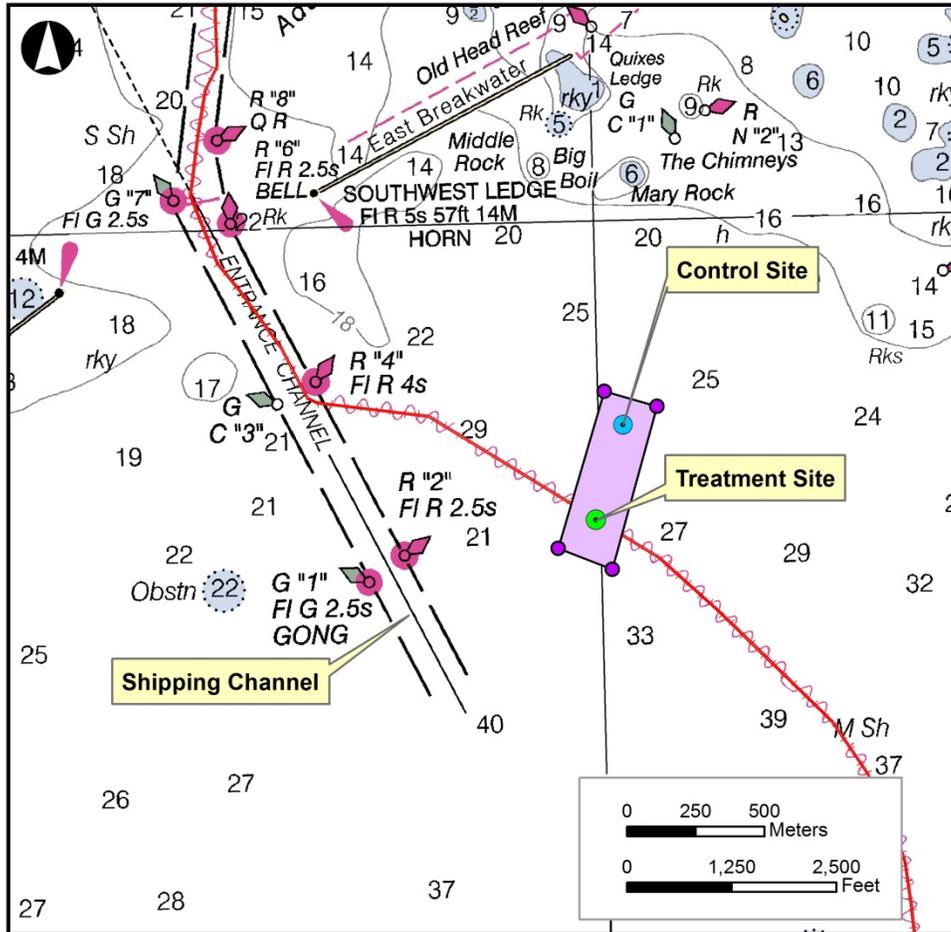
### **5.2.2.1 Site**

The study focused on the subsea HVDC Cross Sound Cable. Cable details, operational information and characterization of the emitted EMF are detailed in Chapter 3. In brief, SEMLA transect surveys characterized the deviation of the magnetic field emitted from the cable to be 3 to 4  $\mu\text{T}$  at an electric current of 345 Amps. The location chosen as the treatment site was based on the SEMLA transects conducted on 3<sup>rd</sup> May, 2016 (Section 3.12). On selecting this site, further SEMLA surveys were conducted to fully characterize the area. An asymmetrical magnetic field of 65.5  $\mu\text{T}$  (Section 3.12, 3.16) was targeted as the treatment site and an equivalent area with a background magnetic field of 51.3  $\mu\text{T}$  (i.e. the Earth's magnetic field) was targeted as the control site (Section 3.9, 3.15).

The location of the two enclosure deployments is detailed in Table 5.1 and Figure 5.2, the shipping channel and buried Cross Sound Cable are also shown. The treatment site was approximately 665 m from the shipping channel (nearest point). The control site was located 358 m from the treatment site and approximately 915 m from the shipping channel (nearest point). Bathymetric information confirmed that the control and treatment site were similar (NOAA, 2012, 2013, USGS, 1997). The entire work area incorporating both the treatment and the control site was marked with four cautionary regulatory buoys (Figure 5.2), (Coast Guard approved 700 mm diameter buoy with can top in yellow, marked ‘hazard below’ with a 1-2+ nm Solar Marine Lantern; Sealite USA LLC).

**Table 5.1. The geographical co-ordinates, depth and distance from channel for each enclosure study site.**

	<b>Treatment site</b>	<b>Control site</b>
Coordinates (lat, long)	41.223563, -72.900229	41.226639, -72.898889
Distance from channel (m (ft))	665 (2182)	915 (3002)
Depth (m (ft))	10 (33)	10 (33)
Seabed type	Mud/Sand	Mud/Sand



Map Contact: John King, GSO-URI | 401.874.6182 | jwking@uri.edu

**Figure 5.2. The location of the study sites.**

The two study sites are shown in relation to the shipping channel and the buried Cross Sound Cable (red) in Long Island Sound, CT.

### 5.2.2.2 Enclosures

Two identical enclosures were constructed with approximate dimensions of 5 x 3.5 x 2.5 m (lwh). The plan was to position the enclosure on the seabed such that the buried cable ran perpendicular to the length

of the enclosure through the center giving approximately 2.5 m on either side of the cable. The presumed degree of error for the acoustic tracking equipment was set conservatively at  $\pm 1$  m. Therefore if the cable alignment in the enclosure was off-center the animals would still be able to be acoustically positioned ( $\pm 1$  m) within the enclosure, relative to the cable. The enclosure height was important in order to allow animals the opportunity to either swim, or climb over an EMF emitted from the buried cable, again with more than the 1 m margin of error. The height was capped to enable the enclosure to be lifted by the vessel's crane for deployment.

The specific internal dimensions of the enclosures once constructed were 196 x 146 x 92.5" (497.8 x 370.8 x 235.0 cm) and external dimensions 199 x 149 x 99.5" (505.5 x 378.5 x 252.7 cm). Each enclosure was built using kiln dried spruce (2x4", 2x6", Arnold Lumber, RI) and three pressure treated 4x6" timbers in the base for structural integrity. In addition wooden cradles built from spruce and 1/2" plywood were incorporated to hold ballast. The wood was bolted and screwed together using silicone bronze and non-magnetic stainless steel (SS 316) bolts. The two enclosures were built to the same specifications using non-magnetic materials from one supplier and any differences in internal dimensions were less than 1 inch in each dimension.

In each enclosure, 72 lead bricks (26 lb each), equaling 1872 lb per enclosure were used as ballast. The lead ballast was supplemented by an additional 739 lb ( $\pm 5$  lb) of scrapped cut marble per enclosure. All ballast was non-magnetic and the correct amount of ballast was confirmed by deploying the enclosure off the Miller Marine dock.

Net panels retained the animals in the enclosures, but allowed them to be fully exposed to currents, light, nutrients and food from the surrounding environment. Fishing net (1000 x 200.5 deep, 8 cm, #21 net; Trawlworks Inc.) was prepared using nylon mending twine (#21) as separate panels that could be hung on the wooden frame. The base nets were reinforced using 3/8" Super Pro Rope (Trawlworks Inc. RI). Nets were attached to the inside of the wooden frame using plastic flexible strip pipe holder and screwed in place securely. Care was taken that there were no holes between nets, areas of sagging net or spaces through which animals could either escape, or take refuge.

For each enclosure, hydrophones cables (Section 5.2.3) were fed through a central point on the top of the enclosure along its length but offset to one side. Hydrophones (Section 5.2.3) were secured by heavy duty VELCRO<sup>®</sup> and zip ties through drilled holes in the wooden frame. It was important that the hydrophones remained in the same position for the duration of the study and remained steady even in the strongest currents. Hydrophone cables were secured on the inner side of the enclosure by zip ties passed through the wooden frame. This design prevented possible snagging while the enclosure was being deployed and recovered. The cables were flush with the wood on the inside, such that they did not interfere with animal movements. At the point of exit from both of the enclosures, the six hydrophone cables were bundled together and approximately 70 ft of cable was passed from the top of the enclosure up to the platform with sufficient slack for the tidal range and surge caused by adverse weather conditions. Excess cable was coiled on the platform and releasable, if required. On the platform the hydrophone cables were passed through pelican cases that housed the electronics (Section 5.2.3).

In addition to the HTI hardware, each enclosure was fitted with a sonde (In Situ Inc. Troll 9000 Pro), mounted externally, to collect environmental data (temperature, oxygen, salinity; 5 minute frequency). Accurate daylight regimes were recorded (timeanddate.com). A GoPro<sup>®</sup> was mounted inside the enclosure to collect video data to truth the animal movements recorded by HTI equipment. The mount was on one side of the enclosure 45 cm from the base, angled to maximize the view of the enclosure. A beacon tag was secured on the ceiling of the enclosure that acted as a control signal. A low current velocity meter was placed approximately 25 ft from each enclosure on the seabed (5 minute frequency). The magnetic field at each site was also recorded, see Section 5.2.4.

### 5.2.2.3 Platforms

There were two platforms deployed, one at either site, to house the electronics. The first was constructed from 80 full-float dock-blocks (Dock-Blocks™). The platform was 9 by 9 blocks minus one in the middle where the hydrophone cables came through. Transfer from the boat to the sea required that the platform be lifted in its built state. In order to reduce the flex and stabilize the platform during lifting, the platform was reinforced with a 2x4” wooden frame on either side connected by a steel rod (Figure 5.3). The second platform was constructed from a 2x4” wooden frame and eight blue floats (26” diameter; tinypontoonboats.com), topped with ¾” plywood (Figure 5.3). The platforms had to be large enough and stable enough for research personnel to transfer onto and access the electronics for data download and reset between trials. Platforms were 15 and 16 square feet, respectively.



**Figure 5.3. Photos showing platform construction.**

Platforms were built to house electronics at the surface and provide a workstation for personnel. The platform built from dock-blocks was reinforced with wood for lifting (a) and a second platform was built using 8 floats and a wooden frame (b). The enclosures are also pictured in (a), one behind the other.

The material that the platforms were constructed from had no bearing on the research. The purpose of the platforms was to provide a platform for personnel to work from and to house the electronic equipment (Section 5.2.3), which was left at site overnight for a prolonged period of time. For this reason, the electronics were housed in a series of three pelican cases; one for the Newmar® transformer which released a lot of heat, one for the batteries and transformer and one for the HTI electronic equipment and laptop (Section 5.2.3). All of this equipment was connected in sequence by electronic cables between devices; the pelican cases remained watertight by installing inverted plumbing fixtures for cables to pass through which were made watertight using caps, clamps and sealant. Heat tests were conducted prior to field deployment by running the electronics in the sealed pelican cases and monitoring the temperature to ensure the equipment did not overheat. The water tightness of the pelican cases was important since the electronics would be left at sea for a prolonged period of time in an area with potential high wave fetch. The platforms were marked with a yellow flashing light (Solar Marine Lantern, 2-3+ nm, Sealite USA LLC) raised by a yellow drum 4-6 ft from sea level.

### 5.2.2.4 Anchorage

The enclosures were anchored using Dor Mor anchors (135 lb) off each corner deployed approximately 25 ft from the enclosures to ensure there was no interference with the emitted EMF. The platforms were

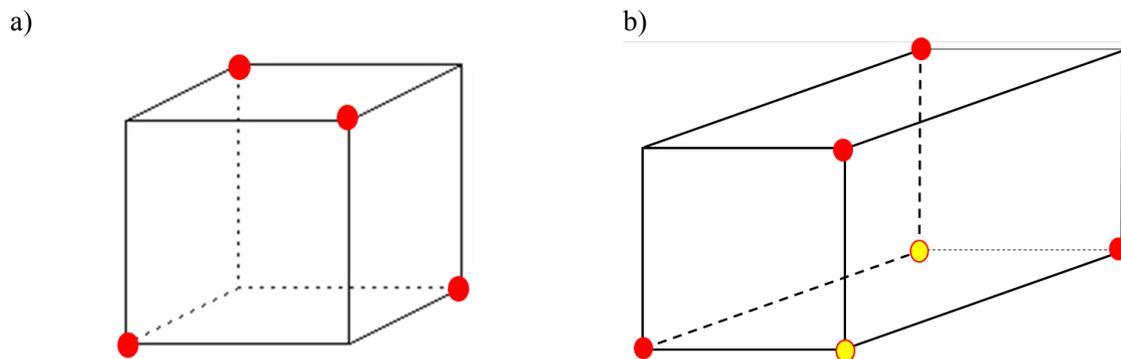
each connected by ropes to the top corners of each enclosure (TrawlWorks Inc.). Ropes were reinforced with protective hose at each end to prevent chaffing. Each platform was also yolk anchored by one 400 lb anchor offset from the enclosure. The regulatory buoys were anchored using five 25 lb zinc weights bound together (125 lb total anchorage per buoy). Zinc was an appropriate material to use due to the distant proximity to the enclosures. The zincs and regulatory buoys were successfully installed using ¼” stainless steel cable rather than rope.

### 5.2.3 Acoustic telemetry

#### 5.2.3.1 Hardware

All hydroacoustic hardware was supplied from Hydroacoustic Technology Inc. (HTI). A portable Acoustic Tag Receiver (ATR, Model 291) was used to receive signals from four hydrophones simultaneously. This receiver was supplied with a Newmar® power converter (model 115-12-8) allowing it to be operated on 120V or 220V AC power. The four hydrophones connected to the ATR were supplemented with two Micro Data Loggers (MDL, Model 395) capable of receiving signals from one hydrophone each. This design gave an array of six hydrophones in total.

HTI were consulted on the position of the hydrophones. The optimal geometry for the hydrophones is to form a cuboid, two up, two down array (Figure 5.4a). The 3D positioning within that array has maximum accuracy but accuracy outside of the array is less. The enclosures were not cuboid and to position the array in a cuboid formation would reduce the accuracy of positioning at the ends of the enclosures. For this reason, the ATR hydrophones were fixed in the corners of the enclosures and supplemented with two additional hydrophones from the MDL’s. The four hydrophones from the ATR were in a two up, two down diagonal configuration with the two MDL hydrophones in the remaining bottom corners (Figure 5.4b, Table 5.2). To obtain 3D tracking within the enclosure, a triangulation of position fixes from four independent hydrophones was required. The addition of MDL hydrophones also maximized the likelihood of obtaining 3D positions for each specimen regardless of its position in the enclosure (noting potential obstruction from hydrophones by other specimens). In order to synchronize the data, each device had a GPS antenna that was situated outside of the pelican cases in full view of the sky. This was not to collect location data but to provide an accurate time stamp for synchronization of the data collected from all three devices.



**Figure 5.4. Hydrophone array geometry.**

The optimal hydrophone array suggested by HTI (a) using four ATR hydrophones (red) and the hydrophone array using four ATR hydrophones (red) and two additional MDL hydrophones (yellow) developed in consultation with HTI for the enclosures (b).

**Table 5.2. Hydrophone positions for each enclosure.**

Note that the origin is set at 10, 10, 10 and subsequent measurements were in meters. Hydrophones 1-4 were connected to the ATR and hydrophones 5 and 6 connected to the MDL's. Hydrophones were either mounted on the bottom (B) or the top (T) of the enclosures. These hydrophone positions were also used in the data processing databases (Section 5.2.6; Chapter 6: Troubleshooting).

Hydrophone	Enclosure: Control				Enclosure: Treatment			
	x	y	z	Mount	x	y	x	Mount
H1	10.000	10.000	10.000	B	10.000	10.000	10.000	B
H2	13.555	10.000	11.725	T	13.580	10.000	11.725	T
H3	13.555	14.930	10.000	B	13.565	14.940	10.000	B
H4	10.000	14.930	11.728	T	10.000	14.940	11.730	T
H5	13.555	10.000	10.000	B	13.580	10.000	10.000	B
H6	10.000	14.935	10.000	B	10.000	14.940	10.000	B

The hydrophones (Model 590) had a 330° field of detection for 307 kHz acoustic tags (Model 795 series). Each hydrophone was connected to the ATR/MDL's by a 100 ft (30.5 m) hydrophone cable (Model 690). The acoustic tags used in this study were 795-LG and 795-LY (Table 5.3). A combination of tags, 795-LG and 795-LY were used. Tags were customized by HTI by adding a wire loop at the end to provide secondary backup attachment using a zip tie. In future, it is suggested that the wire loop be omitted; zip ties provided secure attachment (see Section 5.2.6 for tag attachment details). Furthermore, the zip tie pulled on the wire loop and compromised the water tight seal. Tags used in this study, operating at 307 kHz, are reported by HTI to have a 1 km detection range in freshwater, with fine scale sub-meter resolution. Prior to being attached to specimens, tags were programmed with an ID using a Tag Programmer and software (TagProg® v06.00). Tag ID's were unique double pulse acoustic signals, mathematically defined by HTI to prevent signal collision and maximize frequency (2000-2999 msec period, 0.5 msec pulse width).

**Table 5.3. Tag parameters.**

The parameters as reported by HTI; PRI is Pulse Rate Interval, the lifetime quoted is based on 1.0 ms pulse width, single pulse at 10 °C. Diameter, length and volume may vary by ±10 % (<http://www.htisonar.com/795-900-acoustic-tags-for-fish.htm>).

	Diameter (mm)	Length (mm)	Vol (cm <sup>3</sup> )	Freq. (kHz)	Source Level (dB/uPa)	Weight in air (g)	Weight in f/w (g)	Lifespan 3 sec PRI	Lifespan 10 sec PRI
795-LG	11.0	25.0	1.40	307	152	4.60	3.10	220 d	400 d
795-LY	16.0	48.0	5.70	307	152	11.90	7.30	2.5 yr	4 yr

The MDL's typically collect data internally on an SD card whereas the ATR data was written directly to the laptop hard disk. To enable rapid switching between all three receivers without disconnection, the devices were networked together using a hub (Netgear® ProSafe® Model GS105) and ethernet cables (rather than crossover cables supplied with the HTI hardware). The data from all three receivers was then written to a common file for rapid download in the field.

### 5.2.3.2 Software and settings

For data collection, the ATR was connected to a laptop running Acoustic Tag v6.02. In Acoustic Tag, a project database specifically for data collection was created and used every day in the field. This database saved project specific parameters. The hydrophone gain was set to 20, Mini-volts was 0.10, Signal to Noise Ratio (SNR) was 3.0 and a SNR filter of 1. Encoding was set to 'none' and the Pulse Width Filter was 0.5 (to match the tag programming). The internal GPS module of the unit was enabled. The computer time was set via the current UTC time and the ATR hydrophone synchronization number was 199. Each time the Acoustic Tag was opened, the program automatically detected the ATR and the database with the aforementioned settings. The same project database was in use at the control and

treatment sites albeit on different laptops. The MDLs were operated through TightVNC v1.2.9 (Free Software Foundation Inc.) and/or ViewTag v01.00.00-1. Essentially the same settings were employed and saved to each MDL device but it was operated through different software. The MDL hydrophone synchronization numbers were 201 and 301 at each site.

#### **5.2.4 Monitoring the Magnetic Field**

An autonomous magnetometer was placed at the treatment site and was mounted on the outside bottom beam of the treatment enclosure. At the control site, the magnetic field was monitored continuously by the fluxgate that was detached from the SEMLA (Section 3.7). The fluxgate was mounted in the same position described for the treatment enclosure. The fluxgate was hardwired to a laptop at the surface encased with marine batteries in a pelican case as described for the other electronics on the platform (Section 5.2.2.). Data was collected on each device continuously (5 minute frequency). In order to characterize the magnetic field in 3D, diver transects took place at each site (Section 3.16). The power in the Cross Sound Cable was obtained as ‘Real-Time Market Actual Scheduled Interchange’ data from ISO New England

#### **5.2.5 Enclosure Field Deployment**

Deployment of the hardware was completed using two vessels. The URI Research Vessel, Shanna Rose (SR) is a 42’ Westmac lobster boat outfitted for research with a 15’ A-frame. The SR was suitable for daily specimen deployments (Section 5.2.7-8) but due to the size and weight of the ballasted enclosures, a larger vessel was required. The Jennifer Miller (JM), a 74’ landing craft with a 7.5 ton hydraulic turret crane from Miller Marine Services was contracted to deploy the enclosures and platforms.

The JM was assisted by the SR to accurately position on the pre-selected co-ordinates (Section 5.2.2, Table 5.1, Figure 5.2). The vessel positioned perpendicular to the buried cable using a four point anchoring system. The magnetic field was surveyed by a surface deployed fluxgate magnetometer. The peak of the magnetic field was marked on the side of the vessel and this was used as a visual aid when positioning the enclosure during deployment. The platform was launched and secured to the side of the JM. Ropes were secured on the platform and the enclosure, ensuring the correct orientation. The enclosure was lifted by the crane, whilst being held by tag lines to prevent swaying/twisting, carefully positioned and lowered to the seabed during slack tide.

A scientific dive team (dive lead on full face mask with communications, buddy, safety diver and surface tender; Appendix 2), completed a fluxgate transect survey and confirmed the position of the enclosure in relation to the magnetic field peak. The enclosure was positioned within reasonable limits of the desired position and redeploying did not guarantee an improvement. The divers released the crane hook and surfaced, the JM vacated the study site and SR personnel/dive team deployed anchors and secured the platforms (Section 5.2.2). The same process was adopted at the control site with no cable, with the omission of the magnetic field survey since there was no cable to align to.

The electronic equipment in pelican cases delivered by SR to the platforms and set up in preparation for data collection. Pelican cases were secured by ratchet straps to eye hooks on the platforms. Cables between pelican cases were sealed.

#### **5.2.6 Specimen handling**

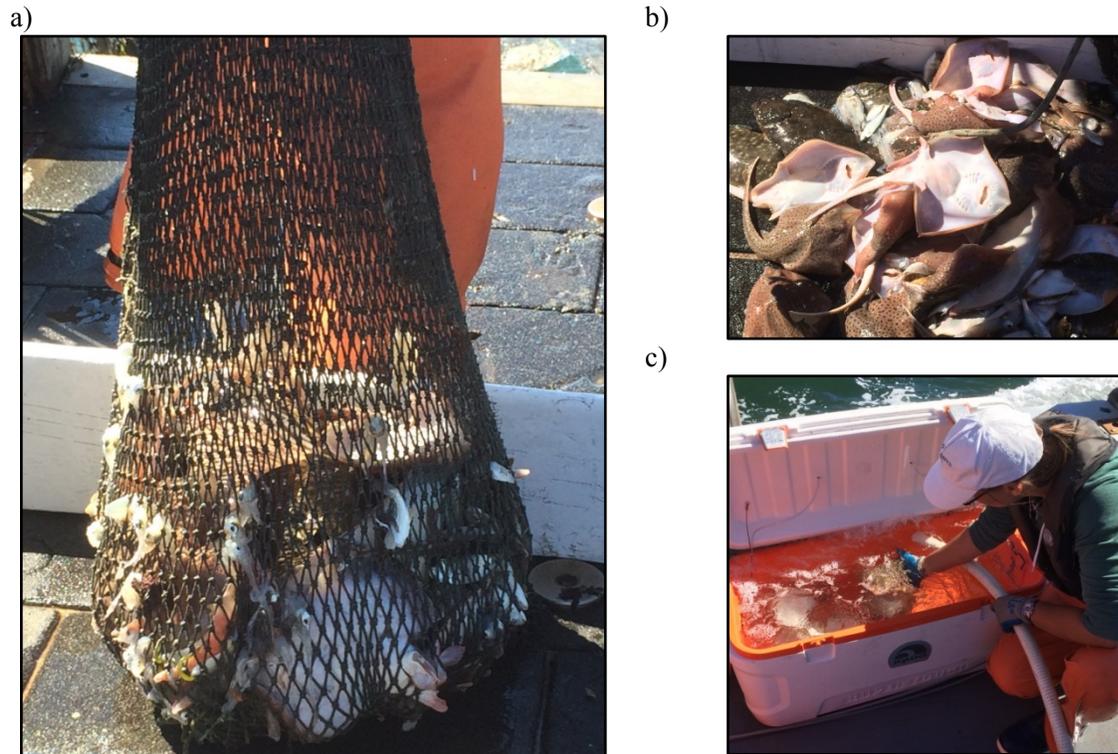
All details of the specimen handling for skates and the experimental protocol were preapproved by the URI Institute of Animal Care and Use Committee in order to ensure the highest ethical standards with regards to the welfare of the animals (Appendix 3). All specimens were housed at the Marine Science Research Facility on the Bay Campus at the Graduate School of Oceanography, University of Rhode Island, hereafter ‘the aquarium’. This facility was supplied by a natural seawater intake from

Narragansett Bay, via two outdoor settling tanks (12' diameter, 8' deep) and a 3' diameter sand filter thereby providing ~30 µm filtered seawater.

### 5.2.6.1 Specimen Collection

Lobsters were obtained from a local commercial lobster fisher under a Scientific Collectors Permit. Lobsters were collected between late July and early September, 2016. Lobsters were transported (<30 minute journey) from the dock to the aquarium in large coolers.

Skates were collected on the Graduate School of Oceanography (GSO) weekly fish trawl on the RV Cap'n Bert (53' stern trawler) in mid-September, 2016. Trawls were non-commercial and <30 minutes in order to reduce stress levels in specimens. On releasing the haul, the specimens were quickly transferred into multiple large coolers, filled with aerated seawater (150 L, max 6 specimens; Figure 5.5). The coolers were frequently flushed with fresh seawater to minimize mucous build up. The skates in aerated seawater filled coolers were transported by truck (<15 minutes) to the aquarium. A higher proportion of females were collected which is typical of the GSO trawl. The small number of males that were collected did not survive, resulting in a solely female study population.



**Figure 5.5. Little skate specimen collection.**

Trawls were short to reduce stress in specimens; this approach resulted in a small haul (a). Once released (b) the specimens were quickly transferred to aerated coolers that were frequently flushed with fresh seawater to remove mucous build up (c).

### **5.2.6.2 Animal Husbandry**

#### **Lobsters**

Lobsters were held in two outdoor runway tanks at the aquarium. The temperature ranged from 17.9 to 26.4 °C ( $\bar{x}$ =22.5) and was monitored continuously. A high in/out flow of seawater prevented build-up of waste and a large air-stone was used to maintain oxygen levels. Lobsters were fed 5-7 times per week on a diet of fresh squid. The carapace size of individuals was closely matched with an average of 85.26 mm (SE=0.14, n=65) and an average individual mass of 498.91 g (SE=4.92, n=46). Lobsters were banded and held communally so that they had plenty of space to roam, encouraging natural behavior and familiarity. The establishment of a dominance hierarchy to reduce aggression was encouraged in groups of lobsters that would be deployed together.

#### **Lobster dominance establishment**

Staged lobster fights took place at night since it is generally accepted that lobsters are nocturnal, although this is highly variable (Golet et al., 2006, Jury et al., 2005). Lobster fight groups were predetermined by the randomly assigned release group (see section; 'Tagging'). Staged lobster fights took place in a circular tank (1 m diameter) in the aquarium. A GoPro<sup>®</sup> camera was fixed overhead. The camera and the tank were covered by black plastic sheeting to maintain darkness. Red lights provided enough light for the recording but maintained the natural light regime for the lobsters. The tank had removable sections; five sections for five lobsters. For the purposes of identification during the fight, the lobsters wore a zip tie identifier (color/pattern coded by electrical tape) around the carapace, between the third and fourth pereopods (walking legs). The lobsters were un-banded, put into the tank and allowed a 10 minute acclimatization period, confirmed by evidence of lobsters exploring the tank sections. The fight started when the section dividers were lifted out overhead. Fights lasted 20 minutes and were observed from a viewing window to ensure an appropriate level of severity was not exceeded. On conclusion of fights, lobsters were re-banded, checked for damage and returned to the communal tank. Between fights, the water was drained from the tank and rinsed before refilling. This protocol helped maintain temperature, oxygen levels, and removed hormonal releases. There was no water flow during the fight to achieve undisturbed surface water aiding the video recording. Staged fights were completed in a standardized fashion such that the dominance of the lobsters could be graded (e.g. Breithaupt & Atema (2000)) however, the data was not analyzed for this study since the focus was only to allow the lobsters familiarity with release group counterparts.

#### **Skates**

Skates were held in an indoor circular tank (10ft/~3m diameter, 3ft/1m deep) with a thin layer of sand on the bottom. The skates were fed 2-3 times per week, also on a diet of squid. The tanks were siphoned 1-2 times per week, the sand was rinsed and returned to the tank. The temperature ranged from 14.1 to 18.9 °C ( $\bar{x}$ =17.2), and was monitored continuously. A high in/out flow of seawater prevented build-up of waste and a large air-stone maintained oxygen levels (9.6 mg/l  $\pm$  1.3).

Skate length ranged between 41.5 and 53.0 cm with one outlier with a stumped tail and was only 30.6 cm ( $\bar{x}$ =46.5, SE=0.38, n=38). The stumped tail had no bearing on the skate's behavior and was fully healed when the skate was collected. Pectoral wingspan ranged from 23.1 to 30.2 cm ( $\bar{x}$ =26.2, SE=0.20, n=39) and the average mass was 554.1 g (SE=12.03, n=37). All specimens used in the field experiment were females.

### **5.6.2.3 Tagging**

Prior to tagging, all specimens were given an ID. For lobsters, the ID was a numbered band paced on the upper segments of the cheliped (claw) that also identified the sex. For skates, the ID was a numbered t-bar (FD-94 Floy Tags, short: 3.8 cm) on the wing, inserted subcutaneously using a scissor gun. These ID's allowed the release groups to be randomized prior to the field study.

#### **Lobsters**

A harness for lobster tag attachment was developed which could be easily and rapidly attached/removed thereby reducing handling time. The harness comprised of three zip ties, one around the tag, one through the zip tie on the tag attached to a third zip tie secured around the lobster carapace between the second and third pereopods (walking legs). A fourth zip tie was passed through the wire loop of the tag used as a backup; however, for future studies of this kind of duration, this is unnecessary. Based on behavioral observations during preliminary trials, the tag and harness did not influence the lobster behavior. The intention was to tag lobsters in advance of field studies but the lobsters held in communal tanks, nibbled the tags of others and broke the water seal. For this reason, tags were attached to lobsters on the vessel prior to field deployment (Section 5.2.7).

#### **Skates**

Skates were tagged with Peterson discs which served as a mount for the HTI tag. The Peterson disc attachment involved a minor piercing through the muscular wing. In brief, the needle was primed with a disc, passed through the muscular wing and another disc paced on top. The needle was trimmed and then gently bent to create a circle that served two purposes; it secured the discs and created a loop for the HTI tag to be attached to. Although this is a minor procedure, the skates were allowed time to adjust prior to any further handling. For the field study, the HTI tag was attached through the loop with two zip ties, one around the tag and one to secure it to the metal loop.

#### **Visual identification**

The HTI tags were color coded for identification in video data for ground-truthing (Section 5.3.1). The lobster and skate predetermined randomized release groups were also color coded. Lobsters were banded with different colored bands according to their grouping and skates were color coded by Peterson discs. This coding allowed rapid identification of groups so that individuals could be easily selected from the communal tanks on the morning of their field deployment.

### **5.2.7 Specimen field deployment**

#### **5.2.7.1 Health checks**

Health checks were conducted to ensure all specimens were viable for experimentation. For lobsters, a natural behavioral response during handling was confirmed; typically a meral spread (raising the claws) and/or a caridoid escape reaction, by curling and uncurling the abdomen, also known as 'lobstering' or 'tail-flipping'. This could also be checked by a 'poke test' whereby, the handler essentially pokes the lobster between the banded chelipeds (claws) and the lobster responds with a meral spread in defense. The natural response in skates was either to rapidly undulate the pectoral fins or curl them tightly. Additionally the gill action was observed as an indication of normal breathing rate. If there were signs of slow, delayed or no response to handling and/or signs of damage to the animal, then the specimens were omitted from the study.

### **5.2.7.2 Transport to site**

Specimens were collected from the aquarium and transported to New Haven, CT, by truck (~1.5 hrs) in large aerated coolers. Partial water removal (temporary) was required to allow manual handling of the large coolers onto the SR vessel. The transport time from the dock to the field site was ~45 minutes. During the transport to site, the HTI tags were attached (by harness for lobsters, to Peterson discs for skates) and at the same time health checks took place.

### **5.2.7.3 Deployment/Collection**

Once ready for deployment, individuals were transferred to mesh specimen bags (max. 2-3 per bag). These were held briefly in the surface water, clipped to the side of the platform while 1) the divers prepared and entered the water and 2) the topside personnel exchanged batteries and set up the electronics. The dive team comprised of one lead diver on full face mask with hardwired communications to top-side personnel, one buddy, one topside safety diver and one topside tender for lead diver (Appendix 2). The divers descended with the specimens, the lead entered the enclosure via the door, mounted and turned on the GoPro<sup>®</sup> and released the specimens. Lobsters were unbanded when released and placed on the bottom of the enclosure. Skates were encouraged to swim out of the mesh bag, sometimes with assistance but with minimal handling. Specimens were observed briefly by the divers for natural behavior. All actions were reported to topside personnel and times recorded. When collecting specimens at the end of a trial, the lead diver took care not to allow specimens out of the enclosure when entering. Specimens were collected and placed in mesh bags, all specimens were counted in and counted out to ensure all were recovered. Where a swap between enclosures was taking place (Section 5.2.8, Table 5.4), the specimens were health checked and returned to the aerated coolers briefly but remained in the mesh bag ready for deployment. On trial completion, the specimens were removed from the mesh bags and returned to the cooler in preparation for travel (lobsters were rebanded) back to the aquarium. Fresh seawater was collected for transport.

### **5.2.8 Data Collection**

To allow for individual variability in behavior, all specimens went to both enclosures (control and treatment). Exposure to both enclosures is referred to as one full trial. Specimens were only used for one trial. To avoid bias in the behaviors at each enclosure due to the order of exposure (naive versus non-naive), the sequence of exposure was alternated between trials. That is, some trials went to the control enclosure followed by the treatment enclosure where other trials went to the treatment enclosure first followed by the control enclosure. To allow a blind interpretation of the results, the enclosures were coded 'A' and 'B' by the researcher conducting the analyses, this was also true for the sequence of exposure which was coded 1 and 2. There was no indication of which was which until after an initial interpretation by a second researcher. The control enclosure was coded 'A' and the treatment enclosure on the cable was coded 'B'. Organisms from sequence 1 went to enclosure 'B' (treatment) then 'A' (control) and those from sequence 2 went to enclosure 'A' (control) followed by enclosure 'B' (treatment). For each trial there was one 'group' of five specimens that were released at each enclosure once, in the pre-designated sequence. Three days in the field were required to achieve a full trial but two trials could be achieved simultaneously (Table 5.4).

**Table 5.4. An overview daily field tasks to obtain two trials simultaneously.**

For the purposes of clarity, the tasks using two lobster groups L01 & L02 are described.

Day	Task	Description
Day 1	Release	Release group L01 at the first enclosure. Release group L02 at the second enclosure.
Day 2	Swap	Retrieve group L01 from the first enclosure. Retrieve group L02 from the second enclosure and simultaneously release group L01 to that enclosure. Return to the first enclosure and release group L01.
Day 3	Retrieve	Retrieve group L01 from the second enclosure. Retrieve group L02 from the first enclosure.

A total of 16 lobster trials were attempted which was 32 releases. The first three trials were discounted as test-runs, so the reported results are based on 13 trials, which were 26 releases. Exposure typically ranged between 17 and 26 hours ( $\bar{x}$  = 22.94 hr,  $sd$  = 2.39,  $n$  = 20). The variation was due to tide regimes and access to the field site for divers/vessel. On occasion, bad weather prevented a normal time schedule and exposure exceeded 48 hours. This affected six of a possible 26 releases of animals. Four of the six were on the last sequential release and are therefore of no importance. Only two releases were affected on the first sequential release. On these two occasions, animals were retrieved and instead of being swapped into the second enclosure, they were returned to the aquarium for a wash-out period (>72 hours) ensuring no influence of a prolonged exposure time.

A total of eight skate trials were completed that included 16 releases. Exposure typically ranged between 18 and 25 hours ( $\bar{x}$  = 23.18 hr,  $sd$  = 2.11,  $n$  = 14). On occasion, bad weather prevented a normal time schedule and exposure time exceeded 48 hours. This affected two of a possible 16 releases of skates. Both were on the second sequential release and therefore had no bearing on the animal movement data collected.

### 5.2.9 Data Processing

Two separate Project Databases were used during data processing, one specific to each enclosure containing the specific measured hydrophone positions (Section 5.2.3, Table 5.2) which were important for accurate 3D positioning. All of the data collected in the field was recorded as ‘Raw Acoustic Tag Signals’ in hourly ‘Raw Tag Detection Files’ (\*.RAT). These files were processed in two software programs; first the data was processed in Mark Tags<sup>®</sup> (v07.00.00-17) to mark the acoustic signals and then in Acoustic Tag<sup>®</sup> (v6.20.10-3) to turn the acoustic signals into 3D positions (x, y, z). The correct Project Database for the dataset being processed was used in both software programs.

The intention was to merge the data collected from the ATR and the MDL’s using the GPS time synchronization; however this was not possible and turned out not to be essential since the four hydrophones collected consistently reliable data. Therefore the data processing focused only on the ATR data and the signals from the four hydrophones. The hourly \*.RAT files from one group release were batch processed in Mark Tags<sup>®</sup>. The Tag ID list was loaded manually for the group and the four ATR hydrophones selected. A pre-prepared ‘Batch Parameters’ text file that employed a Filter file was loaded and Mark Tags automatically loaded and marked the data in each hourly file, returning a ‘Tag Detection File’ (\*.tat) to the same folder. Each \*.tat file was then opened in Mark Tags<sup>®</sup> and manually checked for each individual tag and hydrophone to ensure that all available signals had been marked. Manual marking was typically required to ensure maximum return from the signals due to the continuous nature of the data.

The \*.tat files were then loaded into the Acoustic Tags<sup>®</sup> software and a second batch process was employed via a \*.t3D file. This file held the specifics of how to position the marked signals. This process produced a database (\*.mdb) for each hourly file which could then be appended and exported. Although the positions and tracks of animals could be viewed and ‘played’ in Acoustic Tags<sup>®</sup>, data was exported for manipulation and analyses.

All further work for data preparation was completed in ‘R’ version 3.2.4 (R Core Team, 2016) using RStudio (RStudio Team, 2016). It was evident during the HTI data processing phase that some of the data fell outside of the hydrophone array. This was expected based on the predicted accuracy of the positioning system. Based on a preliminary analysis, a 30 cm buffer was added to the enclosure coordinates and any data that fell outside of this buffer was omitted.

The x, y, z co-ordinates for animal positions and time stamps were extracted from the HTI software output and used to calculate behavioral parameters for each tag. For each step, the distance moved, speed of movement, and relative turn angle was calculated and the z-dimension was used as the height from the seabed. The R package ‘adehabitatLT’ (Calenge, 2006) was used to calculate the relative turn angle, which is a measure of change in direction between steps (0-180° left or right). For each tag, the first 15 minutes of data were removed prior to analyses. This can be considered an acclimatization time in the enclosure after release and is considered sufficient for normal behavior to have resumed after handling.

Over eight million positions were used in the analyses for lobsters and skates. Animal movement datasets were merged with the environmental data, (current speed, current direction, temperature, oxygen, salinity and light regime) and the CSC power data.

The behavioral parameters that were selected for analyses were the total distance traveled by each individual per day, the mean and maximum speed of movement, the height from the seabed and the number of large turns. A preliminary review of data suggested that there may be a higher frequency of ~180° turns at one enclosure than the other, which was considered as a major response as it represented the animals completing a full turnaround of their direction of travel. For this reason the number of left and right turns of 170-180° per individual per day was calculated for the analyses. In addition, the spatial distribution of the animals within the enclosures was assessed both by the frequency of recorded positions and the associated elapsed time.

### **5.2.10 Statistical Analysis**

All statistical analyses were completed in ‘R’ version 3.2.4 (R Core Team, 2016) using RStudio (RStudio Team, 2016). Data exploration was conducted to check the data for outliers, homoscedasticity, relationships and co-linearity between variables, following the protocol outlined by Zuur et al., (2010). The statistical analyses focus on the influence of the EMF from the cable. Therefore the only parameters used in statistical models were the enclosure (cable, no cable), the sequence of exposure to the cable and the grouping of individuals. The environmental parameters were not included since i) they were not the focus of the study and ii) this reduces over-parameterization and therefore reduces the risk of over-fitting.

The total distance traveled, mean and maximum speed of movement and height from the seabed were treated as continuous variables and therefore fitted with a Gaussian distribution. Due to the repeated measures nature of the data, linear mixed effect models were employed which allow a fixed and random structure to be incorporated (Zuur et al., 2009). Linear mixed effect models were fitted using the ‘nlme’ package (Pinheiro et al., 2016). In the maximal model, the fixed effects were specified as the ‘Enclosure’ and the ‘Sequence’ plus the interaction between the two variables. The random structure of the model had three options; 1) no random term, 2) a random intercept and 3) a random intercept and slope model. Models with and without random structures were fitted using generalized least squares (gls) and linear mixed effect (lme) models in the ‘nlme’ package. Model selection first determined if the incorporation of

a random intercept and/or slope significantly improved the model using restricted maximum likelihood (REML) estimation. Once the random structure of the model had been established, the model selection on the mixed effects was completed using maximum likelihood (ML) estimation and the final model refitted with REML. The final model was validated by plotting the fitted and residual values and if violation of normality, independence or homoscedasticity were detected the model was revised. The procedure followed is described in full by Zuur et al., (2009).

The frequency of large turns was initially treated as a Poisson distribution. For this reason a generalized linear mixed model with a random structure (glmer) was fitted using the 'lme4' package (Bates et al., 2015). The model was found to be over-dispersed and therefore a quasi-correction was required. This correction is no longer possible in lme4 since it has been shown to be unreliable (Bolker, 2017). For this reason, a generalized linear mixed model was fitted using Penalized Quasi-likelihood (glmmPQL) which automatically estimates the over dispersion (Bolker et al., 2009, Zuur et al., 2009) and allowed the random effect to be incorporated. The model validation plots (using Pearson residuals) suggested that the assumptions had been violated. A linear mixed effect (lme) model with the log transformed count data was explored but as expected, the validation of the model failed on the heterogeneity, non-normality and/or non-independence.

The number of large turns was recalculated as a proportion of the total number of turns and a glmmPQL was fitted with a binomial distribution (bound between 0 and 1). The glmmPQL models were fitted using the R package 'MASS' (Venables et al., 2002). Validation of the model was based on plots of the fitted values and the Pearson residuals to check that the model assumptions were met. The random structure must be specified in a glmmPQL so in order to explore a model without a random structure a generalized linear model (glm) was also explored, fitted with binomial distribution and quasi-correction where appropriate. Model selection for the glm (i.e. simplification) was based on the Akaike Information Criterion (AIC) (Burnham et al., 2002), conducted using the drop1 function with a chi-squared/F tests as appropriate. Comparisons between glmmPQL and binomial glm models were based on the validation plots only.

The spatial distribution of the animals along the longest length of the enclosure (i.e. y-axis; perpendicular to the cable at the treatment) was also compared between the two enclosures and analyzed. Two parameters were used; the number of positions recorded and the total elapsed time. The distribution within each enclosure was determined by calculating the proportion of positions recorded and the proportion of time spent within 40 equal bins (each c.a. 14 cm) along the enclosure length (y-axis). The resulting group mean distributions of the animals within each enclosure were then compared using the non-parametric Kolmogorov-Smirnov two sample test. To assess the distribution of animals away from the potential influence of the ends of the enclosure a subset of the data was also analyzed which represented the central space of the enclosure (bins 7 to 34 of 40). The space omitted (c.a.84 cm from either end) was greater than the maximum length of the animals (including antennae for lobster) and was therefore assumed to take into account the space where the animals would most likely detect the end of the enclosure, plus the buffer for tag positional error.

To further assess the influence of the EMF on the behavioral parameters, the space in the enclosures were split into two zones of high and low EMF. The areas of the two zones were defined by the magnetic field being above or below the Earth's magnetic field and a 'buffer' area between the two zones to ensure no overlap. Although the zones were defined based on the magnetic field at the treatment enclosure, the same zones were defined at the control enclosure for the purposes of comparison; however, at the control site, the Earth's magnetic field was constant. Only the behavioral parameters which showed significant differences between enclosures were assessed in this way. For each of the parameters of interest, the differences between zones were assessed for each individual and the group means (i.e. per release) compared between control and treatment enclosures using a Welch's two sample t-test.

All data plots were produced using the R packages ‘ggplot2’ (Wickham, 2009) and ‘circular’ (Agostinelli et al., 2013).

## 5.3 Results

For context, this section starts with a technical overview of the effort versus return for the number of individual releases together with an assessment of the accuracy of the HTI positioning system (Section 5.3.1). The environmental conditions during the two field periods of the lobster and skate study are reported in Section 5.3.2. The results for the assessment of differences in lobster and skate behavior are then reported in Section 5.3.3 and 5.3.4 respectively. These sections are divided by behavioral parameter analyzed; the total distance traveled per day, the speed of movement (mean and maximum), the height from seabed, the proportion of large turns and their spatial distribution. The results are also summarized for each species.

### 5.3.1 Technical overview

#### 5.3.1.1 Number of individuals and releases

A total of 65 lobsters were prepared for release, which is a total of 130 possible individual releases, of which, 109 were included in the analyses, organized in 13 groups (Table 5.5). A total of 40 skates were released, that is a total of 80 possible individual releases, of which 76 were included in the analyses, organized in 8 groups (Table 5.5). A summary of tag omissions is provided in Table 5.6.

**Table 5.5. The number of individuals included in the analyses.**

Study	Lobster		Skate	
Enclosure	A	B	A	B
Group				
1	5	5	5	5
2	5	4	4	4
3	2	5	5	4
4	4	4	5	5
5	4	4	5	5
6	5	5	5	4
7	3	5	5	5
8	3	4	5	5
9	4	4	-	-
10	4	4	-	-
11	5	5	-	-
12	5	5	-	-
13	4	2	-	-
Subtotal	53	56	39	37
Total releases	109		76	
Total individuals	56		39	

**Table 5.6. A summary of tag omissions for the lobster and skate studies.**

Summary	Lobster	Skate
Intended number of releases	130	80
Not released for biological reasons	4	0
Omitted due to biological reasons	5	2
Omitted due to tag failure	12	2
Total releases used in analysis	109	76

### 5.3.1.2 Position Accuracy

Animal movements recorded by HTI positioning system were ‘ground-truthed’ by comparison with video footage prior to the full data processing in HTI software. A total of 16 videos (four releases; 2 enclosures) were consulted and 77 movements from 17 individuals confirmed. Animal movements past the camera were matched to HTI data based on time, direction of travel and pattern.

The beacon tags in each enclosure remained in place for the full duration of the lobster and skate study. The lobster study beacon tag assessment was based on 183,761 positions at the control enclosure (A) and 177,735 positions at the treatment enclosure (B) and that of the skate study was based on 86,688 positions at the control enclosure (A) and 97,454 positions at the treatment enclosure (B). For the purposes of comparison between x, y and z dimensions, the positions are reported as a percentage of available space. The means, standard deviations, coefficients of variation and confidence intervals are provided for comparison in Table 5.7 and 5.8. Note that the beacon tag positions in each enclosure (A & B) were not identical but they did not move between studies. During both studies, the lowest variance was in the y dimension (CV <0.5%) and the highest variance was in the z dimension (CV 3-12%). The variance was lower in the skate study than the lobster study. The means from the two studies for axes x, y and z were within 0.63%, 0.02% and 2.15% respectively at the control enclosure (A) and 0.44%, 0.13% and 1.47% respectively at the treatment enclosure (B). Using the confidence intervals (Table 5.7) the tag accuracy during the lobster study was within 1.54 to 1.79 cm (A, B) in the x dimension, 1.05 to 1.15 cm (A, B) in the y dimension and 3.66 to 4.11 cm (B, A) in the z dimension. Similarly, during the skate study, the tag accuracy was within 1.38 to 1.62 cm (A, B) in the x dimension, 0.81 to 1.07 cm (A, B) in the y dimension and 2.15 to 2.42 cm (A, B) in the z dimension.

**Table 5.7. Beacon tag position accuracy during the lobster study.**

The mean, standard deviation, coefficient of variation and confidence intervals for the beacon tag positions in each enclosure. The means are shown as a percentage of available space to allow comparisons between dimensions.

Axis	Enclosure A				Enclosure B			
	Mean	SD	CV	95% CI	Mean	SD	CV	95% CI
X	48.06	0.91	0.83	47.88 48.24	46.21	1.06	1.12	46.00 46.42
Y	49.84	0.48	0.24	49.75 49.93	48.93	0.53	0.28	48.83 49.03
Z	79.89	3.56	12.64	79.19 80.59	77.19	3.17	10.07	76.57 77.81

**Table 5.8. Beacon tag position accuracy during the skate study.**

The mean, standard deviation and coefficient of variation for the beacon tag positions in each enclosure. The means are shown as a percentage of available space to allow comparisons between dimensions.

Axis	Enclosure A				Enclosure B			
	Mean	SD	CV	95% CI	Mean	SD	CV	95% CI
X	47.43	0.82	0.66	47.27 27.59	46.65	0.96	0.92	46.46 46.84
Y	49.82	0.37	0.13	49.76 48.89	49.06	0.49	0.24	48.96 49.16
Z	82.04	1.86	3.46	81.58 82.40	75.72	2.09	4.36	75.31 76.13

## 5.3.2 Environment

### 5.3.2.1 Temperature, oxygen, salinity

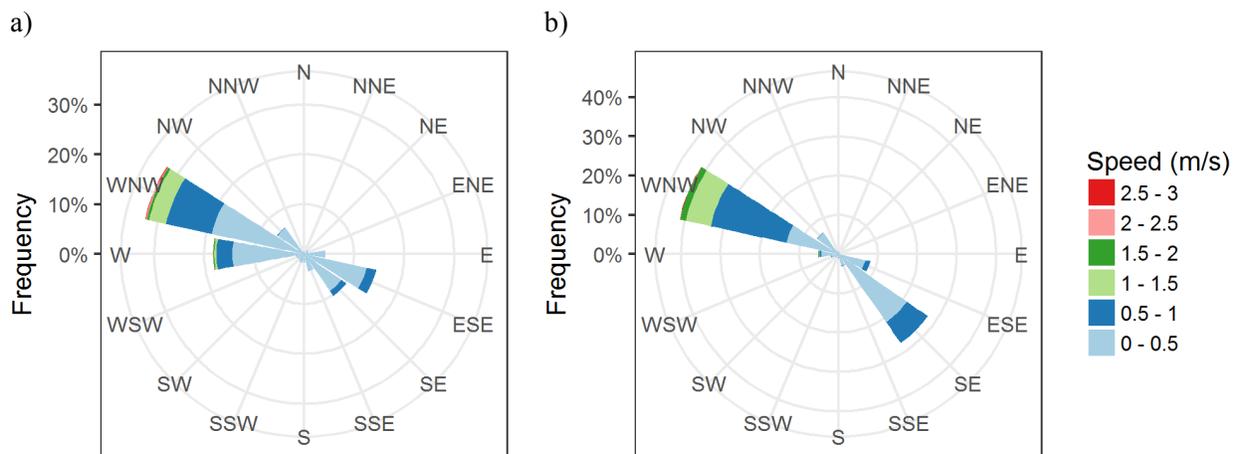
During the lobster study the temperature at the control enclosure (A) ranged from 22.52 to 25.36 °C ( $\bar{x}$ =24.09, SD=0.85) and was similar at the treatment enclosure (B) where it ranged from 24.02 to 25.32 °C ( $\bar{x}$ = 24.02, SD=0.86). The dissolved oxygen at the control enclosure (A) ranged from 5.08 to 8.86 mg l<sup>-1</sup> ( $\bar{x}$ =6.67, SD=0.74) and was similar at the treatment enclosure (B) where it ranged from 5.15 to 8.14 mg l<sup>-1</sup> ( $\bar{x}$ =6.62, SD=0.46). The salinity at the control enclosure (A) varied from 26.8 to 29.7 psu ( $\bar{x}$ =29.26, SD=0.22) and at the treatment enclosure (B) ranged from 28.8 to 29.7 psu ( $\bar{x}$ =29.21, SD=0.19).

The salinity at the control enclosure (A) was typically very similar to that of the treatment enclosure (B) aside from two outliers that decreased the lower range. Exploratory analysis of environmental variables with lobster movement parameters revealed that the temperature was collinear with the release group (VIF>3).

During the skate study the temperature at the control enclosure (A) ranged from 16.93 to 19.91 °C ( $\bar{x}$ =18.73, SD=0.73) and was similar at the treatment enclosure (B) where it ranged from 17.05 to 19.96 °C ( $\bar{x}$ =18.84, SD=0.71). The dissolved oxygen at the control enclosure (A) ranged from 7.23 to 10.38 mg l<sup>-1</sup> ( $\bar{x}$ =8.65, SD=0.65) and was similar at the treatment enclosure (B) where it ranged from 7.24 to 11.04 mg l<sup>-1</sup> ( $\bar{x}$ =8.76, SD=0.82). The salinity at the control enclosure (A) varied from 29.0 to 29.5 psu ( $\bar{x}$ =29.17, SD=0.09) and at the treatment enclosure (B) ranged from 28.8 to 29.9 psu ( $\bar{x}$ =29.43, SD=0.24). Exploratory analysis of environmental variables with skate movement parameters did not reveal any collinearity.

### 5.3.2.2 Current regime

The lobster study started during a period of neap tides and completed during spring tides. The mean current speed that the lobsters were exposed to was 0.33 m s<sup>-1</sup> (SD=0.33) with a maximum of 2.84 m s<sup>-1</sup>. The dominant current direction was west-northwest with stronger speeds and a weaker east-southeast current (Figure 5.6a). The mean current speed that the skates were exposed to was 0.48 m s<sup>-1</sup> (SD=0.34) with a maximum of 2.54 m s<sup>-1</sup>. The dominant current direction was west-northwest with stronger speeds and a weaker southeast current (Figure 5.6b).



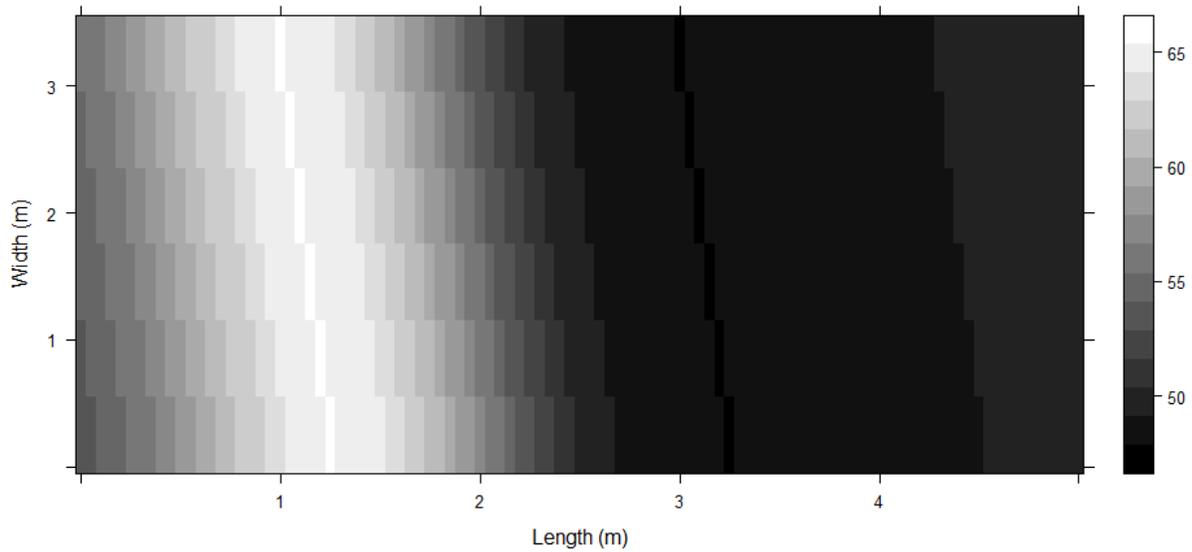
**Figure 5.6. The current direction and speed.**

Note that this is the current regime that the animals were exposed to rather than the current regime throughout the full duration of each study, for the lobster (a) and skate (b) study.

### 5.3.2.3 Electromagnetic Field

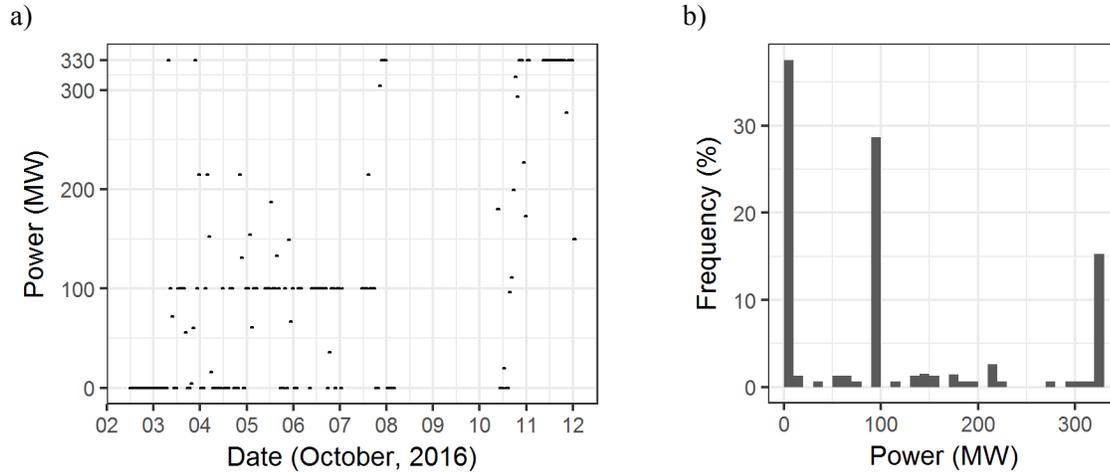
The power in the cable during the lobster study was constant at 330 MW. The magnetic field across the dimensions of the enclosure was assessed during the constant power (Section 3.16). From these data, the magnetic field on the base of the enclosure was extrapolated in order to show the gradient of magnetic field that the lobsters were exposed to (Figure 5.7). The gradient of magnetic field ranged from 47.8 to 65.3 μT. This is a maximal positive deviation of 14 μT from the Earth's magnetic field of 51.3 μT. During the skate study the power varied between 0 and 330 MW (Figure 5.8a). The dominant power levels in the cable during the skate study were 0, 100 and 330 MW (Figure 5.8b), which corresponds to

16, 345, and 1175 Amps. The magnetic fields for these electric currents can be derived by using the optimization-based model in Section 4.0. The maximal magnetic fields in the treatment enclosure at these power levels were modeled to be 51.6, 55.3 and 65.3  $\mu\text{T}$ , respectively, which is a maximal positive deviation of 0.3, 4.0 and 14  $\mu\text{T}$  from the Earth's magnetic field (51.3  $\mu\text{T}$ ). Therefore, even when the power was 0 MW (16 Amps), there was still a 0.3  $\mu\text{T}$  deviation of the Earth's magnetic field. During the course of the skate study, the cable was energized however the power transmitted was 0 MW for 37.5% of the time, 100 MW for 28.6% of the time and 330MW for 15.2% of the time. In total the cable was powered ( $>0$  MW) for 62.4% of the time. The mean power level during the exposure period for the full skate study was 118 MW (SE=33.35). During the exposure period for Sequence 1 skates the mean power level in the cable was 80 MW (SE=34.44) and for Sequence 2 skates, it was 156 MW (SE=55.07).



**Figure 5.7. The magnetic field at the treatment enclosure.**

The figure shows a matrix of the magnetic field ( $\mu\text{T}$ ) gradient in the x and y dimensions of the treatment enclosure, i.e. a top down view of the enclosure showing the magnetic field at the seabed. The buried cable crossed the enclosure at the diagonal between 1 and 2 m on the length axis.



**Figure 5.8. The power in the Cross Sound Cable.**

During the skate study the power varied between 0 and 330 MW (a). Note that there were no skates released on October 8-10 so the data for that period was omitted. The power in the cable is also shown as a statistical frequency (b).

Zones of high and low EMF were defined based on the magnetic field when the cable was operating at full power (330 MW) and were based on two dimensions only ( $x, y$ ). Zone 1 was defined as an area of high magnetic field, which ranged from 52.6 to 65.4  $\mu\text{T}$  with a mean of 60.1  $\mu\text{T}$ . Zone 2 was defined as an area of low magnetic field which ranged from 47.8 to 49.7  $\mu\text{T}$  with a mean of 48.7  $\mu\text{T}$ . The area of each zone differed; Zone 1 was 10.58  $\text{m}^2$  while Zone 2 was 12.18  $\text{m}^2$ . For the purposes of comparison, a correction factor was applied (where appropriate) to behavioral parameters measured in Zone 2. Note that Zone 1 and Zone 2 were separated by a buffer of 30 cm to ensure no overlap. Zone 1 and Zone 2 were also spatially defined at the control enclosure for comparison but the magnetic field was constant throughout at 51.3  $\mu\text{T}$ .

### 5.3.3 Lobster behavior

Each of the behavioral parameters were analyzed in turn in order to systematically assess any effects on the lobster behavior when comparing the behaviors within the EMF treatment enclosure (B) and those in the control enclosure (A).

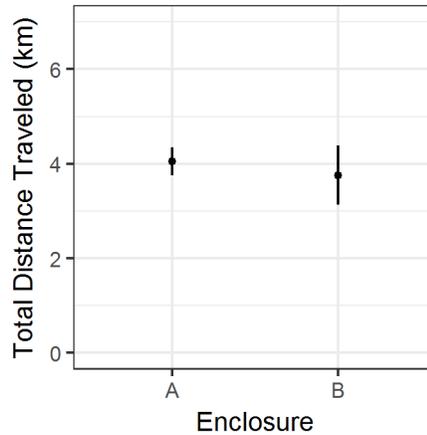
#### 5.3.3.1 Total distance traveled

The inclusion of 'Group' as a random intercept significantly improved the model ( $p=0.005$ ) and was retained. The best-fit minimal model for the total distance traveled containing the fixed factor 'Enclosure' and the 'Group' as a random intercept. The fixed factor 'Enclosure' was not significant ( $p=0.077$ ). The model output is shown in Table 5.9 and the modeled relationship is plotted in Figure 5.9. There was a correlation of 0.15 between observations from lobsters in the same group.

**Table 5.9. The model estimates for the total distance traveled by lobsters.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) on the total distance traveled by lobsters. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	4.05	3.75	4.35
Enclosure: B	-0.29	-0.61	0.031



**Figure 5.9. Total distance traveled by lobsters.**

The modeled estimates of the mean total distance traveled by individual lobsters at each enclosure (A: control, B: treatment) with 95% confidence intervals.

The mean total distance traveled by lobsters (per 24 hours) was highest at the control enclosure (A) where individuals traveled a mean total of 4.05 km (95% CI 3.75-4.35 km) while those at treatment enclosure (B) traveled 3.76 km (95% CI 3.13-4.38 km). Therefore based on the mean estimate, lobsters at treatment enclosure (B) traveled 7.17 % less far. However the 95% CI's from the treatment enclosure (B) were wide indicating high variation in the total distance traveled and that it is possible there was little overall difference in distance traveled at each enclosure.

### 5.3.3.2 Speed of movement

#### Mean speed

The response variable (mean speed) was log transformed since the data were skewed. This approach improved the model validation plots. Further improvement was gained by removing two influential data points. These data points were from the same lobster at each enclosure where the mean speed was 32.39 and 30.61 cm s<sup>-1</sup> respectively. There was no biological reason for these data points to be removed, but their removal did improve the fit of the model as judged by the validation plots of residual and fitted values. For this reason, the results of both models are reported.

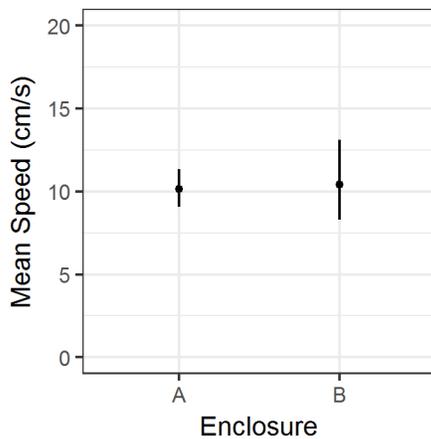
For both models the inclusion of 'Group' as a random intercept significantly improved the model ( $p=0.005$ ,  $p=0.004$ ) but a random slope did not ( $p=1$ ,  $p=1$ ) and therefore was not included. In both models, there was a correlation of 0.16 between observations from lobsters in the same group. For both models, the best fit minimal model which described the mean speed was a linear mixed effect model which included 'Enclosure' as a fixed effect, however this was not statistically significant ( $p=0.646$ ,  $p=0.584$ ). The model output is shown in Table 5.10 and the modeled relationship is plotted in Figure 5.10.

**Table 5.10. The model estimates for the mean speed of movement by lobsters.**

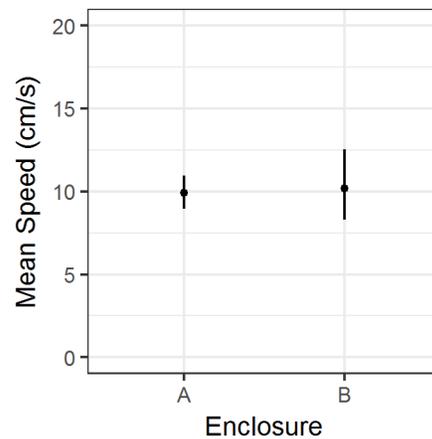
The estimates of the effect of the ‘Enclosure’ (A: control, B: treatment) on the logged mean speed of lobster movement. The estimates from the two models are shown; (a) with all data and (b) with two data points removed. The 2.5% and 97.5 % quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

<b>(a) Model with all data</b>			
<b>Parameter</b>	<b>Estimate (mean)</b>	<b>2.5%</b>	<b>97.5%</b>
(Intercept)	2.32	2.20	2.43
Enclosure: B	0.03	-0.09	0.14
<b>(b) Model with two data points removed</b>			
<b>Parameter</b>	<b>Estimate (mean)</b>	<b>2.5%</b>	<b>97.5%</b>
(Intercept)	2.29	2.19	2.39
Enclosure: B	0.03	-0.08	0.14

a)



b)



**Figure 5.10. The mean speed of lobster movement.**

The modeled estimates of mean speed of lobster movement at each enclosure (A: control, B: treatment) with 95% confidence intervals for the model with all data (a) and the model with two data points removed (b). The estimates were back-transformed.

Based on the model output that was back-transformed, the estimated mean speed of lobster movement at the control enclosure (A) was 10.14 cm s<sup>-1</sup> (95% CI; 9.06-11.34) while at the treatment enclosure (B) it was 10.41 cm s<sup>-1</sup> (95% CI; 8.28-13.10). The model, where the outliers were removed, was very similar and estimated that lobsters at the control enclosure (A) moved at a mean speed of 9.91 cm s<sup>-1</sup> (95% CI; 8.96-10.96) and those at the treatment enclosure (B) moved at a mean speed of 10.18 cm s<sup>-1</sup> (95% CI; 8.30-12.55). Therefore, both models agreed that the speed of movement of the lobsters was very similar with only 2.77% difference between enclosures.

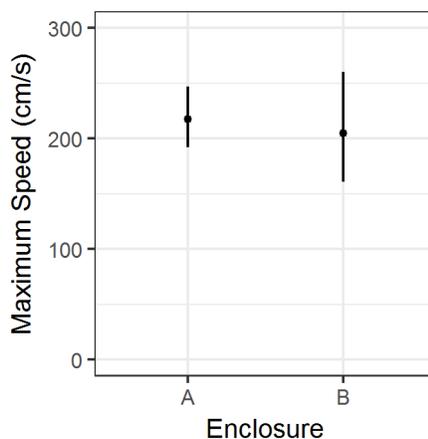
### Maximum speed

The response variable (maximum speed) was log transformed since the data were skewed. This transform improved the model validation plots. The inclusion of ‘Group’ as a random intercept significantly improved the model ( $p < 0.001$ ) but a random slope did not converge. There was a correlation of 0.15 between observations from lobsters in the same group. The best fit minimal model that described the maximum speed was a linear mixed effect model which included ‘Enclosure’ as a fixed effect however was not significant ( $p = 0.288$ ). The model output is shown in Table 5.11 and the modeled relationship is plotted in Figure 5.11.

**Table 5.11. The model estimates for the maximum speed of movement by lobsters.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) on the logged maximum speed of lobster movement. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	5.38	5.26	5.51
Enclosure: B	-0.06	-0.18	0.05



**Figure 5.11. The maximum speed of lobster movement.**

The modeled estimates of maximum speed of lobster movement at each enclosure (A: control, B: treatment) with 95% confidence intervals. The estimates were back-transformed.

Based on the model output that was back-transformed, the estimated maximum speed of lobster movement at the control enclosure (A) was 217.73 cm s<sup>-1</sup> (95% CI; 192.01-246.90) while at the treatment enclosure (B) it was 204.69 cm s<sup>-1</sup> (95% CI; 161.00-269.24). The lobsters at the treatment enclosure (B) were 5.99% slower, however the 95% CI's from the treatment enclosure (B) were wide indicating high variation in the maximum speed of movement and that it is possible there was little overall difference.

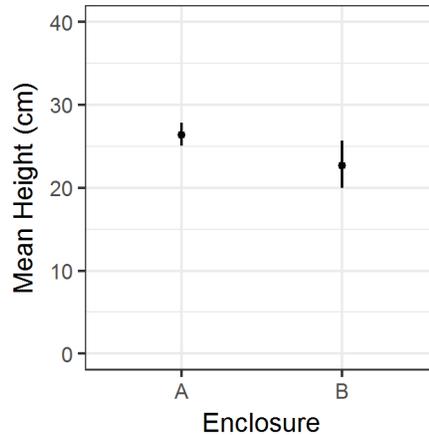
### 5.3.3.3 Height from seabed

The height from seabed is essentially the level of elevation of the organisms within the enclosure. The response variable (height) was log transformed, since the data were strongly skewed. This ensured that the residuals met the model assumptions confirmed by validation plots for the final model. The inclusion of a random intercept and random slope did not improve the model ( $p=0.056$ ,  $p=1$  respectively), therefore were not included. The best fit minimal model which described the mean height from the seabed was a generalized least squares model which included 'Enclosure' as a fixed effect and was statistically significant ( $p<0.001$ ). The model output is shown in Table 5.12 and the modeled relationship is plotted in Figure 5.12. The estimated mean height from the seabed at the control enclosure (A) was 26.40 cm (95% CI; 25.06-27.81 cm) while at the treatment enclosure (B) it was 22.65 cm (95% CI; 20.00-25.66 cm) from the seabed. The lobsters at the treatment enclosure (B) were 14.17% closer to the seabed.

**Table 5.12. The model estimates of the mean height of the lobsters from the seabed.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) on the logged mean height of the lobsters from the seabed. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	3.27	3.22	3.33
Enclosure: B	-0.15	-0.23	-0.08

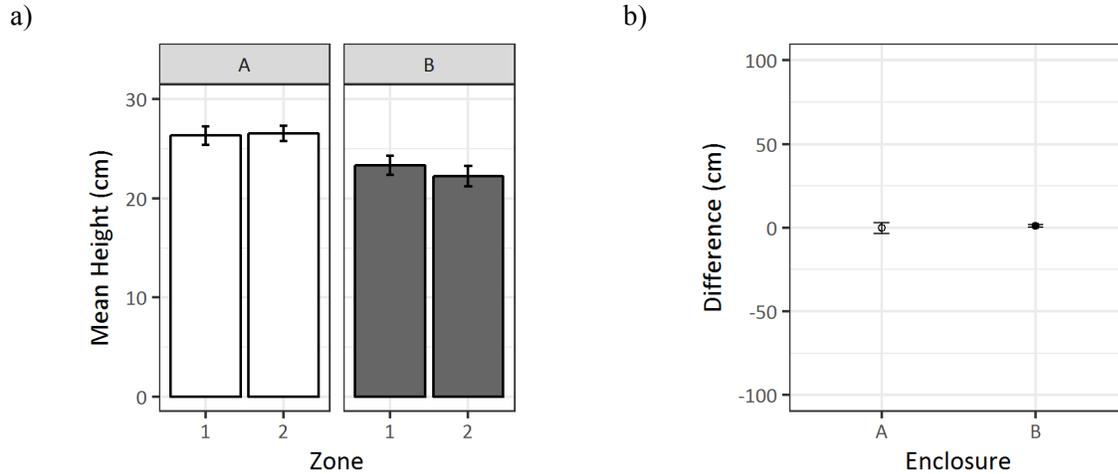


**Figure 5.12. The height of lobsters from the seabed.**

The modeled estimates of mean height of the lobsters from the seabed at each enclosure (A: control, B: treatment) with 95% confidence intervals. The estimates were back-transformed.

To assess if the decreased height from seabed at the treatment enclosure (B) was associated with high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF, the height from seabed within the two predefined spatial zones were analyzed. The group mean of the height of lobsters from the seabed in each zone was assessed at both enclosures and is described. The arithmetic difference in height in each zone (i.e. Zone 1 - Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.13a shows that the overall mean height from seabed was similar in Zone 1 and Zone 2 at both the control (A) and treatment (B) enclosures. At the control enclosure (A), the mean height of the lobsters from the seabed in Zone 1 was 26.32 cm and in Zone 2 it was 26.56 cm, a mean difference of -0.23 cm (Figure 5.13b). At the treatment enclosure (B), the mean height of the lobsters from the seabed in Zone 1 (>52.6  $\mu\text{T}$ ) was 23.31 cm and in Zone 2 (<49.7  $\mu\text{T}$ ) it was 22.23 cm, a mean difference of 1.08 cm (Figure 5.13b).



**Figure 5.13. The height of lobsters in different zones.**

(a) The group mean ( $\pm$ SE) height of lobsters from the seabed in each zone (Zone 1  $>52.6 \mu\text{T}$ , Zone 2  $<49.7 \mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in mean height in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference in the height of lobsters from seabed between zones was not statistically significant when comparing the treatment with the control enclosure ( $p=0.173$ ; Table 5.13, Figure 5.13b). This was also explored for the two different sequence groups (1. B then A; 2. A then B). The mean difference between zones, in the height of lobsters from the seabed, was not significantly different when compared between enclosures for lobsters from Sequence 1 and those from Sequence 2 (Table 5.13).

**Table 5.13. Results of the t-test of the difference between enclosures in height difference recorded in zones.**

The mean difference in the height of groups of lobsters in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, p-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI	
Overall	-0.23	1.08	13	-1.410	21.7	0.173	-3.26	0.62
Sequence 1	0.27	0.63	7	-0.253	9.3	0.806	-3.60	2.88
Sequence 2	-0.82	1.61	6	-2.044	9.9	0.068	-5.08	0.22

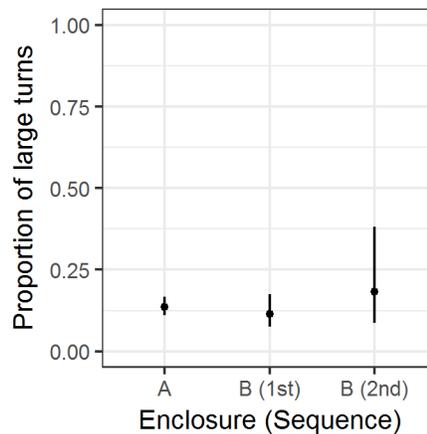
### 5.3.3.4 Proportion of large turns

The proportion of large turns ( $170-180^\circ$ ) in lobsters was modeled as a generalized linear mixed model fitted with a Penalized Quasi-likelihood (glmmPQL) with a binomial distribution. The interaction between the 'Enclosure' and the 'Sequence' of exposure to the enclosure was significant ( $p=0.004$ ) and was retained in the model together with the 'Enclosure' ( $p=0.122$ ) and 'Sequence' ( $p=0.957$ ). The model also included the random effect of 'Group'. The model output is shown in Table 5.14 and the modeled relationship is plotted in Figure 5.14.

**Table 5.14. The model estimates for the proportion of large turns by lobsters.**

The estimates of the effect of the interaction of 'Enclosure' (A: control, B: treatment) and the 'Sequence' of exposure to the enclosures on the proportion of large (170-180°) turns. The 2.5% and 97.5% quantiles which represent the 95% Confidence Intervals around the parameter estimates are also shown. Note that the binomial glmmPQL predicts on the logistic link function.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	-1.99	-2.20	-1.79
Enclosure: B	-0.18	-0.40	0.04
Sequence: 2	0.01	-0.31	0.33
Enc.B*Seq.2	0.47	0.16	0.78



**Figure 5.14. The proportion of large turns by lobsters.**

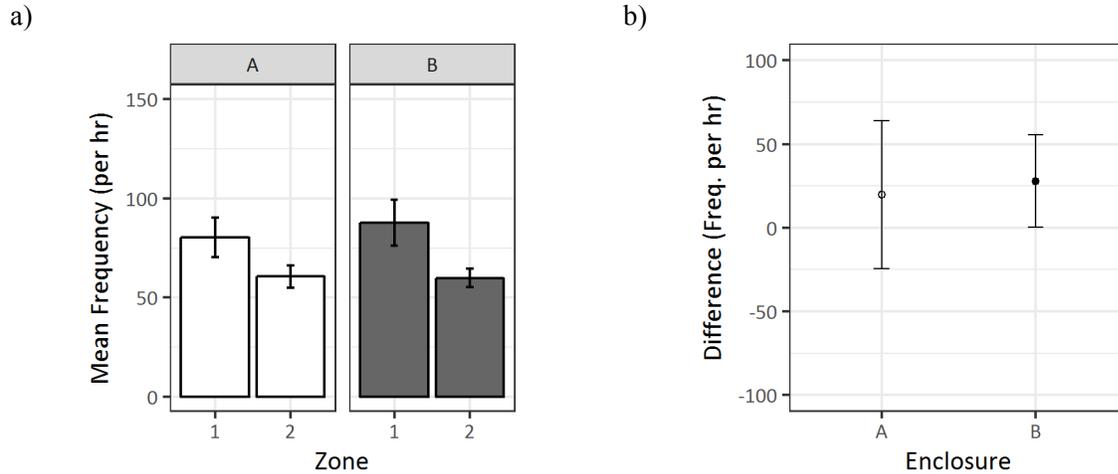
The modeled estimates of the mean proportion of large (170-180°) turns by lobsters at each enclosure (A: control, B: treatment) as influenced by the sequence of exposure to the enclosures. The estimates and the 95% confidence intervals are shown.

The glmmPQL estimates on the logit link function and therefore the estimates were back transformed for the following text; note that the proportions reported are bound between 0 and 1. The estimated mean proportion of large turns at the control enclosure (A) was 0.14 (95% CI; 0.11-0.17) while at the treatment enclosure (B) it was 0.11 (95% CI; 0.07-0.17). The lobsters at the treatment enclosure (B) showed a 16.23% lower proportion of large turns than those at the control enclosure (A). For the lobsters exposed to the treatment enclosure (B) second in the sequence, the proportion of large turns was 0.18 (95% CI; 0.08-0.23), therefore they showed a 34.15% higher proportion of large turns. Lobsters exhibited an increased proportion of large turns at the enclosure second in the sequence of exposure, regardless of which enclosure that was. However, this trend was stronger when the second enclosure was the treatment enclosure (B) where the increase was 34.15% compare to when the second enclosure was the control enclosure (A) where the increase was 16.23%.

To assess if the increased frequency of large turns by the lobsters in the treatment enclosure (B) was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF, the frequency of large turns per hour within the two predefined spatial zones were analyzed. The group mean of the frequency of large turns per hour by lobsters in each zone was assessed at both enclosures and is described. The arithmetic difference in the frequency of large turns per hour in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.15a shows that the overall mean frequency of large turns was higher in Zone 1 than Zone 2 at both the control (A) and treatment (B) enclosures. At the control enclosure (A), the lobsters made a mean

total of 80.17 large turns per hour in Zone 1 and 60.58 large turns per hour in Zone 2 (Figure 5.15a); a mean difference of 19.58 turns per hour (Figure 5.15b). At the treatment enclosure (B), the lobsters made a mean total of 87.79 large turns per hour in Zone 1 (>52.6  $\mu$ T) and 59.89 large turns per hour in Zone 2 (>52.6  $\mu$ T; Figure 5.15a); a mean difference of 27.90 turns per hour (Figure 5.15b).



**Figure 5.15. The proportion of large turns in different zones.**

(a) The group mean ( $\pm$ SE) of the frequency of large turns per hour by lobsters in each zone (Zone 1 >52.6  $\mu$ T, Zone 2 <49.7  $\mu$ T) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in frequency of large turns per hour in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference in the frequency of large turns per hour between the zones was not statistically significant when comparing the treatment with the control enclosure ( $p=0.636$ ; Table 5.15, Figure 5. 15b). This was also explored for the two different sequence groups (1. B then A; 2. A then B). The mean difference between zones, in the frequency of large turns per hour by the lobsters, was not significantly different when compared between enclosures for lobsters from Sequence 1 and those from Sequence 2 (Table 5.15).

**Table 5.15. Results of the t-test of the difference between enclosures in the frequency of large turns recorded in zones.**

The mean difference in the frequency of large turns per hour by lobsters in zone 1 (>52.6  $\mu$ T) and zone 2 (<49.7  $\mu$ T), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom,  $p$ -value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	$p$	95% CI	
Overall	19.58	27.90	13	-0.479	23.1	0.636	-44.23	27.59
Sequence 1	11.47	12.06	7	-0.037	10.4	0.971	-36.10	34.91
Sequence 2	29.05	46.38	6	-0.535	7.9	0.607	-92.16	57.50

### 5.3.3.5 Spatial Distribution

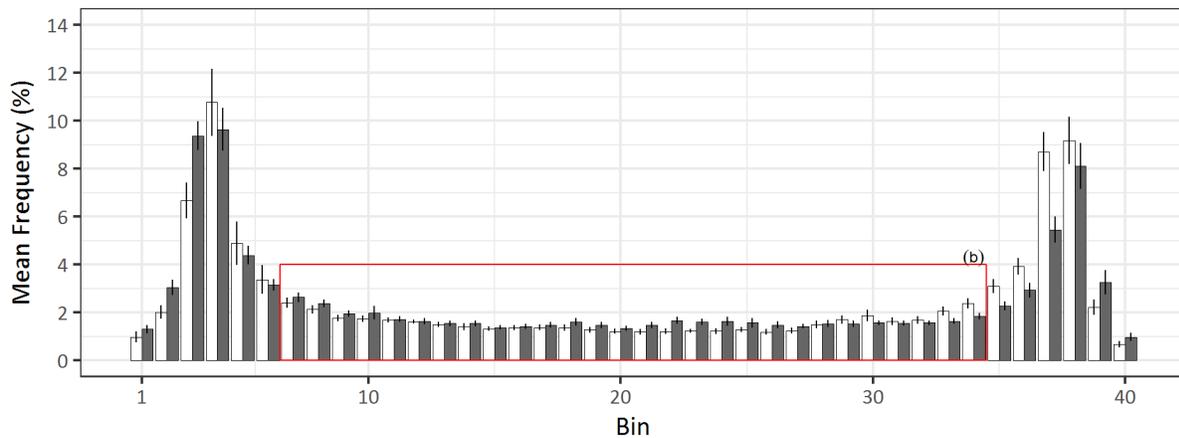
The spatial distribution of lobsters within the enclosures was explored to assess how they made use of the enclosure space. This analysis was done by comparing the spatial distribution along the y axis (perpendicular to the cable at the treatment enclosure (B)) between enclosures. To do so, the length of the enclosure was split into 40 bins and the distribution in each enclosure was assessed and compared in terms of 1) the proportional frequency of positions recorded and 2) the proportion of time spent in those bins. The proportional frequency of positions recorded and time spent in each zone were also analyzed to determine if there was an association with zones of high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF.

## Spatial distribution of recorded positions

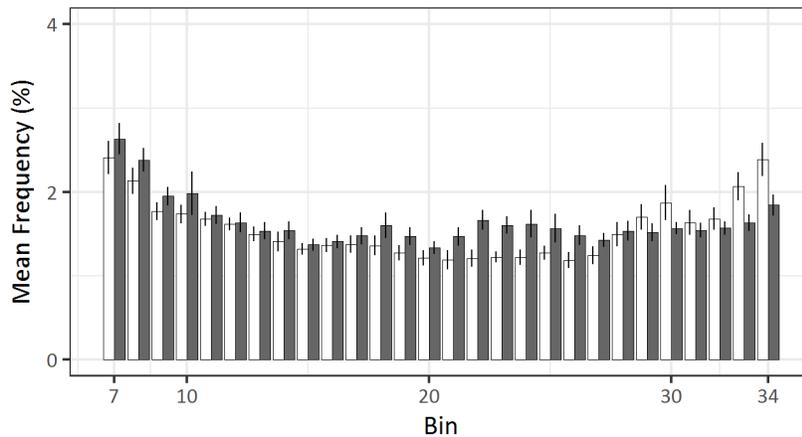
The frequency of positions within the enclosure was recorded along the length of the enclosure (y-axis), which was perpendicular to the cable at the treatment enclosure (B). Similar data were recorded at the control enclosure (A) to provide a spatial comparison when there was no cable. The group mean ( $\pm$  SE) frequencies of positions were calculated for the 40 bins along the enclosure length and translated to a percentage of the total recorded positions, which allowed the spatial distributions in each enclosure to be compared (Figure 5.16).

Figure 5.16a shows that the lobsters were recorded throughout the full extent of the enclosures and were most frequently recorded at the ends of both the control (A) and treatment (B) enclosures. The lobsters were however more frequently found in the central space of the treatment (B) enclosure than they were in the central space of the control (A) enclosure (Figure 5.17b).

a)



b)



**Figure 5.16. The mean frequency of lobster positions recorded.**

The mean frequency (%) of lobster positions recorded within the control enclosure (A: white) and the treatment enclosure (B: grey). The full length of the enclosure (a) and the subset of data (b) focusing on the central area of the enclosures (red box in (a)).

To determine whether the frequency of recorded positions of lobsters was statistically significantly different in the treatment enclosure (B) compared to the control (A), a cumulative distribution analysis was conducted applying the Kolmogorov-Smirnov (K.S.) two sample test. The K.S. is a non-parametric

test that compares the overall pattern of the data distributions. The analysis confirmed that lobsters had a different distribution pattern within the treatment enclosure (B) compared with the control enclosure (A). This was also true when tested for lobsters from Sequence 1 and those from Sequence 2 (Table 5.16). To reduce any influence of the ends of the enclosure a subset of the positional data was analysed to compare the patterns of distribution in the central space (Figure 5.16b). The lobsters were recorded more frequently and in a different pattern across the central space of the treatment enclosure (B) compared with the control (A; Figure 5.16b Table 5.16).

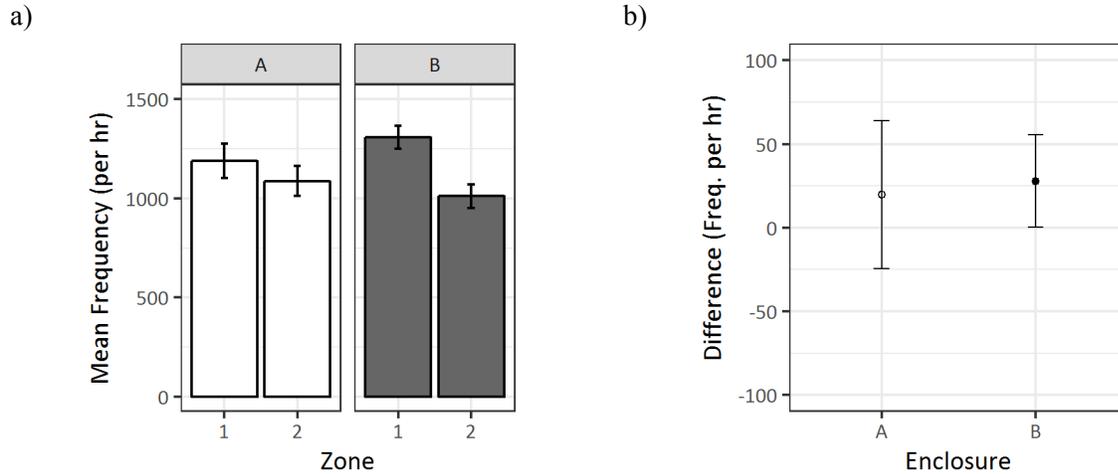
**Table 5.16. The results of the Kolmogorov-Smirnov test applied to the spatial distribution of lobsters assessed by the proportional frequency of positions recorded.**

Kolmogorov-Smirnov test statistic D and statistical probability of the cumulative lobster distributions within the treatment (A) and control (B) enclosures being different in the overall dataset and the two sequence groups. The statistical results for the full dataset and the subset for the central space are reported. Significant values at  $p \leq 0.05$  are highlighted in bold.

	Full		Subset	
	D	<i>p</i>	D	<i>p</i>
Overall	0.300	<b>0.043</b>	0.427	<b>0.008</b>
Sequence 1	0.300	<b>0.043</b>	0.429	<b>0.008</b>
Sequence 2	0.35	<b>0.011</b>	0.464	<b>0.003</b>

To assess if the position of the lobsters in the treatment enclosure (B) was associated with high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF, the frequency of positions recorded per hour within the two predefined spatial zones were analyzed. The group mean of frequency of lobster positions recorded in each zone was assessed at both enclosures and is described. The arithmetic difference in positions recorded in each zone (i.e. Zone 1 - Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.17a shows that the overall mean frequency of position fixes per hour was higher in Zone 1 than in Zone 2 at both the control (A) and treatment (B) enclosures. At the control enclosure (A), there were a mean total of 1188.61 records per hour in Zone 1 (>52.6  $\mu\text{T}$ ) and 1086.78 records per hour in Zone 2 (<49.7  $\mu\text{T}$ ), a mean difference of 101.82 records per hour (Figure 5.17b). At the treatment enclosure (B), there were a mean total of 1307.00 records per hour in Zone 1 (>52.6  $\mu\text{T}$ ) and 1010.80 records per hour in Zone 2 (<49.7  $\mu\text{T}$ ), a mean difference of 296.20 records per hour (Figure 5.17b).



**Figure 5.17. The mean frequency of lobster positions recorded in each zone.** (a) The group mean ( $\pm$ SE) of mean frequency of lobster positions recorded in each zone (Zone 1  $>52.6 \mu\text{T}$ , Zone 2  $<49.7 \mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in frequency of positions recorded in each zone (i.e. Zone 1 - Zone 2) at each enclosure.

The overall mean difference in the frequency of lobster positions recorded per hour between the zones was not statistically significant when comparing the treatment with the control enclosure ( $p=0.323$ ; Table 5.17, Figure 5. 17b). This relationship was also explored for the two different sequence groups (1. B then A; 2. A then B). The mean difference between zones, in the frequency of lobster positions recorded, was not significantly different when compared between enclosures for lobsters from Sequence 1 and those from Sequence 2 (Table 5.17).

**Table 5.17. Results of the t-test of the difference between enclosures in the frequency of large turns recorded in zones.**

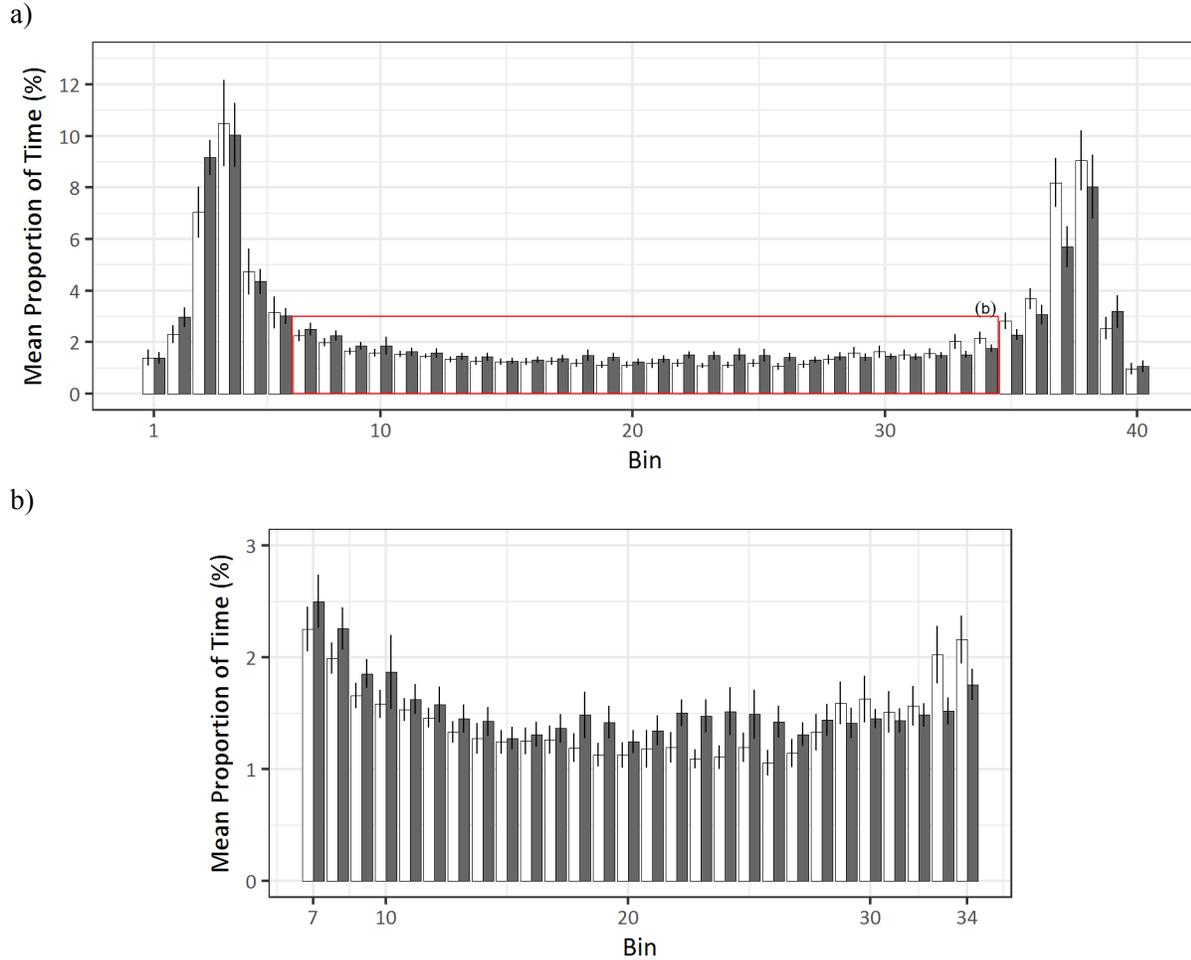
The mean difference in the frequency of lobster position fixes in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom,  $p$ -value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI
Overall	101.82	296.20	13	-1.013	21.6	0.323	-592.95 2014.19
Sequence 1	15.72	136.11	7	-0.593	10.7	0.565	-568.44 327.66
Sequence 2	202.28	482.97	6	-0.820	6.1	0.443	-1114.35 552.97

### Spatial distribution of time

The time spent by the lobsters across the enclosure space was also recorded along the length of the enclosure (y-axis), perpendicular to the cable at the treatment enclosure (B). Similar data were recorded at the control enclosure (A) to provide a spatial comparison when there was no cable. The group mean ( $\pm$ SE) proportion of time was calculated for the 40 bins along the enclosure length and translated to a percentage, which allowed the distribution time spent across the length of each enclosure to be compared (Figure 5.18a).

Figures 5.18a and b show that the lobsters were recorded over the full extent of the enclosures and spent the most time at the ends of both the control (A) and treatment (B) enclosure. At the treatment enclosure (B), the lobsters spent more time in the central space of the enclosure than they did at the control (A) enclosure (Figure 5.18b; Table 5.18).



**Figure 5.18. The distribution of lobsters as a mean proportion of time.**

The distribution of lobsters shown as the mean ( $\pm$ SE) proportion of time (%) spent in each bin within the control (A: white) and treatment (B: grey) enclosures. The full length of the enclosure (a) and the subset of data (b) focusing on the central area of the enclosures (red box in (a)).

To determine whether the distribution of time was statistically significantly different at the treatment enclosure (B) compared to the control (A) a cumulative distribution analysis was conducted applying the Kolmogorov-Smirnov (K.S.) two sample test. The K.S. is a non-parametric test that compares the overall pattern of the data distributions. The pattern of time spent in the enclosures was statistically significantly different when compared between the treatment (B) and the control (A) enclosures (Table 5.18). This result was also true when assessed for the lobsters from Sequence 1 (B then A), but not for those from Sequence 2 (A then B). There was a statistically significantly difference when comparing the spatial distribution of time in the central space of the treatment (B) and the control (A) enclosures (Table 5.31, Figure 5.31b) when assessed for the overall group (Table 5.18). This observation was also true for both sequences of exposure (Table 5.18).

**Table 5.18. The results of the Kolmogorov-Smirnov test applied to the spatial distribution of lobsters assessed by the proportion of time.**

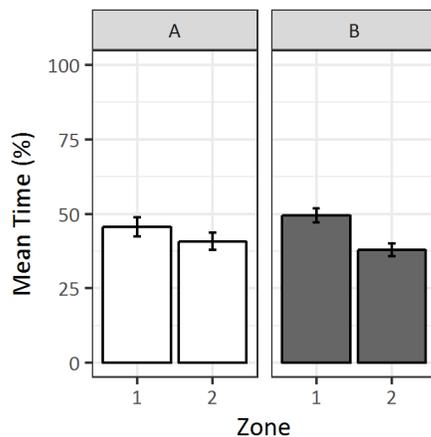
Kolmogorov-Smirnov test statistic D and statistical probability of the lobster time distributions within the treatment (A) and control (B) enclosures being different. Significant values at  $p \leq 0.05$  are highlighted in bold.

	Full		Subset	
	D	<i>p</i>	D	<i>p</i>
Overall	0.325	<b>0.022</b>	0.464	<b>0.003</b>
Sequence 1	0.139	0.139	0.464	<b>0.003</b>
Sequence 2	0.375	<b>0.005</b>	0.500	<b>0.001</b>

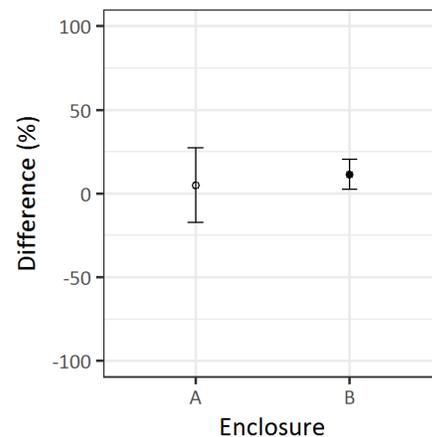
The time spent in each zone was also used to assess if the lobsters spent more time associated with high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF at the treatment enclosure (B). The group mean of the proportion of time that lobsters spent in each zone was assessed at both enclosures and is described. The arithmetic difference in proportion of time spent in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.19a shows that the overall mean proportion of time spent in Zone 1 was higher than time spent in Zone 2 at both the control (A) and treatment (B) enclosures. At the control enclosure (A), the lobsters spent a mean of 45.66% of time in Zone 1 and 40.74% of time in Zone 2 (Figure 5.19a); a mean difference of 4.93% (Figure 5.19b). At the treatment enclosure (B), the lobsters spent a mean of 49.48% of time in Zone 1 and 37.93% of time in Zone 2 (Figure 5.19a); a mean difference of 11.54% (Figure 5.19b).

a)



b)



**Figure 5.19. The mean proportion of time lobsters spent in each zone.**

(a) The group mean ( $\pm\text{SE}$ ) of the mean proportion of time lobsters spent in each zone (Zone 1 >52.6  $\mu\text{T}$ , Zone 2 <49.7  $\mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm 95\%$  CI) in time spent in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall difference in the proportion of time spent in each zone was not statistically significant when comparing the treatment with the control enclosure ( $p=0.391$ ; Table 5.19, Figure 5.19b). This relationship was also explored for the two different sequence groups (1. B then A; 2. A then B). The mean difference in time spent between zones, was not significantly different when compared between enclosures for lobsters from Sequence 1 and those from Sequence 2 (Table 5.19).

**Table 5.19. Results of the t-test of the difference between enclosures in the proportion of time recorded in zones.**

The mean difference in the proportion of time lobsters spent in zone 1 (>52.6  $\mu$ T) and zone 2 (<49.7  $\mu$ T), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, *p*-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	<i>p</i>	95% CI	
Overall	4.93	11.54	13	-0.874	21.9	0.391	-22.32	9.08
Sequence 1	2.34	6.19	7	-0.458	10.0	0.657	-22.63	14.92
Sequence 2	7.95	17.79	6	-0.732	6.0	0.492	-42.77	23.08

### 5.3.3.6 Summary of results

To aid understanding, a summary of the results of the statistical analyses of the lobster behavioral responses to the cable EMF are presented in Table 5.20 and 5.21. In brief, there were no significant differences in the total distance traveled by lobsters or their speed of movement when compared between the control (A) and treatment (B) enclosures. The lobsters at the treatment enclosure (B) were found to be significantly, but marginally closer to the seabed however there was no indication that this was associated with zones of high or low EMF. The lobsters exhibited a larger proportion of large turns in their direction of travel at the enclosure that they went to second in the sequence, and this observation was most pronounced at the treatment enclosure (B) when it was second in the sequence. There was however, no indication that the increased proportion of large turns was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF. The comparison of spatial distributions between enclosures confirmed that lobsters used the full available space in both enclosures, and they were most frequently recorded and spent most of their time at the ends of the enclosure. Although the lobsters were most frequently found at the ends of the enclosures, they were also found across the central space of the enclosure more frequently and in a different pattern of distribution within the treatment enclosure (B) compared with the control enclosure (A). This difference in distribution pattern was consistent regardless of the sequence of release into the enclosures. There was no indication that this pattern was related to zones of high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF.

**Table 5.20. A summary of the results of the analyses of the lobster behavioral parameters.**

Summary of the mixed modelling results for the analyses of lobster movements in the control (A) and treatment (B) enclosures and subsequent t-test for differences in zones between enclosures.

Behavioral Parameter	Summary of mixed modeling results		Summary of t-test results	
	Sig. terms	Effect	Sig.	Difference between zones in enclosures
Total distance traveled (per day)	N.S.	There was a minor non-significant decrease (7%) in mean total distance traveled by lobsters at the treatment enclosure (B) compared to the control enclosure (A).	-	-
Speed of movement	N.S.	There was a minor decrease in the mean speed (<3%) and maximum speed (<6%) in lobsters at the treatment enclosure (B) compared to the control enclosure (A).	-	-
Height from seabed	Enclosure	A significant difference in the height from seabed was detected. Lobsters at the treatment enclosure (B) were approximately 14% closer to the seabed than those at control enclosure (A).	N.S.	The height from seabed was similar in both zones, at both enclosures.
Proportion of large turns (170-180°)	Interaction between the Enclosure & Sequence	For lobsters that went to the treatment enclosure (B) first, there was a 16% lower proportion of large turns in lobsters at enclosure B.  For lobsters that went to the control enclosure (A) followed by the treatment enclosure (B), there was a 34% higher proportion of large turns at enclosure B.	N.S.	The proportion of large turns was greater in Zone 1 than Zone 2 at both enclosures. There was no significant difference between enclosures.

**Table 5.21. A summary of the results of the statistical analyses relating to the spatial distribution of lobsters within the enclosures.**

Summary of the Kolmogorov-Smirnov (K-S) two sample test results for the analyses of lobster spatial distribution in the control (A) and treatment (B) enclosures and subsequent t-test for differences in zones between enclosures. Spatial distribution throughout the length of the enclosure was assessed by the frequency of positions recorded and the proportion of time.

Parameter	Summary of K-S two sample test		Summary of t-test results	
	Sig.	Effect	Sig.	Difference
Recorded positions	Yes	<p>The spatial distribution was significantly different when compared between enclosures for the full range of the enclosure.</p> <p>The lobsters were recorded more frequently and in a different pattern across the central space of the treatment enclosure (B) compared with the control enclosure (A).</p>	N.S.	<p>The frequency of positions recorded per hour was higher in Zone 1 than in Zone 2 at both enclosures. There was no significant difference between enclosures.</p>
Time	Yes	<p>The pattern of time spent in the enclosures was statistically significantly different when compared between the treatment (B) and the control (A) enclosures. This result was true for the overall group and Sequence 2 (A then B), but not Sequence 1 (B then A) lobsters.</p> <p>There was a statistically significant difference when comparing the spatial distribution of time in the central space of the treatment (B) and the control (A) enclosures.</p>	N.S.	<p>The lobsters spent more time in Zone 1 than in Zone 2 at both enclosures. There was no significant different between enclosures.</p>

### 5.3.4 Skate behavior

Each of the behavioral parameters was analyzed in turn in order to systematically assess any effects on the skate behavior when comparing the skate movements within the EMF treatment enclosure (B) and those in the control enclosure (A).

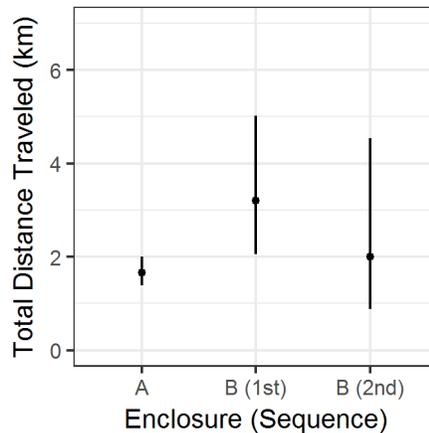
#### 5.3.4.1 Total distance traveled

The data for the total distance traveled by the skates was skewed and therefore was log transformed. This improved the model fit assessed by validation plots of the residual and fitted values. The inclusion of a random intercept and random slope did not significantly improve the model; therefore a generalized least squares model was fitted. The best-fit minimal model included the 'Enclosure' ( $p < 0.001$ ) and the interaction between the 'Enclosure' and the 'Sequence' of exposure to the enclosures ( $p = 0.013$ ) as a significant terms and was retained with the 'Sequence' ( $p = 0.343$ ). The model output is shown in Table 5.22 and the modeled relationship is plotted in Figure 5.20.

**Table 5.22. The model estimates for the total distance traveled by skates.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment), 'Sequence' of exposure to the enclosures and the interaction of the two terms on the logged total distance traveled by skates. The 2.5% and 97.5% quantiles which represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	0.51	0.32	0.69
Enclosure B	0.66	0.39	0.92
Sequence 2	0.12	-0.13	0.38
Encl.B*Seq.2	-0.47	-0.84	-0.10



**Figure 5.20. The total distance traveled by skates.**

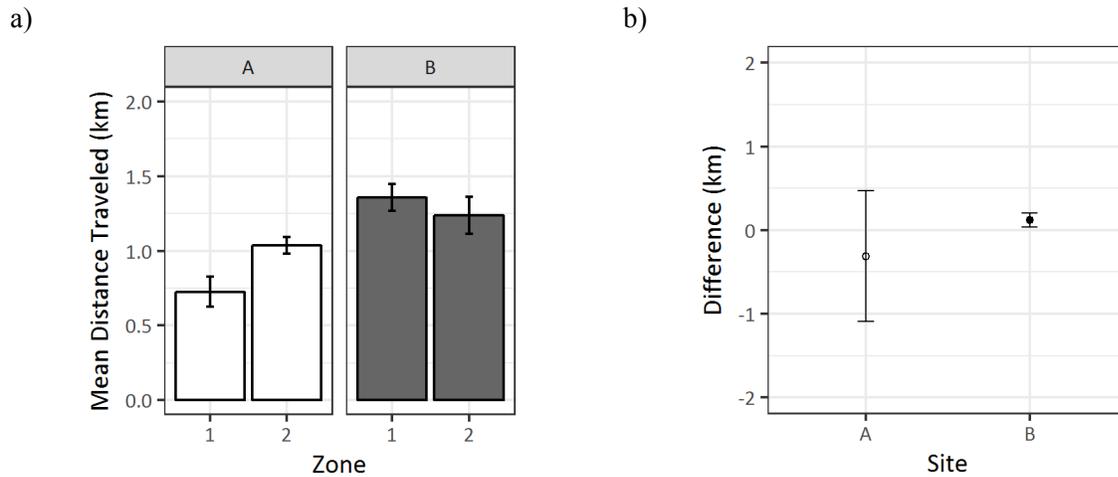
The modeled estimates of the mean total distance traveled by skates at each enclosure (A: control, B: treatment) as influenced by the sequence of exposure to the enclosures. The estimates were back transformed and the 95% confidence intervals are shown.

Based on the model output, which was back-transformed, the estimated mean total distance traveled by skates at the control enclosure (A) was 1.66 km while at the treatment enclosure (B) skates traveled 3.21 km. The skates at the treatment enclosure (B) when first in the sequence, traveled 93.02% further than those at the control enclosure (A). The 95% CI from the model suggest that the distance traveled by skates at the treatment enclosure ranged from 2.05-5.02 km (B, 1st). The sequence of exposure to the enclosures influenced the distance traveled. The increase in distance traveled was less pronounced in skates that had been exposed to the control enclosure (A) prior to the treatment enclosure (B); in this instance the skates only traveled 0.22 km further, which is an increase of 20.71%. In this case, the 95% CI from the model were broader and suggest the distance traveled ranged from 0.89 to 4.54 km.

To assess if the increased distance traveled by the skates per day in the treatment enclosure (B) was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF, the distances traveled within the two predefined spatial zones were analyzed. The group mean of the distance traveled per day by skates in each zone was assessed at both enclosures and is described. The arithmetic difference in distance traveled in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.21a shows that the overall mean distance traveled per day was lower in Zone 1 than in Zone 2 at the control enclosure (A), with the skates traveling a total of 0.73 km in Zone 1 and 1.04 km in Zone 2 (Figure 5.21a); a mean difference of -0.31 km (Figure 5.21b). In contrast, at the treatment enclosure (B) there was an overall increase in the mean distance traveled in Zone 1 (>52.6  $\mu$ T) compared to Zone 2 (<49.7  $\mu$ T) however the distances traveled in each zone were more similar than the situation in the control enclosure (A). At the treatment enclosure (B), the skates traveled a mean total of 1.36 km in Zone 1

(>52.6  $\mu\text{T}$ ) and a mean total of 1.24 km in Zone 2 (<49.7  $\mu\text{T}$ ) (B; Figure 5.21a); a mean difference of 0.12 km (Figure 5.21b).



**Figure 5.21. The total distance traveled by skates in each zone.**

(a) The group mean ( $\pm$ SE) of the total distance traveled per day by skates in each zone (Zone 1 >52.6  $\mu\text{T}$ , Zone 2 <49.7  $\mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in distance traveled in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference in distance traveled between the zones was statistically significant when comparing the treatment with the control enclosure ( $p=0.019$ ; Table 5.23, Figure 5. 21b). This difference was also explored for the two different sequence groups (1. (B then A); 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference between zones, in the distance traveled by the skates, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.23).

**Table 5.23. Results of the t-test of the difference between enclosures in the total distance traveled in zones.**

The group mean of the total distance traveled by skates in zone 1 (>52.6  $\mu\text{T}$ ) and zone 2 (<49.7  $\mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, p-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI	
Overall	-0.31	0.12	8	-2.662	13.6	<b>0.019</b>	-0.78	-0.08
Sequence 1	-0.46	0.002	4	-2.001	5.9	0.093	-1.03	0.10
Sequence 2	-0.16	0.23	4	-1.881	5.2	0.116	-0.95	0.14

### 5.3.4.2 Speed of movement

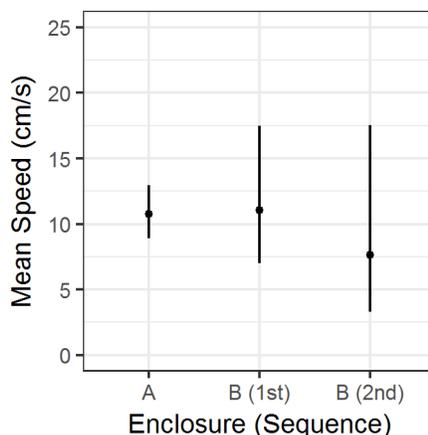
#### Mean speed

The data for the mean speed of movement by the skates were skewed and therefore were log transformed. The inclusion of a random intercept and random slope did not significantly improve the model ( $p=0.240$ ,  $p=1$ , respectively). Therefore a generalized least squares model was fitted. The best fit minimal model included the 'Enclosure' ( $p=0.830$ ), the 'Sequence' of exposure to the enclosures ( $p=0.129$ ) and the interaction between the 'Enclosure' and the 'Sequence' ( $p=0.051$ ). The significance of the interaction between the two terms was on the borderline in the model selection, but retaining the interaction between the two terms improved the validation plots of the fitted and residual values and therefore was retained. The model output is shown in Table 5.24 and the modeled relationship is plotted in Figure 5.22

**Table 5.24. The model estimates of the mean speed of movement by skates.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment), 'Sequence' of exposure to the enclosures and the interaction of the two terms on the logged mean speed of skate movement. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	2.37	2.19	2.56
Enclosure: B	0.03	-0.24	0.30
Sequence: 2	0.20	-0.06	0.47
Enc.B*Seq.2	-0.37	-0.75	0.00



**Figure 5.22. The mean speed of skate movement.**

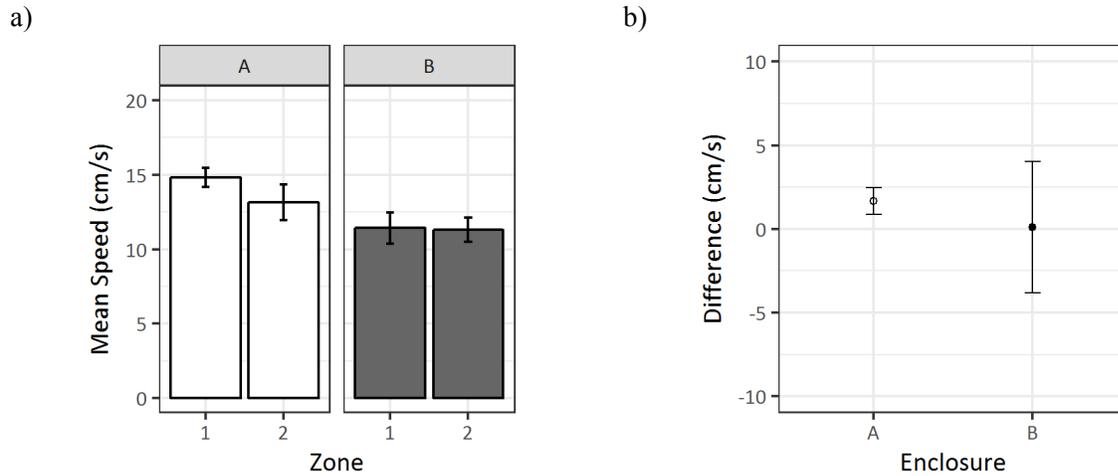
The modeled estimates of the mean speed of movement by skates at each enclosure (A: control, B: treatment) as influenced by the sequence of exposure to the enclosures. The estimates were back transformed and the 95% confidence intervals are shown.

Based on the model output which was back-transformed, the estimated mean speed of movement by skates at the control enclosure (A) was 10.75 cm s<sup>-1</sup> (95% CI: 8.90-12.98). The sequence of exposure to the enclosures influenced the mean speed of movement. When exposed to the treatment enclosure (B) first in the sequence, skates traveled 11.07 cm s<sup>-1</sup> (95% CI: 7.00-17.50); the skates moved 2.96% faster than those at the control enclosure (A). Skates that had been exposed to the control enclosure (A) prior to the treatment enclosure (B) moved at a mean of 7.62 cm s<sup>-1</sup> (95% CI: 3.30-17.55) which is 29.12% slower than the estimate for the control enclosure (A). Skates moved faster at the enclosure second in the sequence of exposure, regardless of which enclosure that was. However, the difference was larger when the second enclosure was the treatment (B) where the increase was 29.12 % compared to when the second enclosure was the control (A) where the increase was 2.96%.

To assess if the decrease in mean at the treatment enclosure (B) was associated with high (>52.6 μT) or low (<49.7 μT) EMF, the mean speed within the two predefined spatial zones were analyzed. The mean speed of the skates in each zone was assessed at both enclosures and the arithmetic difference in mean speed of movement (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.23a shows that the overall mean speed of the skates was slightly higher in Zone 1 than Zone 2 at the control enclosure (A), with skates moving at a mean speed of 14.81 cm/s in Zone 1 and 13.13 cm/s in Zone 2 (Figure 5.23a), a mean difference of 1.68 cm/s (Figure 5.23b). The speed of movement of skates at the treatment enclosure (B) was more similar in Zone 1 (>52.6 μT) and Zone 2 (<49.7 μT). The skates

moved at a mean speed of 11.43 cm/s in Zone 1 ( $>52.6 \mu\text{T}$ ) and 11.31 cm/s in Zone 2 ( $<49.7 \mu\text{T}$ ), a mean difference of 0.11 cm/s (Figure 5.23b).



**Figure 5.23. The mean speed of skate movement in each zone.**

(a) The group mean ( $\pm$ SE) of the speed of skates in each zone (Zone 1  $>52.6 \mu\text{T}$ , Zone 2  $<49.7 \mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% C. I.) in the mean speed of movement in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference between zones in speed of movement was not statistically significant when comparing the treatment and control enclosure ( $p=0.171$ ; Table 5.25). This relationship was also explored for the two different sequence groups (1. B then A; 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference between zones, in the mean speed of movement by the skates, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.25).

**Table 5.25. Results of the t-test of the difference between enclosures in the mean speed of movement recorded in zones.**

The group mean of the speed of skates in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, p-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI	
Overall	1.68	0.11	8	1.476	9.8	0.171	-0.80	3.93
Sequence 1	3.12	0.06	4	1.992	4.4	0.110	-1.04	7.16
Sequence 2	0.24	0.17	4	0.057	5.1	0.957	-3.06	3.20

### Maximum speed

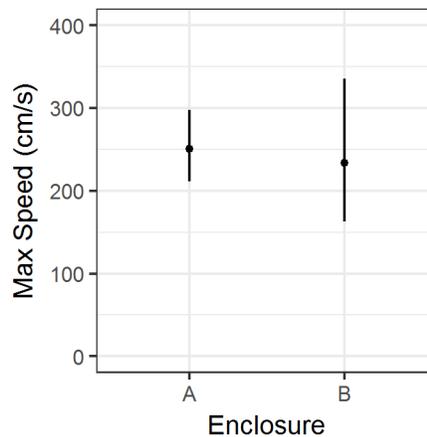
The data for the maximum speed of movement by the skates was skewed and therefore was log transformed. The inclusion of a random intercept significantly improved the model ( $p=0.030$ ) but a random slope did not ( $p=1$ ). Therefore a linear mixed effect model with a random effect of 'Group' was fitted. There was a correlation of 0.12 between observations from skates in the same release. The best-fit minimal model included 'Enclosure' as a fixed term but this was not a significant term ( $p=0.463$ ). The model output is shown in Table 5.26 and the modeled relationship is plotted in Figure 5.24. Based on the model output which was back-transformed, the estimated mean for the maximum speed of movement by skates at the control enclosure (A) was  $250.99 \text{ cm s}^{-1}$  (95% CI: 211.60-297.71) while at the treatment

enclosure (B) skates moved at  $233.94 \text{ cm s}^{-1}$  (95% CI: 163.04-335.68). The skates at the treatment enclosure (B) moved 6.79% slower than those at the control enclosure (A).

**Table 5.26. The model estimates of the maximum speed of movement by skates.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) on the logged maximum speed of skate movement. The 2.5% and 97.5 % quantiles which represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	5.53	5.35	5.70
Enclosure: B	-0.07	-0.26	0.12



**Figure 5.24. The maximum speed of skate movement.**

The modeled estimated means for the maximum speed of movement by skates at each enclosure (A: control, B: treatment) and the 95% confidence intervals. The estimates were back transformed.

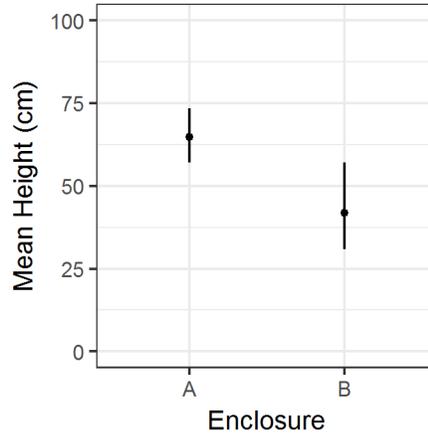
### 5.3.4.3 Height from seabed

The response variable (height) was log transformed, since the data were skewed. This approach ensured that the model assumptions were met. The inclusion of a random intercept and random slope did not improve the model, therefore were not included ( $p=0.412$ ,  $p=1$ , respectively). The best fit minimal model that described the mean height from the seabed was a generalized least squares model that included 'Enclosure' as a significant fixed effect ( $p \leq 0.001$ ). The model output is shown in Table 5.27 and the modeled relationship is plotted in Figure 5.25. The estimated mean height from the seabed at the control enclosure (A) was 64.68 cm (95% CI; 57.05-73.55) while at the treatment enclosure (B) it was 41.96 cm (95% CI; 30.81-57.16) from the seabed. The skates at the treatment enclosure (B) were 35.22% closer to the seabed.

**Table 5.27. The model estimates of the mean height of skates.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) on the mean height of the skates from the seabed. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	4.1709691	4.0439437	4.297994
Enclosure: B	-0.4341874	-0.6162398	-0.251351

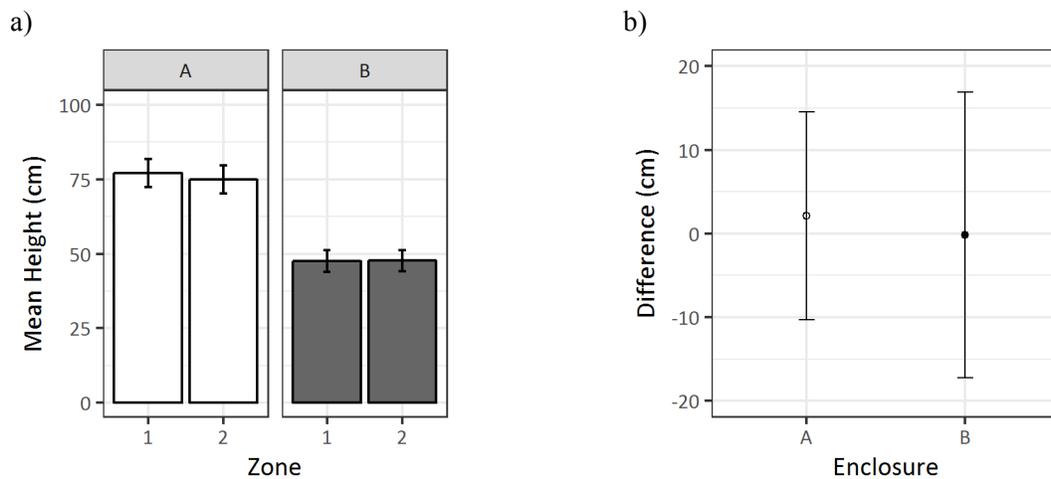


**Figure 5.25. The height of skates from the seabed.**

The modeled estimates of mean height of the skates from the seabed at each enclosure (A: control, B: treatment) with 95% confidence intervals. The estimates were back-transformed.

To assess if the decreased height from seabed at the treatment enclosure (B) was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF, the height from seabed within the two predefined spatial zones were analyzed. The group mean of the height of skates from the seabed in each zone was assessed at both enclosures and is described. The arithmetic difference in height in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Although the mean height was higher at the control enclosure (A), Figure 5.26a shows that the overall mean height from seabed was similar in Zone 1 and Zone 2 at both the control (A) and treatment (B) enclosures. At the control enclosure (A), the mean height of the skates from the seabed in Zone 1 was 77.11 cm and in Zone 2 it was 74.97 cm, a mean difference of 2.14 cm (Figure 5.26b). At the treatment enclosure (B), the mean height of the skates from the seabed in Zone 1 (>52.6  $\mu$ T) was 47.56 cm and in Zone 2 (<49.7  $\mu$ T) it was 47.73 cm, a mean difference of -0.18 cm (Figure 5.26b).



**Figure 5.26. The height of skates from the seabed in each zone.**

(a) The group mean ( $\pm$ SE) height of skates from the seabed in each zone (Zone 1 >52.6  $\mu$ T, Zone 2 <49.7  $\mu$ T) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in mean height in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference in the height of skates from seabed between zones was not statistically significant when comparing the treatment with the control enclosure ( $p=0.731$ ; Table 5.26, Figure 5. 28b). This was also explored for the two different sequence groups (1. B then A; 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference between zones, in the height of skates from the seabed, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.28).

**Table 5.28. Results of the t-test of the difference between enclosures in the height difference recorded in zones.**

The mean difference in the height of groups of skates in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, p-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI	
Overall	2.14	-0.18	8	0.355	9.0	0.731	-12.42	17.05
Sequence 1	10.48	1.08	4	1.193	4.0	0.298	-12.41	31.20
Sequence 2	-6.21	-1.44	4	-0.507	4.2	0.638	-30.51	20.97

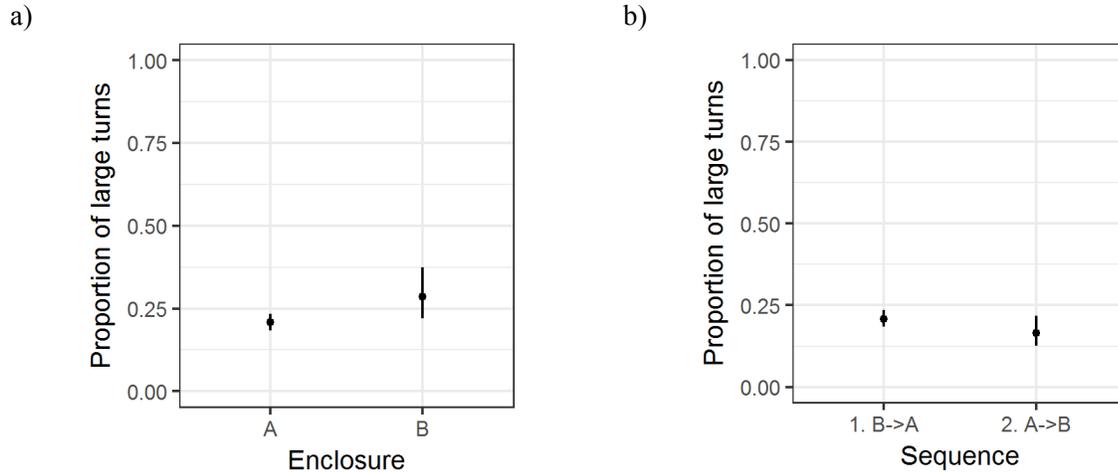
#### 5.3.4.4 Proportion of large turns

The proportion of large turns ( $170-180^\circ$ ) was first modeled using a glmmPQL which incorporated the random effect of the 'Group'. The validation plots of the Pearson residuals suggested that this model could be improved. In order to simplify the model and in keeping with previous models fitted for the skate data, the random structure was removed and a binomial glm was fitted. Again the validation plots suggested that this model could be improved and under-dispersion was detected. To correct for the under-dispersion, a quasi-binomial family was used in the glm. The interaction between 'Enclosure' and 'Sequence' was dropped from the model and the final model retained the 'Enclosure' ( $p<0.001$ ) and the 'Sequence' ( $p=0.004$ ) as significant terms. The model output is reported in Table 5.29 and the modeled relationships are plotted in Figure 5.27.

**Table 5.29. The model estimates of the proportion of large turns by skates.**

The estimates of the effect of the 'Enclosure' (A: control, B: treatment) and the 'Sequence' on the proportion of large ( $170-180^\circ$ ) turns in skates. The 2.5% and 97.5% quantiles that represent the 95% Confidence Intervals around the parameter estimates are also shown. Note that the binomial glm predicts on the logistic link function.

Parameter	Estimate (mean)	2.5%	97.5%
(Intercept)	-1.57	-1.69	-1.45
Enclosure: B	0.32	0.17	0.47
Sequence: 2	-0.23	-0.38	-0.08



**Figure 5.27. The proportion of large turns by skates.**

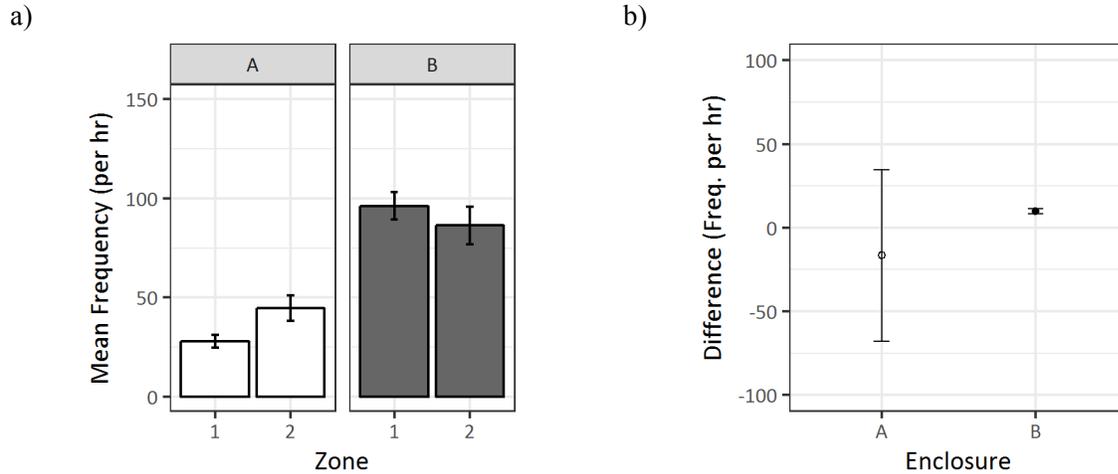
The modeled estimates of the mean proportion of large (170-180°) turns by skates at each enclosure (A: control, B: treatment; (a)) and for each sequence (b). The estimates and the 95% confidence intervals are shown.

The quasi-binomial glm estimates on the logit link function and therefore the estimates were back transformed for the following text. Please note that the proportions reported are bound between 0 and 1. The estimated mean proportion of 170-180 degree turns at the control enclosure (A) was 0.21 (95% CI; 0.18-0.23) while at the treatment enclosure (B) it was 0.29 (95% CI; 0.22-0.37). The skates at the treatment enclosure (B) showed a 37.65% higher proportion of large turns than those at the control enclosure (A).

For the skates from Sequence 1, (i.e. B then A) the proportion of large turns was 0.21 (95% CI; 0.18-0.23) whereas for skates from Sequence 2 (i.e. A then B), the proportion of large turns was 0.17 (95% CI; 0.13-0.22). Therefore skates from Sequence 2 showed 20.49 % lower proportion of large turns.

To assess if the increased proportion of large turns by the skates in the treatment enclosure (B) was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF, the frequency of large turns per hour within the two predefined spatial zones were analyzed. The group mean of the frequency of large turns per hour by skates in each zone was assessed at both enclosures and is described. The arithmetic difference in the frequency of large turns per hour in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.28a shows that the mean frequency of large turns per hour was lower in Zone 1 than in Zone 2 at the control enclosure (A) but the opposite was true at the treatment enclosure (B); there was a higher frequency of large turns in Zone 1 (>52.6  $\mu$ T) than in Zone 2 (<49.7  $\mu$ T) at the treatment enclosures (B). At the control enclosure (A) the skates made a mean total of 28.00 large turns per hour in Zone 1 and 44.60 large turns per hour in Zone 2 (Figure 5.28a); a mean difference of -16.59 turns per hour (Figure 5.28b). At the treatment enclosure (B) the skates made a mean total of 96.16 large turns per hour in Zone 1 (>52.6  $\mu$ T) and 86.31 large turns per hour in Zone 2 <49.7  $\mu$ T; Figure 5.28a); a mean difference of 9.85 turns per hour (Figure 5.28b).



**Figure 5.28. The frequency of large turns by skates in each zone.**

(a) The group mean ( $\pm$ SE) of the frequency of large turns per hour by skates in each zone (Zone 1  $>52.6 \mu\text{T}$ , Zone 2  $<49.7 \mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in frequency of large turns per hour in each zone (i.e. Zone 1 - Zone 2) at each enclosure.

The overall mean difference in the frequency of large turns per hour between the zones was statistically significant when comparing the treatment with the control enclosure ( $p=0.039$ ; Table 5.28, Figure 5. 30b). This difference was also explored for the two different sequence groups (1. B then A; 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference between zones, in the frequency of large turns per hour by the skates, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.30).

**Table 5.30. Results of the t-test of the difference between enclosures in the frequency of large turns recorded in zones.**

The mean difference in the frequency of large turns per hour by skates in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom,  $p$ -value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI	
Overall	-16.59	9.85	8	-2.284	14.0	<b>0.039</b>	-51.27	-1.61
Sequence 1	-20.60	7.07	4	-1.670	7.9	0.134	-66.00	10.66
Sequence 2	-9.92	14.47	4	-1.452	3.0	0.241	-77.41	28.64

### 5.3.4.5 Spatial Distribution

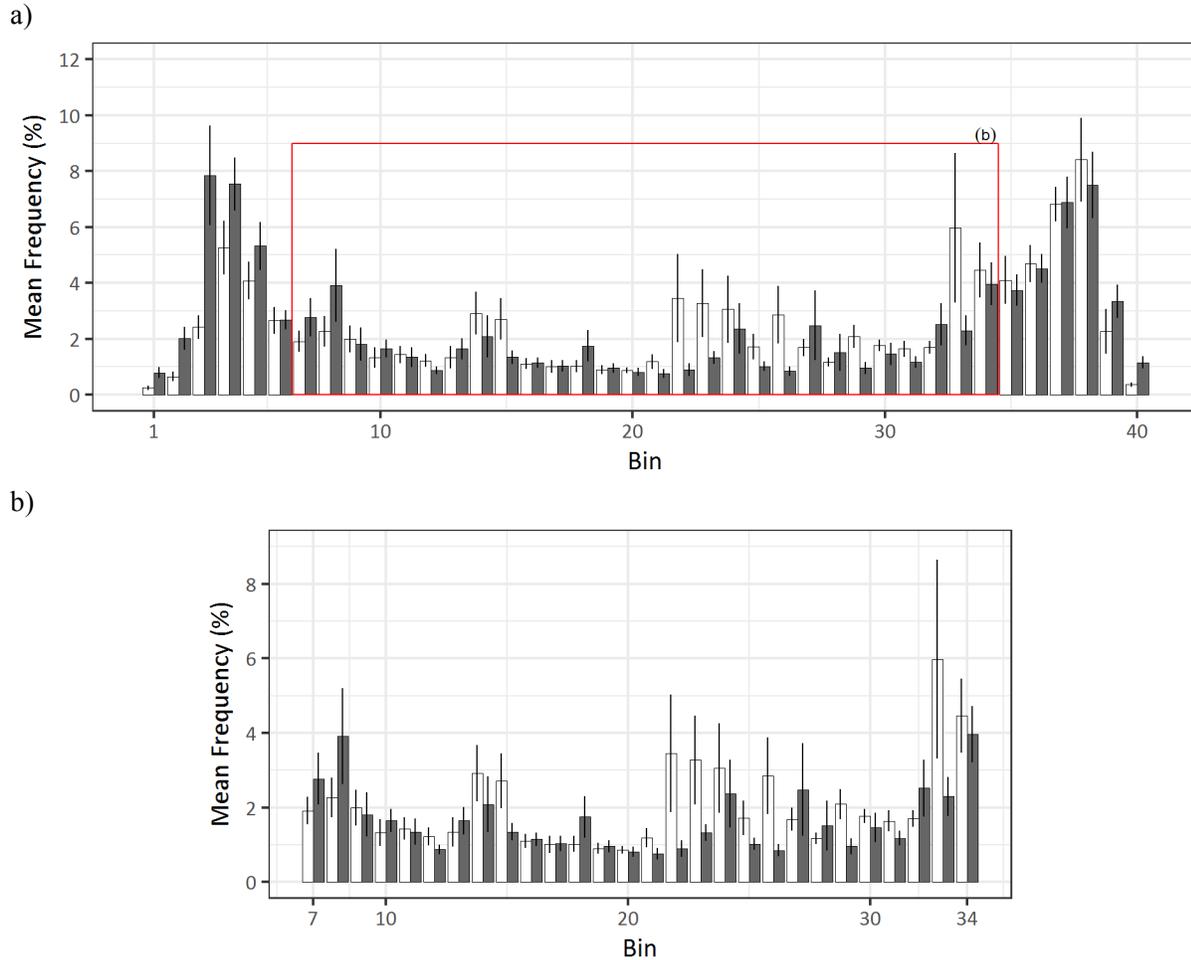
The spatial distribution of skates within the enclosures was explored to assess how they made use of the enclosure space. This analysis was done by comparing the spatial distribution along the y axis (perpendicular to the cable at the treatment enclosure (B)) between enclosures. To do so, the length of the enclosure was split into 40 bins and the distribution in each enclosure was assessed and compared in terms of 1) the proportional frequency of positions recorded and 2) the proportion of time spent in those bins. The proportional frequency of positions recorded and time spent in each zone were also analyzed to determine if there was an association with high ( $>52.6 \mu\text{T}$ ) or low ( $<49.7 \mu\text{T}$ ) EMF.

#### Spatial distribution of recorded positions

The skates use of the enclosure space was determined from the frequency of positions recorded along the length of the enclosure (y-axis), which was perpendicular to the cable at the treatment enclosure (B).

Similar data were recorded at the control enclosure (A) to provide a spatial comparison when there was no cable. The group mean ( $\pm$ SE) frequencies of positions were calculated for the 40 bins along the enclosure length and translated to a percentage of the total recorded frequencies, which allowed the spatial distributions in each enclosure to be compared (Figure 5.29).

Figure 5.29a and 5.29b show that the skates were recorded over the full extent of the enclosures and were most frequently found at the edges of both the control (A) and treatment (B) enclosures. The skates occurred more frequently in the central space of the control (A) enclosure compared to the treatment B; Figure 5.29b).



**Figure 5.29. The frequency of recorded skate positions.**

The mean frequency (%) of skate positions recorded within the control enclosure (A: white) and the treatment enclosure (B: grey). The full length of the enclosure (a) and the subset of data (b) focusing on the central area of the enclosures (red box in (a)).

To determine whether the frequency of recorded skate positions was statistically significantly different at the treatment enclosure (B) compared to the control (A) a cumulative distribution analysis was conducted applying the Kolmogorov-Smirnov (K.S.) two sample test. The K.S. is a non-parametric test that compares the overall pattern of the data distributions. The analysis showed that skates had a similar pattern of distribution within the treatment enclosure (B) compared with the control enclosure (A; Table

5.31). This result was also true when tested for skates from Sequence 1 and those from Sequence 2 (Table 5.31).

To reduce any influence of the ends of the enclosure, a subset of the positional data was analyzed to compare the patterns of distribution in the central space of the enclosure (Figure 5.29b). The skates were recorded more frequently across the central space of the control enclosure (A) compared with the treatment (B; Figure 5.29b) although the pattern of distribution was similar, except when the skates experienced the control enclosure (A) before the treatment enclosure (B) (Sequence 2 subset, Table 5.31).

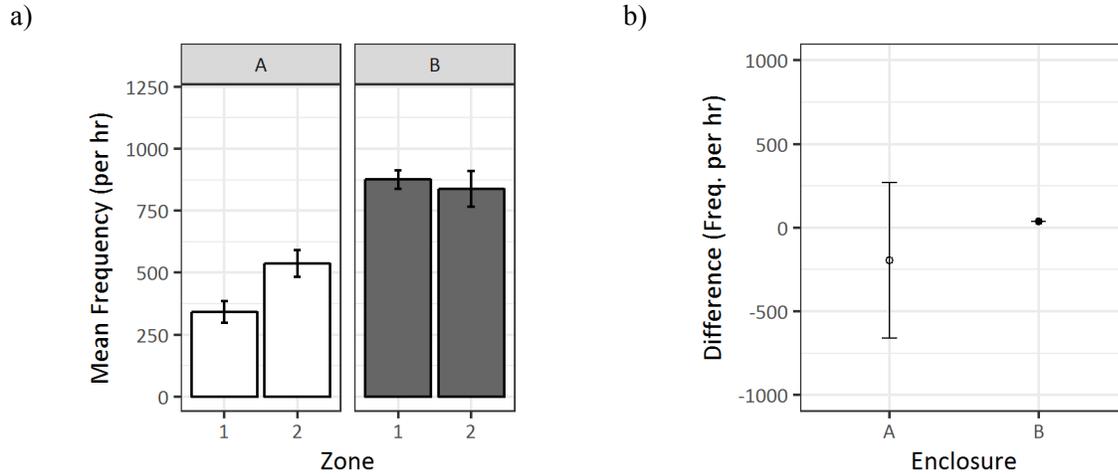
**Table 5.31. The results of the Kolmogorov-Smirnov test applied to the spatial distribution of skates assessed by the proportional frequency of positions recorded**

Kolmogorov-Smirnov test statistic D and statistical probability of the skate positional frequency distributions within the treatment (A) and control (B) enclosures being different. Significant differences between enclosures at  $p \leq 0.05$  are highlighted in bold.

	Full		Subset	
	D	<i>p</i>	D	<i>p</i>
Overall	0.125	0.893	0.214	0.490
Sequence 1	0.175	0.531	0.179	0.720
Sequence 2	0.275	0.080	0.429	<b>0.008</b>

To assess if the position of the skates in the treatment enclosure (B) was associated with high ( $>52.6 \mu\text{T}$ ) or low ( $<49.7 \mu\text{T}$ ) EMF, the frequency of positions recorded per hour within the two predefined spatial zones were analyzed. The group mean of frequency of skate positions recorded in each zone was assessed at both enclosures and is described. The arithmetic difference in positions recorded in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.30a shows that the overall mean frequency of skate positions recorded per hour was lower in Zone 1 than in Zone 2 at the control enclosure (A), with a total of 342.11 records per hour in Zone 1 and 537.44 records per hour in Zone 2 (Figure 5.30a); a mean difference of -195.33 records per hour (Figure 5.30b). In contrast, at the treatment enclosure (B) the mean frequency of recorded positions was more similar in each zone. At the treatment enclosure (B), there were a mean total of 875.26 records per hour in Zone 1 ( $>52.6 \mu\text{T}$ ) and 837.22 records per hour in Zone 2 ( $<49.7 \mu\text{T}$ ), a mean difference of 38.04 records per hour (Figure 5.30b).



**Figure 5.30. The frequency of recorded skate positions in each zone.** (a) The group mean ( $\pm$ SE) of mean frequency of skate positions recorded in each zone (Zone 1  $>52.6 \mu\text{T}$ , Zone 2  $<49.7 \mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in frequency of positions recorded in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall mean difference in the frequency of skate positions recorded per hour between the zones was statistically significant when comparing the treatment with the control enclosure ( $p=0.050$ ; Table 5.32, Figure 5. 30b). This relationship was also explored for the two different sequence groups (1. B then A; 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference between zones, in the frequency of skate positions recorded, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.32).

**Table 5.32. Results of the t-test of the difference between enclosures in the frequency of positons recorded in zones.**

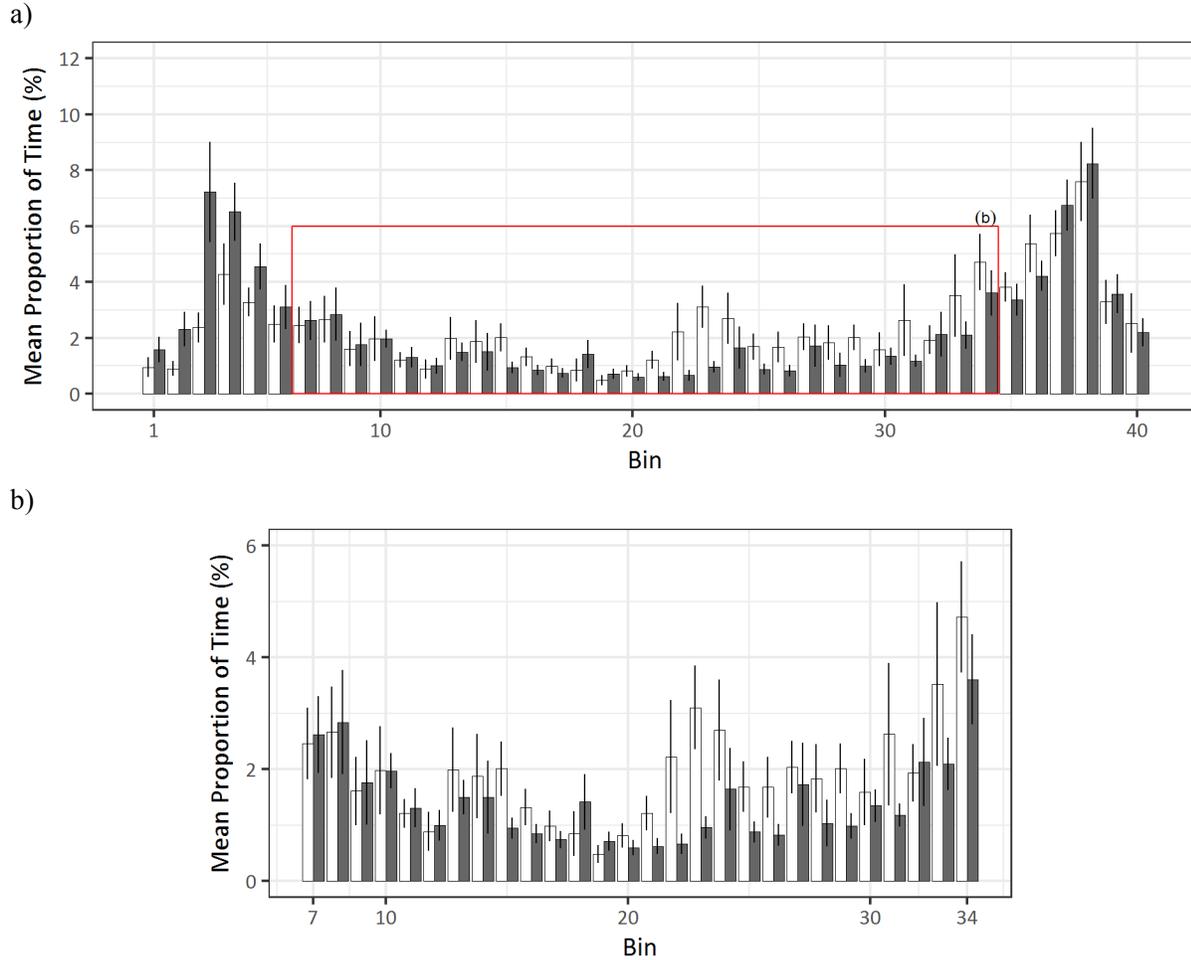
The mean difference in the frequency of skate position fixes in zone 1 ( $>52.6 \mu\text{T}$ ) and zone 2 ( $<49.7 \mu\text{T}$ ), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom,  $p$ -value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	p	95% CI
Overall	-195.33	38.04	8	-2.149	14.0	<b>0.050</b>	-466.33 -0.40
Sequence 1	-303.53	-25.53	4	-1.595	5.8	0.163	-707.27 151.27
Sequence 2	-87.12	101.61	4	-1.587	5.8	0.165	-481.97 104.50

### Spatial distribution of time

The time spent by the skates within the enclosure space was recorded along the length of the enclosure (y-axis), which was perpendicular to the cable at the treatment enclosure (B). Similar data were recorded at the control enclosure (A) to provide a comparison when there was no cable. The group mean ( $\pm$ SE) proportion of time was calculated for the 40 bins along the enclosure length and translated to a percentage, which allowed the distributions of time spent across the length of each enclosure to be compared (Figure 5.31).

Figure 5.31a and b show that the skates were recorded over the full extent of the enclosures and spent most of their time at the edges of both the control (A) and treatment (B) enclosures. In the central space of the control enclosure the skates spent more time compared to the treatment (Figure 5.31b; Table 5.33).



**Figure 5.31. The distribution of skates as a mean proportion of time.** The distribution of skates shown as the mean ( $\pm$ SE) proportion of time (%) spent in each bin within the control (A: white) and treatment (B: grey) enclosures. The full length of the enclosure (a) and the subset of data (b) focusing on the central area of the enclosures (red box in (a)).

To determine whether the distribution of time was statistically significantly different at the treatment enclosure (B) compared to the control (A) a cumulative distribution analysis was conducted applying the Kolmogorov-Smirnov (K.S.) two sample test. The K.S. is a non-parametric test that compares the overall pattern of the data distributions. The pattern of time spent in the enclosures was similar when considering the full range of distribution for the overall dataset and when separated for Sequence 1 skates (B then A). However, there was a significant difference in the pattern of time spent in the enclosures for the Sequence 2 skates (A then B, Table 5.33). There was however, a statistically significant difference when comparing the central space of the treatment (B) and the control (A) enclosures (Table 5.33, Figure 5.31b) when assessed for the overall group. The pattern of time spent in the treatment enclosure was also significantly different with the skates experiencing the treatment (B) enclosure after the control (A), i.e. Sequence 2 (Table 5.33), but not for those from Sequence 1 (A then B, Table 5.33).

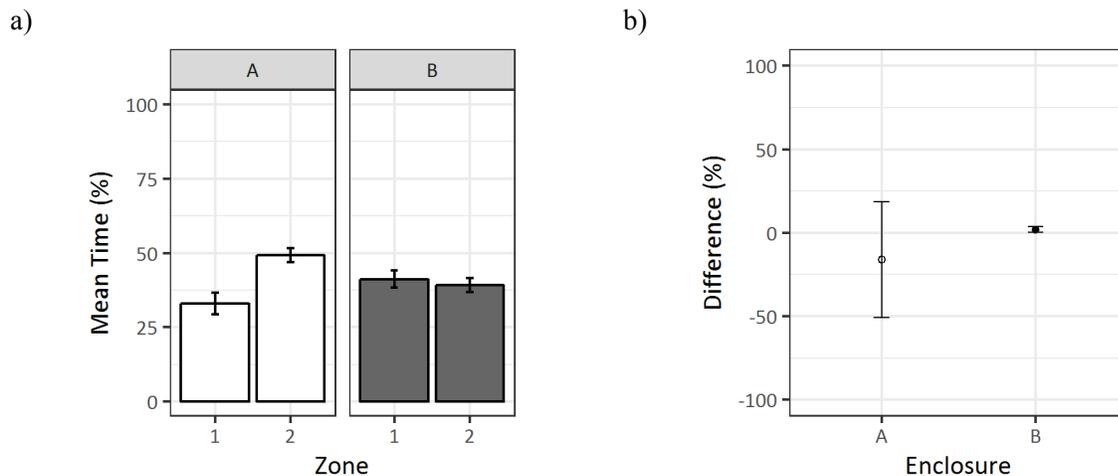
**Table 5.33. The results of the Kolmogorov-Smirnov test applied to the spatial distribution of skates assessed by the proportion of time.**

Kolmogorov-Smirnov test statistic D and statistical probability of the skate time distributions within the treatment (A) and control (B) enclosures being different. Significant values at  $p \leq 0.05$  are highlighted in bold.

	Full		Subset	
	D	<i>p</i>	D	<i>p</i>
Overall	0.250	0.139	0.393	<b>0.019</b>
Sequence 1	0.150	0.724	0.214	0.490
Sequence 2	0.325	<b>0.022</b>	0.571	<b>&lt;0.001</b>

The time spent in each zone was also used to assess if the skates spent more time associated with high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF at the treatment enclosure (B). The group mean of the proportion of time that skates spent in each zone was assessed at both enclosures and is described. The arithmetic difference in proportion of time spent in each zone (i.e. Zone 1- Zone 2) was then compared between the control (A) and treatment (B) enclosures.

Figure 5.32a shows that the overall mean proportion of time spent in Zone 1 was lower than in Zone 2 at the control enclosure (A), whereas the skates in the treatment enclosure (B) spent a similar amount of time in Zone 1 (>52.6  $\mu\text{T}$ ) and Zone 2 (<49.7  $\mu\text{T}$ ). At the control enclosure (A), the skates spent a mean of 33.00% of time in Zone 1 and 49.21% of time in Zone 2 (Figure 5.32a); a mean difference of -16.21% (Figure 5.32b). At the treatment enclosure (B), there was little difference between zones with the skates spending a mean of 41.17% of their time in Zone 1 (>52.6  $\mu\text{T}$ ) compared to 39.17% of time in Zone 2 (<49.7  $\mu\text{T}$ ); a mean difference of 2.01% (Figure 5.32b).



**Figure 5.32. The proportion of time skates spent in each zone.**

(a) The group mean ( $\pm\text{SE}$ ) of the mean proportion of time skates spent in each zone (Zone 1 >52.6  $\mu\text{T}$ , Zone 2 <49.7  $\mu\text{T}$ ) at each enclosure (A: control, B: treatment). (b) The arithmetic mean difference ( $\pm$  95% CI) in time spent in each zone (i.e. Zone 1- Zone 2) at each enclosure.

The overall difference in the proportion of time spent in each zone was statistically significant when comparing the treatment with the control enclosure ( $p=0.033$ ; Table 5.34, Figure 5.32b). This difference was also explored for the two different sequence groups (1. B then A; 2. A then B) although the sample size for the groups were notably small ( $n=4$ ). The mean difference in time spent between zones, was not significantly different when compared between enclosures for skates from Sequence 1 and those from Sequence 2 (Table 5.34).

**Table 5.34. Results of the t-test of the difference between enclosures in the time spent in zones.**

The mean difference in the proportion of time skates spent in zone 1 (>52.6  $\mu$ T) and zone 2 (<49.7  $\mu$ T), at each enclosure and the results of the Welch's two sample t-test. The t-statistic, degrees of freedom, *p*-value and confidence intervals are reported.

Difference	Control	Treatment	n	t	df	<i>p</i>	95% CI	
Overall	-16.21	2.01	8	-2.366	13.9	<b>0.033</b>	-34.75	-1.69
Sequence 1	-23.93	-3.69	4	-2.078	5.4	0.088	-44.75	4.27
Sequence 2	-8.49	7.71	4	-1.475	5.4	0.196	-43.76	11.38

### 5.3.4.6 Summary of results

To aid understanding, a summary of the results of the statistical analyses of the skate behavioral responses to the cable EMF are presented in Table 5.35 and 5.36. In brief there were a number of significant differences in behavioral parameters when compared between the control (A) and treatment (B) enclosures.

The skates traveled further at the treatment enclosure (B). This effect was more pronounced when they were exposed to the treatment enclosure first (93%) than when they were exposed to the treatment enclosure second in the sequence (21%). The distances traveled in each zone differed significantly when compared between enclosures, suggesting that the skates traveled further in the zone of high EMF (>52.6  $\mu$ T) at the treatment enclosure (B).

Skates moved faster within the enclosure when it was second in the sequence of exposure, regardless of which enclosure that was. However, the difference was larger when the second enclosure was the treatment (B, Seq. 2) where the increase was 29 % compared to when the second enclosure was the control (A, Seq. 1), where there was a slight increase of 3%. There was however no indication that the change in mean speed was associated with zones of high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF.

Skates were on average closer to the seabed (35%) at the treatment enclosure (B) compared to the control enclosure (A). There was however, no indication that being closer to the seabed was associated with high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF zones.

At the treatment enclosure (B), the skates exhibited a significantly higher proportion of large turns (38%) compared to the control enclosure (A). Skates exhibited a larger proportion of large turns in Zone 2 at the control enclosure (A), but the reverse was true at the treatment enclosure (B) suggesting that the proportion of large turns may have been associated with the zone of high EMF (>52.5  $\mu$ T). Independent of the enclosure, skates from Sequence 1 exhibited a higher proportion of large turns (20%) than those from Sequence 2.

The distribution analysis highlighted that the skates used the whole of the enclosure length of both the treatment (B) and the control (A) and were frequently recorded at the ends of the enclosure where they also spent a lot of their time. No significant difference in recorded positions of skates was found when comparing the treatment (B) and control (A) enclosures, except there was a discernible difference for Sequence 2 skates in terms of their distribution in the central space of the enclosure. There was however an indication that the skates (overall) spent more time in the central space of the control enclosure (A) compared to the treatment enclosure (B).

The skates were recorded more frequently and spent more time in zone 2 at the control enclosure (A), whereas there was no difference in their distribution across zones 1 and 2 at the treatment enclosure (B). Comparing the difference in the use of zones between enclosures indicated that the skates were found more frequently and spent a greater amount of time in zone 1, the zone of high EMF (>52.6  $\mu$ T), at the treatment enclosure (B), compared to zone 1 in the control enclosure (A).

**Table 5.35. A summary of the results of the analyses of the skate behavioral parameters.**

Summary of the mixed modeling results for the analyses of skate movements in the control (A) and treatment (B) enclosures and subsequent t-test for differences in zones between enclosures.

Summary of mixed modeling results			Summary of t-test results	
Behavioral Parameter	Sig. terms	Effect	Sig.	Difference between zones in enclosures
Total distance traveled (per day)	Enclosure & the interaction between the Enclosure & Sequence	The mean distance traveled was significantly higher at the treatment enclosure (B). This difference was most pronounced in skates that went to enclosure B first where the increase was 93%, whereas for skates that went to the control enclosure (A) followed by enclosure B the increase in mean distance traveled was 21%.	Yes	Skates traveled further in Zone 2 at the control enclosure. The reverse was true at the treatment enclosure (B); they traveled further in Zone 1 (higher EMF). The difference between zones was significantly different when compared between enclosures.
Speed of movement	The interaction between the Enclosure & Sequence	Based on the mean speed of movement, the skates which were released at the treatment enclosure (B) first, moved 3% faster at enclosure B compared to the control enclosure (A). Skates which were released at enclosure A followed by B moved 29% slower at enclosure B.  There was a 7% reduction in maximum speed at enclosure B compared to enclosure A (not statistically significant).	N.S.	The mean speed of skates was marginally higher in Zone 1 at the control enclosure. The mean speed of skates was very similar in each zone at the treatment enclosure. The difference between zones was not significantly different when compared between enclosures.
Height from seabed	Enclosure	The mean height of skates at enclosure B was significantly lower than that of A; skates were 35% closer to the seabed.	N.S.	The height from seabed was similar in each zone at the control enclosure (A). This was also true at the treatment enclosure (B).
Proportion of large turns (170-180°)	Enclosure & Sequence (no interaction)	Skates showed a 38% higher proportion of large turns when at enclosure B, compared to A.  Skates which were exposed to enclosure A followed by B, showed a 20% lower proportion of turns compared to those that were released at enclosure B followed by A.	Yes	The proportion of large turns was higher in Zone 2 at the control enclosure (A). The reverse was true at the treatment enclosure (B), with a higher frequency of large turns in zone 1. The difference between zones was significantly different when compared between enclosures.

**Table 5.36. A summary of the results of the statistical analyses relating to the spatial distribution of skates within the enclosures.**

Summary of the Kolmogorov-Smirnov (K-S) two sample test results for the analyses of skate spatial distribution in the control (A) and treatment (B) enclosures and subsequent t-test for differences in zones between enclosures. Spatial distribution throughout the length of the enclosure was assessed by the frequency of positions recorded and the proportion of time.

Parameter	Summary of K-S two sample test		Summary of t-test results	
	Sig.	Effect	Sig.	Difference
Recorded positions	Yes (Seq 2 subset only)	The spatial distribution was not significantly different when compared between enclosures for the full range of the enclosure.  The skates were recorded more frequently and in a different pattern across the central space of the control enclosure (A), compared with the treatment enclosure (B) but this was only significantly different for Sequence 2 skates (A then B).	Yes	The frequency of positions recorded per hr was higher in Zone 1 than in Zone 2 at the control enclosure (A). The frequency of positions recorded was more similar at the treatment enclosure (B) but was slightly higher in Zone 1. The difference between zones was significantly different when compared between enclosures.
Time	Yes (Seq 2)  Yes (not Seq 1 subset)	The pattern of time spent in the enclosures was only statistically significantly different when compared between the treatment (B) and the control (A) enclosures, for Sequence 2 skates (B then A).  There was a statistically significantly different distribution of time in that skates spent a greater amount of time in the central space of the control (A) compared to the treatment (B) enclosure. This observation was true for the overall group assessment and for the Sequence 2 skates (B then A) but not Sequence 1 (A then B).	Yes	The skates spent more time in Zone 2 than in Zone 1 at the control enclosure. In contrast, they spent a similar amount of time in each zone at the treatment enclosure (B). The difference between zones was significantly different when compared between enclosures.

## 5.4 Discussion

This study developed and tested a robust method for the *in situ* assessment of ecologically important behavioral responses of sensitive animals to the electromagnetic field from a subsea buried cable. Two enclosures equipped with acoustic telemetry technology were deployed; one on top of the buried HVDC Cross Sound cable (treatment enclosure B) and one at a site for reference (control enclosure A). These

experiments allowed the behavioral responses of the commercially important *Homarus americanus* and electro-sensitive *Leucoraja erinacea* to the electromagnetic field from the cable to be assessed.

Statistically significant behavioral differences were found between enclosures in both species. At the treatment enclosure (B), *H. americanus* was on average, closer to the seabed (14%) and showed a higher tendency to turn around 170 to 180° from the direction of travel. The proportion of large turns was 34% higher at the treatment enclosure (B) when second in the sequence compared to a 16 % higher at the control enclosure when second in the sequence. Furthermore, the spatial distribution of the lobsters was significantly different at the treatment enclosure when compared to the control enclosure. Importantly, it has been shown that the lobsters made full use of the enclosure and were able to cross the cable. Stronger differences in the behaviors of *L. erinacea* were observed between enclosures where they traveled 20-93% further, at slower mean speeds (29%) and did so closer to the seabed (35%) with a higher proportion of large turns (38%). The increased distance traveled and the higher proportion of large turns was shown to be associated with the zone of high EMF (>52.6  $\mu$ T) where they also spent significantly more time. The sequence of exposure to each enclosure was important in some but not all behavioral parameters assessed. Each individual lobster and skate was released at both enclosures, which accounted for individual variation in behavior. However there was notably larger confidence intervals at enclosure B suggesting high individual variation in the response to the treatment.

A methodological review explains the benefits and shortfalls of the enclosure experiment developed to assess the behavioral responses of benthic species to the electromagnetic field of the HVDC cable (Section 5.4.1). The blind interpretation of the results is then explained (Section 5.4.2) before discussing the behavioral results for both *H. americanus* (Section 5.4.3) and *L. erinacea* (Section 5.4.4) in detail.

#### **5.4.1 Methodological review**

The primary objective was to determine whether two benthic species, the American lobster and the Little Skate, showed changes in movement behavior/activity in response to encountering the EMF emitted by an operational HVDC power cable. The approach chosen needed to guarantee suitable numbers of animals for a robust study thereby overcoming the potential problem of low numbers of wild animals in the area since American lobster populations were known to be very low in Long Island Sound (ASMFC, 2015). For this reason, a free-ranging study would have been unlikely to be statistically robust – a major objective of the research.

Our solution and a major achievement of the project, is that we developed, tested, deployed and completed a set of scientifically robust *in situ* experiments using enclosures and a large enough number of animals while also allowing for the considerable individual variability noted in previous studies. Enclosures were deployed on the Cross Sound Cable (CSC) and at a reference site. The site on the CSC was chosen based on the SEMLA surveys conducted prior to experimentation. It was the site with the highest magnetic field of those surveyed and was chosen since it was expected to provide the greatest chance of detecting any response by animals encountering the EMF. The reference site was, away from the cable, but nearby (approx. 360m) with similar seabed and environmental conditions. Novel acoustic telemetry was used to monitor the animal movements in three dimensions. This approach produced experimental results with a temporal and spatial resolution an order of magnitude higher than previous similar approaches. The proof of this experimental concept is a major breakthrough in studies of fine-scale 3D animal behavior.

The behavioral parameters recorded to indicate a response, were changes in movement/activity within the enclosures. The enclosure approach ensured that the animals would have to encounter the EMF from the cable and the enclosure dimensions allowed the possibility of the animals to move either towards, away, or parallel to the cable (in the treatment enclosure), or move off the seabed if they chose to. By having a

series of replicates with different groups of animals we were able to ensure the statistical rigor of the study to determine an effect (or not).

Normadeau et al., (2011) made some recommendations for decapod mesocosm studies to assess behaviors to HVDC cables. Specifically for lobsters, it was stated that mesocosms should contain refugia to provide shelter for lobsters and allow natural behaviors such as feeding excursions and homing to be assessed. This study was specifically interested in addressing migratory behavior. The provision of shelters was considered, however this was discounted due to the risk that lobsters would stay in shelters and not move. Not including shelters encouraged lobsters to move and explore the enclosure and therefore increased the likelihood of exposure to the EMF at the treatment enclosure (B). Additionally, there is no evidence of how often lobsters shelter during migration. Similarly, there was no option for either the lobsters, or skates to burrow or create depressions in the sediment while in the enclosure. Although the enclosure allowed organisms to be close to the seabed and exposed to the EMF, the netting prevented burrowing activity and the wooden frame of the enclosure elevated the base from the seabed by approximately 2-4”.

#### **5.4.1.1 Tag Accuracy**

During the planning for the response to the original RFP, time was taken to consider the most appropriate acoustic tagging and tracking methodology to address the project objectives. Based on previous experience of both free-ranging and enclosure type tracking studies, we identified limitations in these previous studies that needed to be addressed from the outset in the new study. The principle factors were positional accuracy, frequency of recorded positions, size of tags for attachment and the number of individual animals that could be identified at any given point in time. These factors were also influential in the design of the research protocol and the dimensions chosen for the enclosures.

At the time of planning the research project, the acoustic tag systems available were focused on 2-D movement supplemented with depth loggers to add the third dimension. Furthermore, tracking system receivers are generally located as far apart as possible to maximize coverage of the environment available to free-ranging animals. There is an acknowledged trade-off between the accuracy of the position fix on an animal, the distance between the receivers and the depth of the water. With the use of the enclosures, we did not have these restrictions and therefore could focus on the accuracy of the recorded position. Furthermore, in order to obtain 3D positional data, a system that collected 3D data directly was used rather than having separate tags for 2D position and a depth logger. The 3D system from the company HTI was developed for river systems where the overall movement of the animals is restricted within the channel but where small scale 3D positional data can be recorded. In discussions with HTI, we understood that the 3D positional accuracy would definitely be sub-meter and the expectation was sub-50 cm. The frequency of acoustic pinging was user defined with predetermined codes in the second to milliseconds range. The most important factor in the accuracy of the recorded position was the geometry of the hydrophone receivers, with a cube being the best geometry (Section 5.2.3.1, Figure 5.4). However, in this study a cuboid enclosure was most suitable and allowed the animals to move both perpendicular and parallel to the cable at the treatment enclosure.

To assess the best positional accuracy, a stationary beacon tag attached to each mesocosm was included. This fixed tag is the best possible estimator of the accuracy of the recorded position and allowed the x, y and z dimensions to be considered separately. The accuracy was best in the y axis and worst in the z axis, however overall based on the confidence intervals, the positional accuracy is estimated to be within 5 cm (<2 cm in the x and y dimension and <5 cm in the z dimension; Section 5.3.1.2). Such accuracy is a great advancement particularly when these recorded positions occur over periods of 2-3 seconds. Previous studies, such as those by Gill et al., (2009), had position fixes of +/-1 m at best, for a maximum of eight individuals with the shortest time between positions of 2.5 to 3 minutes. Other field based studies have been more anecdotal, using opportunistic visual observation of interactions between focal animals and energized cables (e.g. Love et al (2016) and Dhanak et al., (2015)). Considering the complexities of

studying animal behavior, multiple encounters are required to confirm a true response. Methods must be objective, consider context dependent responses and be quantified over appropriate temporal and spatial scales. The final fine-scale tracking method applied here has proven its worth for meeting this specific objective of assessing behavioral responses.

#### **5.4.2 Blind Interpretation of Results**

The animal movement data from each enclosure were assigned the label of either A, or B to conceal but represent one enclosure that was located on top of the subsea cable and associated magnetic field and the second being the control enclosure for reference. This approach ensured that during the data analyses and subsequent interpretation, the team minimized the potential for any bias in the interpretation of the results.

One of the research team processed the animal tracking data, extracted the behavioral parameters of interest and built the statistical models for the analyses. The results were summarized graphically and in tabular form. In isolation, the same team member interpreted the outputs. The next step was for a second member of the research team with expertise in interpreting animal behavior and movement data to separately construct explanations of the results for the lobsters and the skates. Not knowing which enclosure was which, meant that the results had to be considered in turn as potential results from either enclosure. The next stage in the interpretation was to independently integrate the results in order to provide an overview and identify any contrasts or similarities of the responses of the two species to both enclosures, A and B.

Once the independent interpretation was completed the research team members discussed their respective opinions without revealing the identity of the enclosures and looked at the most plausible explanations to explain the results. The second (blind) team member then suggested which enclosure was associated with the cable and EMF, correctly identifying that data from the treatment enclosure (B) were from the enclosure exposed to the cable and EMF. In the discussion of the results here, the narrative retains the identifiers A and B to keep the reader focused on the evidence of any difference between enclosures A and B.

#### **5.4.3 Electromagnetic Field**

The characteristics of the Cross Sound Cable and the associated EMF are reported in full in Section 3.0. It is noteworthy that the EMF from the cable at the treatment enclosure was not present as a narrow area of EMF. Often, the expectation is that the EMF may present a barrier akin to a wall, which will not allow animals to move over the cable. In reality the EMF from the CSC was present as a 3D gradual distortion of the Earth's magnetic field. This degree of distortion varied on either side of the cable due to the twist in the cable axis. The EMF distortion from an HVDC cable was measured as both positive and negative deviation from the Earth's magnetic field and is dependent on the distance between the cable cores and the level of twist in the cable. The greatest deviation measured was positive (i.e. elevated EMF intensity). At the treatment enclosure (B), the distortion of the Earth's magnetic field was detected throughout the full 2D space of the enclosure (i.e. the base, see Section 5.3.2.3; Figure 5.7) and reduced with height from the seabed (Section 3.16). The HVDC EMF from the CSC was detected in 3D space and propagated up to c.a. <5 m from the cable (i.e. <5 m either side). The unexpected AC field was present over greater distances with the magnetic field up to c.a. 10 m (i.e. 10 m either side) and the electric field up to c.a. 100 m perpendicular to the cable axis (i.e. 100 m either side).

#### **5.4.4 American Lobster**

Lobsters are competitive animals; they compete for resources such as space, mates and food. There was a possibility that groups of lobsters released into the enclosures for data collection would fight and potentially result in the death of less dominant specimens. The lobsters were held in communal aquarium

tanks allowing frequent interactions that helped reduce aggressive interactions (Dunham, 1972, Sastry et al., 1980). Additionally staged fights between release groups were incorporated to encourage dominance hierarchies to develop quickly thereby reducing the severity of aggressive interactions (Karavanich et al., 1998). Lobsters recognize each other by hormones released in urine during aggressive interactions (Breithaupt et al., 2000, Johnson et al., 2005, Karavanich et al., 1998) for approximately 2 weeks (Karavanich et al., 1998, Sastry et al., 1980). This ensured that movements were not overly focused on aggressive interactions with other lobsters in the group.

The inclusion of ‘group’ as a random intercept was found to be a significant improvement to the statistical models. Each model agreed that there was typically a weak positive but significant correlation of lobster behaviors within groups. During exploratory analysis, the ‘group’ was found to be collinear with the temperature (VIF >3), so the influence of the grouping structure may also be explained by the influence of the temperature. The temperature range was broader during the lobster study than the skate study due to the timing of the releases being earlier in the summer and continued for a longer period of time. However, this was not regarded as an influence on the interpretation of the results since the temperature at each enclosure for the lobsters was very similar (Section 5.3.2.1). It is generally accepted that temperature is a strong stimulus for the fall migration in lobsters (Cooper et al., 1980, Hoenig et al., 2015). The lobsters in this study were collected offshore and released during peak seasonal temperature, therefore would most likely have been attempting to migrate offshore, which was the targeted behavior under assessment.

The mean total distance traveled per day at each enclosure by lobsters was similar (3-4 km) and within a normal range for migratory lobsters which can be from 1.8 to 11 km/day (Cooper et al., 1971, 1980). There was a marginal decrease (~7%) in the mean distance traveled per day at the treatment enclosure (B); however, this was not statistically significant, nor was it a large effect. The confidence intervals at the treatment enclosure (B) were slightly larger which suggests higher variation between individuals. The speed of movement was also very similar between the two enclosures although again there was more variation in the mean and maximum speed of movement at the treatment enclosure (B) as indicated by the larger confidence intervals. The maximum lobster speed recorded in this study was close to 800 cm/s which was most likely a cardioid escape response from another lobster; the reported maximum speed recorded is 5 m/s (Paille et al., 2008).

There was a statistically significant difference in the height from the seabed at each enclosure. Lobsters were ~14% closer to the seabed at the treatment enclosure (B) with no significant influence of the sequence of exposure. This result suggests that either lobsters at the control enclosure (A) explored the walls of the enclosure more and/or lobsters at the treatment enclosure (B) explored the seabed more. Although the z-dimension had the least accuracy due to the hydrophones being closer together, this result was true for both enclosures and the co-efficient of variation was similar (Section 5.3.1.2, Table 5.7). Although there may be some error (in the cm range) in the true height from seabed, the relative difference between enclosures is most relevant. The lobsters were observed in video footage to explore the vertical walls of the enclosure and this observation supports the variation in vertical position found in the HTI data. Lobsters are known to inhabit rocky habitat and climb on top of rocks and also into net traps (Karnofsky et al., 1989, van der Meeren, 2000), so it is reasonable to interpret these results as evidence of the lobsters climbing the netting/wood on the sides of the enclosures and/or swimming through the water column. However, *Homarus* sp. are also reported to create depressions in sand and burrow in mud (Wahle et al., 2013). Lobsters in this study were prohibited from burrowing in the sediment since they were not in direct contact with the seabed however, they may still have been searching for a suitable area to burrow in. Woodruff et al., (2013) reported that *H. americanus* was observed in laboratory experiments to burrow in a low magnetic field area more frequently than a high magnetic field area. However they acknowledged that the low magnetic field area coincided with the ends of the tank and that there was a shelter available in the high magnetic field area that may have influenced the lobster’s

behavior. In this enclosure study, there was no evidence of the lobster height from seabed being associated with the high ( $>52.6 \mu\text{T}$ ) or low ( $<49.7 \mu\text{T}$ ) EMF zone in the treatment enclosure.

When considering changes in direction of travel, the proportion of large turns ( $170\text{-}180^\circ$ ) was higher at the second enclosure in the sequence of releases, regardless of which enclosure lobsters were placed in first. This result may suggest higher levels of exploration at the second enclosure but this was not linked with an increase in the total distance traveled. The proportion of large turns was higher again when the second enclosure was the treatment enclosure (B) suggesting a response to the EMF. The large turns could be associated with the lobsters meeting each other or the ends of the enclosure and turning around however this is unlikely since there was little difference in the distance traveled by lobsters at each enclosure. They are not associated with parading the perimeter for the enclosure, since that would be shown as  $90^\circ$  turns. There was no evidence of the large turns being associated with the high ( $>52.6 \mu\text{T}$ ) or low ( $<49.7 \mu\text{T}$ ) EMF zone in the treatment enclosure (B) therefore there is no evidence of an attraction or aversion to the high EMF, or equally the low EMF area. In light of being closer to the seabed, it is plausible that the increase in proportion of large turns could be associated with searching for a suitable area to burrow. Lobsters in the enclosures were very close to the seabed but were not able to burrow due to netting and since they were mildly elevated by the base of the enclosure ( $\sim 2\text{-}4''$ ). However, it is again the relative difference between the enclosures that is of importance. Although they were unable to burrow, the activity of searching for a suitable area to burrow may be reflected in the data. It is noteworthy that the increased mean proportion of large turns at the treatment enclosure (B) when second in the sequence had large confidence intervals perhaps associated with high individual variation in the response. The confidence intervals at the treatment enclosure (B) when it was first in the sequence were also larger than at the control enclosure (A) although the difference in means was small.

It was expected that lobsters would explore the perimeter of the enclosures and this expectation was confirmed by the assessments of spatial distribution. However, this assessment also confirmed that the lobsters made full use of the available space within the enclosure and were able to cross the cable despite the EMF distortion. The lobsters were also found more frequently across the central space of the enclosure and in a different pattern of distribution within the treatment enclosure (B) compared with the control enclosure (A). Again, there was no indication of an association with zones of high ( $>52.6 \mu\text{T}$ ) or low ( $<49.7 \mu\text{T}$ ) EMF within the treatment enclosure (B) but there was a general indication of different spatial distribution.

This study has detected a different behavioral response in *H. americanus* at the treatment enclosure (B) compared to that of the control enclosure (A). The lobsters at the treatment enclosure (B) were on average closer to the seabed and exhibited a higher proportion of large turns in their behavior and had a significantly different spatial distribution within the treatment enclosure. This result suggests that the lobsters were responding to the difference in the enclosures, which was the EMF of the HVDC cable, which operated at a constant power of 330 MW, corresponding to 1175 Amps and a maximal magnetic field of  $65.3 \mu\text{T}$  (Section 5.3.2.3). However, although a behavioral response was detected within the treatment enclosure it cannot be attributed to an attraction or aversion to either the higher ( $>52.6 \mu\text{T}$ ), or lower ( $<49.7 \mu\text{T}$ ) EMF areas but as a difference in behavior associated with the EMF.

Very little is known about whether *H. americanus* and other decapods can detect magnetic fields (Section 5.1.1.3). It would perhaps be assumed based on the little information that there would be no response by the lobsters, however our study suggests otherwise. It remains an important question to explore further that can be assisted from further information drawn from the data collected in this study together with further research into the ability of *H. americanus* to detect magnetic fields. These studies could follow approaches similar to studies for *P. argus* where the magneto-reception has been demonstrated collectively by the discovery of ferromagnetic material in the anatomy (Lohmann, 1984), laboratory studies of orientation to geomagnetic cues (Lohmann, 1985), and field studies that test homing abilities while other sensory cues are removed (Boles et al., 2003). It is possible that *H. americanus* possesses a

polarity compass similar to *P. argus* that may be used in homing and/or migration (Boles et al., 2003, Lohmann et al., 1995), but to date there is no evidence for or against this. Although there was no neural responses to magnetic fields in *H. vulgaris* (Ueno et al., 1986), the magnetic field tested were higher than the geomagnetic field and distortions which may occur from cables (Normandeau et al., 2011). In contrast, there have been behavioral responses in other decapods to the geomagnetic field, e.g. the Red King crab, *Paralithodes camtschaticus* (Muraveiko et al., 2013). To understand the importance of the effect of the electromagnetic field on the behavior of *H. americanus*, knowledge of the physiological ability and ecological importance of magneto-reception to *H. americanus* is required.

#### 5.4.5 Little skates

During the skate study the power in the cable at the treatment enclosure (B) was variable between 0-330 MW. The cable was most frequently powered at 0 (37.5% of time), 100 (28.6%) and 330 MW (15.2%), corresponding to 16, 345 and 1175 Amps and a magnetic field of 51.6, 55.3 and 65.3  $\mu\text{T}$ , respectively. It is noteworthy that even when the power in the cable was 0 MW, there was still a 0.3  $\mu\text{T}$  deviation of the Earth's magnetic field. Despite the variability and the cable being powered 62.4% of the time, there were strong differences in the behavioral parameters between the enclosures detected.

There was a distinct increase in the distance traveled by skates at the treatment enclosure (B) with them traveling further per day than those in the control enclosure (A) regardless of the sequence of exposure. Skates traveled 93% further at the treatment enclosure (B) when released at that enclosure first. The difference in the mean distance traveled per day was however less pronounced in skates released at the treatment enclosure (B) second, where the increase was ~20%. In both cases, the confidence intervals surrounding the mean distance traveled per day at the treatment enclosure (B) were larger than for the control enclosure (A). Although there were no specific data available on the typical daily movement of skates, based on the biology of *L. erinacea* (Packer et al., 2003), the distances moved are reasonable. Overall, the difference in distance traveled between zones in each enclosure, indicates that the increased distance traveled was associated with Zone 1, which was the area of higher EMF (>52.6  $\mu\text{T}$ ). Although some studies have noted increased elasmobranch activity in response to magnetic fields (Anderson et al., 2017, Meyer et al., 2005), these have been in studies of conditioned behavior to help determine detection abilities rather than natural behavioral responses and are therefore difficult to compare. An increase in distance traveled between recorded positions was observed in *R. clavata* in response to an AC cable (Gill et al., 2009), although there was no measure of the total distance traveled.

Skates moved at a similar speed in each enclosure when they were released at the treatment enclosure (B) first in the sequence. In this case, there was a minor increase in speed at the treatment enclosure (B), only ~3%, so the speed of movement was similar. A much stronger, difference was observed in skates that were exposed to the treatment enclosure (B) second in the sequence; they moved ~29% slower. In both cases, the confidence intervals of the means at the treatment enclosure (B) were larger indicating higher variation in the speed of movement at the treatment enclosure (B). There was no indication that the change in mean speed of movement was associated with the zones of high (>52.6  $\mu\text{T}$ ) or low (<49.7  $\mu\text{T}$ ) EMF. The average maximum speed of skates was also statistically significantly lower at the treatment enclosure (B) although the difference was small (~7%) with no influence of the sequence of exposure (Figure 5.17).

The mode of motility in *L. erinacea* has been described as a combination of punting and swimming (Koester et al., 2003). Punting occurs when the skates push off the substrate with their crura and glide a short distance while repositioning the crura for their next punt. Forward speeds during punting ranging from 16.6 to 20.4 cm/s in wild skates were recorded (Koester et al., 2003). These speeds are slightly higher than the ranges recorded in this study (Section 5.3.4.2, Figure 5.16) however punting is typically interjected with periods of resting and swimming behavior which would also influence the mean speeds reported in this study. Although punting is suited to their benthic lifestyle, *L. erinacea* can rapidly

transition into swimming mode (Di Santo et al., 2017, Koester et al., 2003). Swimming kinematics and energetic costs in *L. erinacea* have been characterized (Di Santo et al., 2017). They have one of the lowest swimming metabolic rates measured for any elasmobranch, but are not suited to long distance swimming due to a relatively low optimum speed (Di Santo et al., 2016). The maximum speeds recorded in this study confirm that the skates were swimming in the enclosures; the data also showed they made full use of the enclosures. So, although the skates traveled further at the treatment enclosure (B, Figure 5.15) they moved more slowly, as shown by the mean and maximum speed of movement (Figure 5.16 and 5.17). This result may suggest that at the treatment enclosure (B) more time was spent punting than swimming or simply that they were swimming more slowly. However, these trends may also have been due to increased periods of rest combined with periods of faster swimming activity at the control enclosure (A).

There was an anomaly in the data that may support the suggestion of increased periods of rest at the control enclosure (A). There were periods of prolonged elapsed time between recorded positions of skates that was predominant at the control enclosure (A). These gaps cannot be attributed to equipment failure since there were no breaks in the detection of the beacon tag recorded. This lack of breaks in beacon tag data confirms that the hydrophones were always capable of receiving acoustic signals. Likewise the gaps have not been attributed to tag failure since the signal of a failing tag would typically be intermittent but frequent before ceasing all together. In contrast, after the periods of prolonged elapsed time between recorded positions, normal frequency resumed such that the tag was definitely still working. The skates did not block the hydrophones from receiving the signal since the beacon tag signal was continuously received. The only other possibility identified is that a skate may have blocked the signal of another skates tag. There are HTI tags which are designed to be surgically implanted and tags which are capable of signaling when they have been consumed by a predator so the acoustic signal can pass through soft tissues. However, it is not known if the tag signal can penetrate the cartilage or placoid scales of skates. It is possible that skates resting on the seabed may have blocked the tag signal of another skate where an overlap of the tagged pectoral wing occurred, since skates were released to the enclosures in groups of five. This resting behavior and overlap with conspecifics was often observed in skates held in the communal aquarium tanks. Additionally it is known that *L. erinacea* are often found resting in depressions in the seabed during the day (Koester et al., 2003, Packer et al., 2003). Further assessment of the location of skates in proximity to the seabed and to each other in their groups would help confirm if this scenario is true. However, HTI technical experts reviewed the data and their findings support the suggestion that the prolonged periods of elapsed time between position fixes are likely associated with the behavior of the skates (such as resting on top of each other) that was predominant at the control enclosure (A).

The data clearly shows that the skates made full use of the enclosures and despite the periods of prolonged elapsed time between recorded positions, which are proposed to be periods of rest, there was evidence of activity in between these periods. The spatial distribution analyses confirmed that the skates made use of the central space within both enclosures which confirms that skates were able to cross the cable in the treatment enclosure (B). Comparison of the zones between enclosures indicated that the skates were found more frequently and spent a greater amount of time in the zone of high EMF (<52.6  $\mu$ T) at the treatment enclosure (B).

The mean height of the skates at each enclosure confirms that there was swimming activity in between the proposed periods of rest. The mean height was higher at the control enclosure (A) whereas the skates at the treatment enclosure (B) were significantly closer to the seabed (~35%). There was however no indication that the difference in height from seabed was associated with the zones of high (>52.6  $\mu$ T) or low (<49.7  $\mu$ T) EMF in the treatment enclosure (B). During data processing, the skates were observed to

make full use of the area within both enclosures. This result suggests that during periods of activity, skates at the control enclosure (A) were swimming off the seabed and higher in the enclosure than those at the treatment enclosure (B). This observation is representative of normal skate movement; periods of rest interjected between periods of punting on the seabed and swimming midwater (Koester et al., 2003, Packer et al., 2003).

The skates at the treatment enclosure (B) traveled further but slower and did so closer to the seabed. This result, together with the increased proportion of large turns (~38%) at the treatment enclosure (B) may be suggestive of increased exploratory and/or area restricted foraging behavior. The skates in this study were recorded more frequently and spent comparatively more time in Zone 1 at the treatment enclosure (B), which indicates an association with the zone of high EMF (>52.6  $\mu$ T). At the treatment enclosure, the skates also traveled further and exhibited a higher proportion of large turns in the high EMF area (>52.6  $\mu$ T). The sequence of exposure was also found to be a significant influential factor although it was independent of the enclosure; skates from sequence 1 (B-A) showed a 20% increase in the proportion of large turns than those from sequence 2 (A-B). Koester et al., (2003) described the use of the crura, functioning independently to allow sharp or gradual turns which would not be possible with pectoral fin locomotion. They also suggested that the use of crura for locomotion may produce less noise than pectoral fin undulation when trying to detect prey with electro-receptors on the head and wings. Although it is accepted that elasmobranchs can account for their own bioelectric fields as noise (Bodznick et al., 2003), there may also be behavioral adaptations that assist with this ability.

The behavioral differences in this study do not provide detail on whether the skates may be responding to the DC magnetic field, the AC (electric and magnetic) field or the induced electric field from either water movement, or their own movement through the magnetic field (Kalmijn, 1988). Neural responses in skates have shown that the ampullae of Lorenzini are capable of responding to deviations in the magnetic field and induced electric fields (Akoev et al., 1976, Andrianov et al., 1974, Brown et al., 1978). However, it has been suggested that another mode of magneto-reception may exist in elasmobranchs (Anderson et al., 2017, Johnsen et al., 2005, Molteno et al., 2009). To date, studies of behavioral responses to magnetic fields have typically focused on determining the ability of elasmobranchs to detect the magnetic field through conditioning to food (Anderson et al., 2017, Kalmijn, 1981, Kalmijn, 1982, Meyer et al., 2005). Therefore, evidence of natural behavioral responses to magnetic fields is lacking. Prior to this study, the only other evidence was from a mesocosm study by Gill et al., (2009). There was evidence that *S. canicula* were attracted to a powered AC cable since more individuals were found in the high EMF area and this coincided with slower speed, consistent with feeding behavior. An effect was also found in *R. clavata* where there was further distance traveled between recorded positions when the cable was powered. Although it has been shown experimentally that elasmobranchs can habituate to electric fields similar to that of predators (Kempster et al., 2013), and learn that an artificial electric field is not associated with food (Kimber et al., 2011, Kimber et al., 2014), there is no empirical evidence that they can distinguish between magnetic fields and anthropogenic distortions.

Overall, there was a strong difference in multiple behavioral parameters between the treatment (B) and control (A) enclosures. The treatment enclosure (B) was placed on top of a buried DC cable that was most frequently powered at 0, 100 and 330 MW, corresponding to 16, 345 and 1175 Amps and a magnetic field of 51.6, 55.3 and 65.3  $\mu$ T, respectively. The mean power level for each release of skates was explored and represented a wide range however trends with behavioral parameters were not analyzed due to a lack of independent replication for the different power levels (i.e. n=1 for each mean power level). Additionally, although groups of skates were exposed to a variety of power levels, there was temporal non-independence of exposure to the different power levels. Future experimental studies should consider incorporating variable power levels into the experimental plan and the statistical analysis of the behavioral data. The variation in power in the cable during the skate study was high (Section 5.3.2.3) and when the full study is considered, the mean power level was 118 MW. The two sequence groups were

used to prevent bias in the sequence of exposure to the control and treatment group. However, each sequence group is confounded by the variability of the power in the cable. Sequence 1 skates were exposed to a mean power level of 80 MW and went to the treatment enclosure (B) first in the sequence. Sequence 2 skates were exposed to a mean power level of 156 MW and went to the treatment enclosure (B) second in the sequence. During the skate study, the sequence was found to be a significant influential factor in conjunction with the enclosure for the total distance traveled and the mean speed of movement and independently for the proportion of large turns. Reviewing these trends in light of the different mean power levels may suggest that skates traveled less distance and more slowly at a higher mean power level however this cannot be separated from the prior exposure to the control enclosure (i.e. non naïve to the enclosure environment).

Despite the highly variable power in the cable at the treatment enclosure (B), on average the skates traveled further, despite moving slower, while closer to the seabed with an increased proportion of large turns when compared to the control enclosure (A), which had a constant geomagnetic field of 51.3  $\mu\text{T}$ . The confidence intervals for the treatment enclosure were typically large, which suggests a high degree of individual variability in the response to the cable. Strong trends have been detected despite the power in the cable being variable and the increased distance traveled and increased proportion of large turns has been shown to be associated with the area of high EMF. Although the exact mechanism of magnetic reception in elasmobranchs is debated, the electro-sensory system allows electromagnetic fields to be detected. This ability is important for multiple biological and ecological reasons such as the detection of prey, predators, conspecifics for mating, social communication as well as environmental cues (Section 5.1.2.2). Specifically understanding the ecological influences that anthropogenic distortion of the magnetic field present is complex. It will require consideration of the likelihood of the animals encountering the EMF and whether the response occurs consistently through time. The ability of the animals to learn and habituate to the EMF will also be important and will likely be closely linked to the predictability of the EMF associated with the cable. Ensuring that the actual EMF encountered is properly quantified spatially and temporally will remain a key element of the analysis (Section 7.0 provides further comment).

## 5.6 Conclusions

Overall, this study has shown that behavioral responses do occur in both lobsters and skates when exposed to the EMF from a subsea HVDC cable. The responses highlight that exposure to cable EMF was associated with changes to the movement and distribution within an enclosure space, however the EMF did not represent a barrier to either species.

The field-deployed enclosures and acoustic telemetry method developed and fully tested in this study successfully allowed the collection of *in situ*, high frequency three-dimensional positional data on individuals at both an experimental treatment enclosure (B) on the cable and an enclosure at a control site for reference (A). These data were then used to assess for differences in behavioral parameters in *H. americanus* and *L. erinacea* including; the total distance traveled, the speed of movement, the height from the seabed, and the proportion of large turns. Together these behavioral parameters were compared between enclosures to provide an assessment of changes in activity and movement in response to the EMF associated with the single HVDC cable. This method successfully detected statistically significant differences in the movement behavior of both species tested.

Importantly it has shown that both the lobsters and skates made full use of the enclosure space and the cable did not present as a barrier for either species. There were however significant differences in the behavior of both species when exposed to the EMF from the cable.

When exposed to the EMF, *H. americanus* made more use of the central space of the enclosure and was on average, closer to the seabed (14%). They also showed a higher proportion of large turns (34%) when

exposed to the treatment enclosure (B) second in the sequence (compared to 16% when the control was second in sequence). This result suggests that the *H. americanus* responded to the EMF of the HVDC cable, which operated at a constant power of 330 MW, corresponding to 1175 Amps and a maximal magnetic field of 65.3  $\mu$ T. These changes in height from seabed, spatial distribution and the proportion of large turns were not associated with areas of high ( $>52.6 \mu$ T) or low ( $<49.7 \mu$ T) EMF within the treatment enclosure but can be considered together as a statistically significant but subtle change in activity when exposed to the EMF of the cable.

Stronger effects on the behaviors of *L. erinacea* were observed between enclosures despite a variable power in the cable, which was most frequently powered at 0 (37.5% of time), 100 (28.6%) and 330 MW (15.2%), corresponding to 16, 345 and 1175 Amps, and a magnetic field of 51.6, 55.3 and 65.3  $\mu$ T, respectively. Even when the power in the cable was 0 MW, there was still a 0.3  $\mu$ T deviation of the Earth's magnetic field. Despite the variability and the cable only being powered 62.4% of the time, there were strong differences in the behavioral parameters between the enclosures detected. When exposed to the EMF from the cable, *L. erinacea* traveled 20-93% further, at slower mean speeds (29% when second in sequence), and did so closer to the seabed (35%) with a higher proportion of large turns (38%). The increased distance traveled and the higher proportion of large turns were both associated with the zone of high EMF ( $>52.6 \mu$ T) at the treatment enclosure (B), where the skates also spent more time.

The sequence of exposure to each enclosure was important in some but not all behavioral parameters assessed. Each individual lobster and skate was released at both enclosures which controlled for individual variation however there was notably larger confidence intervals at enclosure (B) suggesting high individual variation in the response to the treatment. It is possible that some of the variation in *L. erinacea* is due to the variable power and associated EMF during the study.

The effects on behavior were more strongly detected in the skates than lobsters. For both species the behavioral changes have biological relevance in terms of how the animals will move around and be distributed in a cable EMF zone. Chapter 7 considers these biological effects further in the context of the whether there is potential for the effects being significant enough to be deemed a biological impact.

## 5.6 References

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## **6.0 Lessons Learned**

### **6.1 EMF survey methods**

To survey the EMF of the Cross Sound Cable (CSC), two methods were explored; the use of a remotely operated vehicle (ROV) and the use of the Swedish ElectroMagnetic Low-noise Apparatus (SEMLA). The SEMLA sled proved very capable of providing sensitive, accurate, reliable, and cost-effective measurements of both magnetic and electric fields. Transect measurements across the cable axis provide the most information and the SEMLA was effective during transects in water depths of <50 m. The ROV mounted magnetic sensor provided data that were semi-quantitative for magnetic fields only. It was not calibrated to accurate magnetic units. Due to the high, primarily North-South, tidal currents within the study area on the CSC, the ROV had trouble conducting East -West transects. It essentially functioned well as a cable tracker (its intended use), but not as a measurement device for EMF.

### **6.2 EMF fields associated with DC and AC cables**

The methodology employed in this study made it possible to observe both the magnetic and electric fields generated by submarine power cables. Three cables were surveyed, the Cross Sound Cable, the Neptune Cable, and the sea2shore Cable. The first two cables were transferring DC-power, whereas the latter was transferring AC-power. All three cables were surveyed using the same measurement and data processing methodology. The Cross Sound Cable and the Neptune Cable generated magnetic DC-fields that were highest in close proximity to the cable, as expected. Somewhat surprisingly, the *in situ* measurements revealed that the two DC-cables generated strong AC-fields in addition to the DC-fields. The results show that both the Cross Sound Cable and the Neptune Cable produced AC-fields that were comparable to the field strength observed in the AC-transmission of the sea2shore cable. Furthermore, the analyses showed that the propagation distance (radial distance from the cable) of the electric AC-fields were larger than the corresponding magnetic AC-fields for all three cables. These findings stress two important issues. First, even if a cable is a DC-type, it may generate AC-fields and these fields need to be considered in an environmental assessment. Second, the electric AC-fields have a relatively “long range“ that might be encountered by animals sensitive to the fields.

### **6.3 Use of COMSOL for modeling the EMF of subsea power cables**

In this study, COMSOL software was used as a simulation platform for EMF modeling and simulation. The simulation software is fairly straightforward to use and can provide an accurate calculation of the EMF, given the parameters of the environment, the cable, and the conditions of operation.

Using COMSOL, models can be constructed with the built-in geometries and the materials library. Material properties can be user defined based on project requirements. The mesh generated by COMSOL is smooth and can be easily controlled. COMSOL also provides many options for the equations that allow accurate simulation results to be obtained. The plot function of COMSOL is also very powerful, producing effective visualization of simulation results. Furthermore, COMSOL can simulate the coupling effect of multi-physical fields. Overall, project observations and experience with COMSOL for EMF modeling was positive. COMSOL provides a useful and cost-effective approach for estimation of EMF fields for different project objectives. The only limitation encountered related to the unexpected AC fields associated with the DC cables. COMSOL would not predict this observation. It may be possible in future to use COMSOL to produce the observed AC field if the appropriate parameters were incorporated by the user.

## 6.4 HTI proof of concept, challenges, and ground-truth

To insure that the positions recorded by HTI technology were accurate, animal movements recorded by the HTI positioning system were ‘ground-truthed’ by comparison with video footage prior to the full data processing in HTI software (Section 5.3.1.2). This type of ground-truthing was completed for the main study and also in preliminary trials. Attempts at recording animal movements using HTI technology in the aquarium were unsuccessful due to multi-path issues, so the best method for ground-truthing animal movements recorded by HTI technology was in the deployed enclosures.

The tags employed in this study were sufficient when functioning correctly (Section 5.2.3.1). Unfortunately, there were several occurrences of tag failure. There were two reasons for this problem, seal failure and battery failure. Seal failure was largely due to handling of the tags. The visual identification of tags was achieved by color coding with electrical tape, but this approach also peeled the waterproof coating. This problem was rectified by a protective layer placed between the tag and the tape. Seal failure also occurred when the lobsters were tagged in advance (lobsters found the tags to be edible) and held in communal tanks, for this reason lobsters were tagged immediately prior to release to prevent any damage to the tags. Battery failure was identified as a reason for a full batch of tags to fail immediately on arrival. These tags were returned to HTI, and the problem was traced back to a faulty batch of batteries during tag assembly. To manage tag failures, tags were tested on arrival to ensure that they held a tag code when programmed and a ‘sniffer’ was used to check tags were working when attached to specimens before and after release to the enclosures.

During the development of the enclosure method, the ideal hydrophone geometry of a cube could not be achieved and was therefore supplemented with two additional hydrophones connected to two Micro Data Loggers (MDL, Model 395; Section 5.2.3.1). The intended method was to use the external GPS recorders for three receiver units (2 MDL’s and 1 ATR, Section 5.2.3.1) at each enclosure and merge the data using the GPS time stamp. However, in the end it was not possible to merge the data properly during this study. Despite not being able to incorporate the additional data from the MDL’s, excellent position fixes were obtained for both lobsters and skates using only four hydrophones connected to the ATR.

The typical method for determining the most accurate hydrophone positions while *in situ* is to conduct a ‘ping around’. This method is inbuilt in the HTI software, which can be set to occur at specified time intervals. The hydrophones emit a signal that in turn is detected by the other receiving hydrophones, which then allows the mathematical positions to be verified by HTI. Hydrophone positions determined in this way for the enclosures were highly inaccurate. In the event of using the hydrophones in such close proximity to each other in the enclosures, the best method for determining the hydrophone positions is to manually measure them prior to enclosure deployment.

Taken together, these challenges created significant delays in the whole project, but were all overcome.

## 6.5 Demonstrating biological effects: Enclosure studies versus other approaches

There are typically three ways to try and assess how animals respond to electromagnetic fields: (1) controlled laboratory experiments; (2) free-ranging tracking studies; and (3) controlled field experiments employing enclosures or mesocosms; the approach taken in this study as described in Section 5.0. Readers are referred to Section 2.0 for a literature review of the most recent EMF studies.

Laboratory studies are particularly useful in helping to determine the ability of an animal to detect an electromagnetic field and in the future may help determine thresholds of detection. Free-ranging tracking studies and enclosure studies employing acoustic technology have their own advantages and are best when employed together providing a complimentary approach.

The advantage of free-ranging tracking studies is that the animals are allowed to move naturally in their preferred environment. Typically tagging studies provide presence/absence style data on the movement of animals within a geographically restricted area. Technology is more advanced now and can collect fine-scale movement data in geographically restricted areas defined by receiver positions, but this is often prohibitively expensive owing to the large number of animals that need to be tagged to ensure that a reasonable data set is obtained. Had this free-ranging tracking approach been applied to the 40 km long Cross Sound Cable, only a small section of the cable would have been able to be monitored to achieve fine-scale movements in three dimensions. To record movement of animals across the whole cable would have been extremely expensive and would be unlikely to provide a high return of data for many individuals. Monitoring a small section of the cable to provide high frequency movement data would have reduced the chances of free-ranging animals crossing that particular section of the cable with no guarantee of useful data. This approach would have been particularly risky given that the power in the cable was also variable during the skate study and was not able to be manipulated for the purposes of the study.

The enclosure style approach ensured that a number of animals were exposed under similar conditions to the electromagnetic field from the cable and that their behavior was monitored. Although the animals were restricted within the enclosure which influenced their distribution, both species were recorded moving throughout the available space indicating that the enclosures were large enough to provide a reasonable amount of space for the benthic animals (measuring between 60 and 80 cm total body length). Having a control enclosure at a reference site away from the cable allowed a comparison of animal behaviors within the enclosure environment and controlled for the other environmental variables as well as the -individual variability in behavior, since all animals were released at both enclosures. In this study only one site was used to enable proof of concept to be demonstrated. Despite this limitation, this study successfully demonstrated responses in both lobsters and skates when exposed to EMF from an operational HVDC power cable.

## 7.0 Integration of research findings

The University of Rhode Island and key partners have conducted a study entitled "Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables." The report by Normandeau et al., (2011) provided an excellent point of departure for this project, since it identified number of research priorities and data gaps, which needed to be addressed to improve the state of knowledge regarding EMF effects on marine organisms. Through its specific multidisciplinary field and modeling based approach, the BOEM-URI project has:

1. provided an synthesis of existing information published subsequent to the Normandeau et al., (2011) report to BOEM on EMF and the potential effects on marine species;
2. successfully completed field surveys to characterize the EMF from two high voltage direct current (HVDC) cables; the Cross Sound Cable (CSC) and the Neptune Cable;
3. developed a computer model to predict the EMF generated by HVDC cables and a comparison of EMF model predictions with EMF field measurements for validation and to determine if the model can be extrapolated to higher capacity cables that are likely to be installed in the future;
4. developed and executed a statistically robust field experiment that detected effects of EMF from HVDC cables on the movements of marine species (American lobster, *Homarus americanus* and Little skate, *Leucoraja erinacea*) of concern

An integration, interpretation and evaluation of the multidisciplinary findings from this project is provided below.

The project applied a multidisciplinary research approach to advance knowledge and address questions associated with anthropogenic electromagnetic fields (EMF) and their effects on the marine environment. The previous chapters dealt with three key elements of the research to advance current knowledge, namely (1) the determination of EMF emissions associated with subsea power cables, (2) modeling of the power system to predict EMFs and (3) a biological field experiment to determine the effects, if any, on potentially receptive animals encountering the EMF emitted by an operational HVDC power cable. Here the findings from the research elements are considered together.

The *in situ* measurements of the EMF from the subsea power cables highlighted the importance of validating the electromagnetic (EM) emissions predicted from EM-modeling prior to interpreting the EMF in terms of biological relevance. The measured EM fields were similar to those predicted to be present in the environment by the model, which supports the use of models for determining likely EMFs emitted by cables. However, the measured EMF unexpectedly found that the two HVDC cables also had associated AC magnetic and induced AC electric fields. Without the data from the field surveys the presence of an AC field would not be predicted from the models and therefore the context of the EMF environment associated with subsea cables would be incomplete. Evidently, further field measurements of EMFs emitted by cables combined with comparisons with the output of models, are recommended. This approach will improve knowledge and support the development of models that will provide a more complete and accurate picture of the EM environment associated with emissions from power cables.

### 7.1 Subsea cable EMF measurements and model outputs – the biological interpretation

There are three main findings related to cable emissions that have to be considered from an environmental perspective. First, the magnitudes of the AC fields were comparable for HVDC and HVAC systems and within the range of biologically relevant EMF intensities. Therefore, in terms of the EMF emitted, AC cables are less complex compared to DC cables, since AC cables only emit an AC field, whereas DC cables generate both AC and DC fields. Second, the strength of the EMF within the water column was

dependent on the burial depth of the cable. This result indicates that deeper burial depth leads to lower EMF at the seabed and in the water column where mobile species are found. It is notable that the lower EMF level is due to increasing the distance between the cable and the seabed/water column and not because burial itself dampens the intensity of EMF. It should be noted that burial will reduce the peak strength of the EMF; however, a number of species are attracted to lower EMF intensities so interpretation of the potential effect of the changes in EMF intensity requires knowledge of the range of detection by the receptive species. Third, the observations indicate that if a cable is transmitting power at a constant level, then the EMF strength will still vary along the cable route, which was interpreted to be due to varying burial depth. Therefore, variability of the EMF along the length of the cable needs to be considered in the interpretation of the environmental change that receptive animals may experience when encountering the EMF from a power cable.

The power levels transmitted through the HVDC Cross Sound Cable (CSC) during the lobster study remained, as expected, constant throughout the experimental period. However, during the skate study the power level transmitted was variable and therefore the EMF encountered by the skates changed too. Increases in the EMF emitted by a subsea cable have been suggested to delay the migratory movement of European eels by decreasing their swimming speed as they pass over the cable (Westerberg and Lagenfelt, 2008), although there was an effect it was short lived and the authors determined it to be of minor significance. In the skate study, although there was variability in the power level, there was insufficient replication of different power levels to undertake a robust analysis of the behavioral effects of the associated variable EMF. The analysis of high and low EMF zones did however indicate that the skates responded differently in areas where the EMF was higher. As cables in the future will transmit greater power levels it is recommended that any future studies are designed to assess how the behavioral responses are affected by increased power and associated EMF. Particularly, since higher EMF will potentially enter the upper range of detection and may cause a shift from attraction to avoidance in EM-receptive animals (Kimber et al., 2011).

An EMF has two attributes of particular relevance from a biological perspective: (1) the level or intensity of the field encountered by the animal, measured in  $\mu\text{T}$  for the magnetic field and  $\mu\text{V/m}$  for the electric fields; and (2) the frequency (Hz). This study used a putative magnetoreceptive species, the migratory American lobster and the electroreceptive Little Skate to determine if there was any behavioral response to encountering the EMF associated with the CSC. The experimental study showed that both species had a demonstrable response to the EMF. When exposed to the EMF that was within the range of biologically relevant intensities, they moved throughout the enclosure. Significant differences in behavior and distribution of both the animals (compared to the control) were associated with the presence of the EMF. Neither of the species showed spatial restriction in their movements and at the power levels transmitted, the cable did not act as a barrier to movement.

Inside the enclosure with the EMF emitted from the cable, the skates and the lobsters used the central space differently than when in the control enclosure. Both species freely moved within the enclosure and lobsters were more active in the central space. The increase in lobster activity was associated with being, on average, closer to the seabed, and lobster exhibited a greater proportion of large turns compared to their activity in the control enclosure. Furthermore, the lobsters were recorded more frequently and spent more time away from the edges of the enclosure within the central space. The skates were also found to be generally more active and this activity was across the whole treatment enclosure, shown by more large turns, greater distance traveled at a slower speed, and being closer to the seabed. Additionally, the further distance traveled and more frequent large turns were shown to be associated with the zone of higher EMF ( $>52.6 \mu\text{T}$ ), where they also spent more time. The EMF may have been perceived as either a cue for the presence of food in the case of the skate, or an orientation cue to the lobsters. In a free-ranging situation it is expected that both lobsters and skates would have their movement affected to a degree when in the

vicinity of a cable, but that the cable would not be a barrier to them crossing (at the power levels of the Cross Sound HVDC cable in this study).

When considering the animals' response to the EMF, the assumption is that the lobsters were using the magnetic field component (as taxonomic relatives have been shown to respond to changes in magnetic fields; Lohmann et al., 1995), and the skates were using either the electric field, or the magnetic field, or even both field components. The finding that the HVDC cables also have an AC component to the EMF increases the complexity of interpreting the responses of the skates recorded in the enclosure study. In terms of the EMF from the DC cable, it is expected that the skates detected the magnetic field primarily through induction of electric fields within their bodies' electrosensory apparatus. The induction is caused by the movement of the animals through magnetic fields (as occurs in most elasmobranchs), although recent studies suggest that elasmobranchs may also have an ability to detect magnetic fields directly (Anderson et al., 2017). The significant behavioral response by the skates in the enclosure study (Section 5.0) demonstrates that they responded to the EMF emitted by the cable.

However, there was also a presence of an AC field to consider. The AC electric field in particular was considerable, and well within the range of electric field levels known to attract other benthic elasmobranchs (i.e. E-field 0.5 to 1000  $\mu\text{V}/\text{m}$ ). The study was not able to determine whether the skates were responding to either the electric, or the magnetic field component, or both. It is presumed that since the primary sensory mode in elasmobranchs is electroreception, and the behavior of the skates was consistent with area restricted electroreceptive foraging behavior, the response recorded was linked to the significant electric field emitted by the cable.

## 7.2 Considering effects and impacts

In 2010, Boehlert and Gill highlighted that the objective of many studies is to determine if an anthropogenic activity has an impact on a species of interest. However, the majority of these studies actually show a direct or indirect response or change in the animals (defined as an effect) rather than either a biologically, or ecologically significant change, which for example would affect the species population vital rates (defined as a true impact). The key to determining if the responses demonstrated in Section 5 have potential for biologically significant consequences requires consideration of the biological importance of the behavioral effects recorded and their repeatability through time.

For both species there was no evidence of the cable acting as a barrier to movement. Taken in the context of an HVDC power cable with a maximum power transmission of 330 MW there appears to be no significant effect that would be deemed an impact for lobsters – they were closer to the seabed, increased their turning behavior and were distributed differently in the presence of EMF, but without being confined within an enclosure, the expectation is they would move freely past the cable.

For the skates the determination of the effects of an encounter with the EMF were interpreted as attraction responses, which are consistent with benthic elasmobranch foraging behavior. The significantly larger distance traveled (up to several km more within the EMF) and the greater number of large turns exhibited could represent an increased energetic expense. However as they generally moved at a slower speed and were closer to the seabed at that enclosure the skates were likely to have been shifting from a swimming to a punting mode of movement, which is less energetically costly (Di Santo and Kenaley, 2016) and associated with feeding movements (Koester and Spirito, 2003). If the skates were attracted to the EMF because they associated it with prey items, then a biological impact could occur if the net energy expended is higher than when not encountering the cable EMF.

In the context of free-ranging elasmobranchs encountering a single cable, they will likely respond as if the EMF represents potential food. However, if they do not obtain any prey (i.e. energy input), then they would be expected to move on and search elsewhere, since they are able to learn if an EMF represents

food, but only if the EMF is consistent and predictable (Kimber et al., 2014). The implication in this case, is that there is a low likelihood of significant biological impact associated with a single cable with a constant EMF. However, this interpretation will only hold if the EMF from the single cable is predictable otherwise learning becomes difficult (Kimber et al., 2014). In the case of the EMF measured in the present study, it was shown for both HVDC cables to vary spatially along the length of a cable (as a consequence of cable properties and burial depth), and at different times due to variations in power generation, and/or electrical transfer. In this scenario where the EMF is inconsistent, the elasmobranchs will not be able to learn that there is no prey associated with the cable EMF, resulting in them spending time foraging around cables, but obtaining no food. These outcomes would constitute energetic costs as the animals will expend energy searching with no return of energy intake through consuming prey. There is also the lost opportunity cost of spending time searching and responding to the area where cables are located rather than other more rewarding areas of the seabed. The maximum electric field component measured was at levels that approach the threshold between attraction and avoidance of electric fields found in other species of elasmobranch. If the skates encountered higher intensity fields, then it may lead to some level of avoidance behavior. This scenario would only be considered as a potential impact if avoidance either led to higher net energetic costs, or avoidance of areas important in the life history of the species affected. Further targeted physiological and behavioral free-ranging studies are required to determine the energy and time costs. These should be supported by experimental studies that can also be used to understand species detection ranges and thresholds in relation to different EMF intensities.

The question that cannot be addressed with current knowledge is whether the lobsters and skates would respond in a similar way to each cable encountered or higher powered cables in the future. The EMF measurements highlight that other cables have comparable EMFs. If the altered behavior of the receptive animals was quantified in terms of energetic effects as a consequence of being more active whenever they encounter a power cable, then there is a potential for greater energy expenditure. However, in the case of lobsters, which move over several km's during their migrations the encounter with a single HVDC cable with constant power (i.e. constant EMF intensity) would be regarded as a minor impact from an energy expended perspective. For the skates, which have more restricted movement and are attracted to the EMFs, there is the potential for a higher ecological cost if the response consistently occurs on each encounter with the cable. In both cases the behavioral and physiological consequences of the time and energy costs during all EMF encounters should be assessed in relation to the expected normal time and energy expenditure.

### **7.3 Future outlook**

In the future, more subsea cables (both HVDC and HVAC) with higher power ratings and multiple configurations will be deployed in the marine environment. Therefore, the findings in the present study, which were primarily associated with a single HVDC cable, promote the need to build on the multidiscipline approach to assist in assessing the implications of deploying more cables with the associated greater EMFs. The modeling and field measurements provide a clear approach to understanding the EMF emissions in the future and also have the advantage of enabling scenarios to be examined prior to decision making and investment. These scenarios will require further knowledge to draw from when interpreting the biological relevance of the EMFs. The experimental method using the field-based enclosures, while challenging represents a feasible, repeatable study method that provides robust data. By taking into account the lessons learned in the present study there is clear potential for applying the method in the future. It will be particularly useful to increase the number of paired sites by moving the enclosures to different sites along a cable, and to different cables. The finding that the EMF varies in line with the amount of power transmitted and also along the physical route of the cable prompts the question of how variability in EMF emissions affects the EM-sensitive species. Therefore, the interpretation of the results from future enclosure studies can be more generic since the animal responses can be quantified at different sites along the cable and at different cables. Additionally, using enclosure

studies, it would be possible to assess the ability that responsive species possess to learn or habituate to the anthropogenic electromagnetic field by monitoring responses of individuals to repeated exposures. However, although the enclosures worked well for the study of small benthic animals, larger and/or pelagic animals would be less suited to this type of study due to space and depth restrictions. Additionally, enclosure studies do not allow for the assessment of the likely EMF encounter rate of naturally free-ranging animals. The behavioral response, such as that demonstrated in lobsters and skates in this study, must be considered in conjunction with the likelihood of an encounter. For this reason, there is a need to support these experiments with free-ranging studies for sensitive species to understand if their natural spatial movements are affected. Collectively, with consideration of the current location of cables and projected increased frequency of cable deployment in the sea, the range of encounter probabilities for species and likely response can be explored, which will then be able to be incorporated into environmental risk assessment of the potential impacts on species of concern.

While the behavioral studies conducted in this project provided clear evidence of a behavioral response when receptive animals encountered the EMF, the evidence for a biological impact of a single HVDC cable under the conditions observed in this study would most likely be assessed as minor. This assessment was based on the cable not representing a barrier to movement, but causing a relative change in activity in the cable zone with associated higher energetic costs likely for the animals compared with expected normal behavioral activity. In the future when there are more cables installed and of a higher power rating the potential probability of animals encountering the EMF and the variability of this EMF will be important to understand. For this reason, there is a need to conduct enclosure and laboratory experiments to determine what the effects are on receptive species in conjunction with free-ranging studies to understand their spatial behavior at different sites. Based on the EMF measurement studies, it is evident that for both HVDC and HVAC cables magnetic fields and the associated electric fields have to be taken into account. Therefore, to address the question of an impact on receptive species within future scenarios of subsea cable deployment, there is a need to apply research and modeling methods that collectively consider; the specific cable characteristics, the maximum electrical current and its temporal variability, the location of other existing cables, and the projected increase in the number and type of cables being planned for deployment to determine the encounter probabilities for the species. If taken together with the current population status of the species, its ecological role (e.g. major predator), and the potential likely response within the population, then the impact of EMF from subsea cables will be more explicitly addressed. This approach would be a significant improvement over current environmental assessments that use the lack of data and knowledge to suggest that there is either no, or very little potential impact.

## 7.4 References

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**APPENDICES: Included as a separate attachment.**

**Appendix 1: Field Plan and Comments**

**Appendix 2: Dive Plan**

**Appendix 3: IACUC Documentation**



### **The Department of the Interior Mission**

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.



### **The Bureau of Ocean Energy Management**

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.

### **The BOEM Environmental Studies Program**

The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.

# **Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables**

## **APPENDICES**

March 2018

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## **Appendix 1: Field Plan and Reviewer Comments**

## I. Introduction

This document represents Deliverable H of contract M14PC00009 between BOEM and the University of Rhode Island, entitled "Electromagnetic Field (EMF) Impacts on Elasmobranch (sharks, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables." The purpose of this document is to present the Draft Field Survey Design, which details field operations and protocols for the project's 2015 field season. Elements of the plan extend into a short field season in 2016.

## 2. Field Survey Plan of Long Island Sound Cross Sound Cable and Neptune Cable

### 2.1 Survey Overview

The location of the Cross Sound and Neptune cables is illustrated in Figure 1. Examples of previously-collected geological and geophysical data that will be leveraged as supporting data for the survey are shown in Figure 2. We are currently attempting to locate similar data around the Neptune cable route.

Measuring EMF in the marine environment is relatively well established. The majority of scientific studies have focused on low-frequency phenomena (below cycles per day) and especially EMF induced by ocean flows. Our team (co-PI Sigray) has considerable experience studying such phenomena. In these studies the effect of anthropogenic induced EMF is regarded as noise and not dealt with. However, the technique has been proved to operate in higher frequency bands (mHz to kHz) and can, thus, be used for establishing EMF levels associated with subsea cables. A bottleneck already identified is that measuring electrical fields requires specially made equipment particularly for sensitivities within the range of biological relevance. For this reason, most studies have been addressing magnetic fields (B-fields). Estimating the magnetic fields generated by cables depends on the cable type, configuration and materials. The electric current will directly scale the magnetic field, so stronger currents will induce stronger magnetic fields. A simple rule of thumb is that more conductors in a cable give rise to weaker fields because the magnetic field generated by the individual electric currents cancels out some of the emitted field. Other factors that influence the generated magnetic fields are the magnetic properties of the armouring of the cable and the helicity (twisting) of the conductors in a cable; the extent of the magnetic field depends on both these factors. It is the direct magnetic emission from subsea cables that is within the range of detection by receptor organisms. In addition, the magnetic field induces electric fields in the sea water and seabed as a result of water movement and/or organism

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movement through the field (i.e. electromagnetic induction) and these induced electric fields are within the range of detection by electro-sensitive animals.

With this in mind, a necessary precursor to studies of the impacts of EMF on marine organisms is a detailed field characterization of the EMF generated by a strategically located HVDC transmission cable. The Cross Sound Cable is a 330 MW HVDC electrical transmission cable that connects the grids of New England and Long Island, NY (Figure 1 and 2). The cable is buried subsea and runs from New Haven, CT to Shoreham, NY. We plan detailed surveys of this transmission cable using the URI Saab Falcon ROV and Meridian Ocean Services Innovatum 3 cable and pipeline tracker shown in Figure 3 to stay on the cable. After the ROV surveys are completed, a high-sensitivity EMF sensor developed by co-PI Sigray will be used to measure the EMF generated by the transmission cable in experiments described in a subsequent section. At some points the sensor will be taken to control sites away from the cable to measure ambient (background) EMF in the study area. Furthermore, the sensor will be stopped at sample points over the area to collect data from a static position, thereby enabling EMF decay to be quantified. (These measurements can then be compared with EMF modeling).

We would also note that co-PIs Gill and Sigray recently completed tests, sea trials and study deployment of our EMF sensor package as part of the European Commission MaRVEN project at the Belgian wind farms in the North Sea. The sensor was used in three modes: (1) Static on the seabed, deployed from the research vessel; (2) drifting, which meant it was hanging 5-10m below a zodiac or Rigid Inflatable Boat (RIB); and (3) dragged using the sledge/ski frame that co-PI Sigray developed. In this study, we will be able to detect the subsea export cable by either dragging the sensor over it twice, or using the ROV sensor and marking the cable.

In addition, URI will map the habitat types located along the cable route using a Teledyne Benthos C3D interferometric sonar system that provides both bathymetry and side scan sonar data.

These studies will be done using the URI R/V Shanna Rose a 42' survey vessel shown in Figure 4. In addition, URI will provide a 24' Northwind Marine RIB (Rigid Inflatable Boat) with twin 115 HP Evinrude Motors as a support vessel. The support vessel will be provided at minor cost to the project. URI will provide captains and survey scientists and Meridian will provide sufficient personnel to operate the Falcon ROV with fitted instrumentation packages. The Meridian personnel will include one ROV pilot and one ROV technician. These personnel will integrate the required instrumentation with the Falcon ROV prior to the start of survey operations. Integration will require customized mounting and power supply and communications wiring from subsea to topside. A data management system will be designed for the real time review and post processing of cable survey information.

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Transmission cable and EMF surveys will be done by the URI/Meridian ROV/vessel crew. The ROV pilot technician and the URI captain will collaborate on operating the vessel. The total length of cable to be surveyed is 24 miles, or approximately 21 nautical miles. Assuming a survey speed of 0.3 knots to gather the required high-resolution data, 70 hours of on-cable surveying is expected. Equipment setup and calibration time will be determined upon the acquisition and familiarization of said equipment and will be performed and documented each morning before survey operations begin.

We also propose to do a more limited survey of the 660 MW Neptune transmission cable that connects Long Island to New Jersey. The purpose of that survey will be to acquire field measurements that can be used to help validate our EMF model predictions (co-PI He) for a higher capacity cable. At present, we are funded for a transect day across Long Island, one day of ROV survey and a day of SEMLA studies.

## 2.2. Survey Equipment

- *R/V Shanna Rose:* The Shanna Rose is a 42' Westmac lobster boat outfitted for research. It has a 15' A-frame and winch with a capacity of 5000 lbs, a removable 10'X 6' geophysics lab, and two tanks for the storage of live organisms. It has a separate pot-hauler winch and a pole-mount for the Teledyne-Benthos C3D and an Applanix POS-MV navigation motion sensor package. This vessel is very well set up for geophysical surveys, ROV surveys, and studies that utilize live organisms.
- 24' Northwind Marine RIB (Rigid Inflatable Boat) with twin 115 HP Evinrude Motors as a support vessel during net pen deployments. This vessel is flexible and has a low freeboard and can essentially be used as a stable float to emplace sections of the net pens for assembly and disassembly during deployment and recovery. It can also be during the EMF surveys to deploy the Sigray EMF sensor package.
- *Saab Seaeye Falcon DR ROV:* The Falcon DR ROV is a 1000m depth rated highly capable vehicle for light inspection, intervention and monitoring tasks. The ROV can be fitted with a variety of instrumentation packages including high-resolution acoustic imaging probe and scanning sonar. The Falcon's high power and compact size make it an ideal vehicle for work in confined, high current situations. 6400 lumens of variable intensity LED lighting are designed to tilt with the camera mechanism, ensuring ideal illumination in low light conditions.
- *Innovatum SMARTRAK Pipeline and Cable Tracker:* The Innovatum SMARTRAK is an evolving line of submarine cable and pipeline location, tracking and survey tools. It offers passive magnetic, active AC and active DC tracking techniques in a single unit allowing the user to easily change modes without re-configuring the system. It is designed for fitting to ROVs, AUVs and towed bodies. Despite its compact size, the system can achieve higher levels of accuracy and stability than previous magnetic

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tracking tools. This system requires 17-75 VDC power and communicates with the surface through RS232/RS485.

- *High Resolution EMF Sensor:* Co-PI Sigraay has a long history of developing sensors for measuring EM fields under water and a sensor package called the Stockholm-Electro-Magnetic-Low-Noise Apparatus (SEMLA), has been developed for such studies. The high resolution sensor basically consists of a three-axis electrode that measures the field in the three orthogonal directions. The sensor is also equipped with a fluxgate magnetometer that allows for a simultaneous measurement of the magnetic field. The sensitivity of the sensors is high. Electric fields down to nV and magnetic fields sub-nT can be measured. The signal is often limited by natural background fields or the anthropogenic field diffusing from populated areas. The SEMLA will be mounted on a sledge and towed by the URI RIB or can be deployed in stationary mode on the bottom.

From the initial full length survey we will determine the sections of the cable where the experimental study will take place, based on how representative the EMF is within similar benthic habitats. We will also subsample these sections at different times and tides to assess the variability in the EMF within the water. Reference measurements will also be taken in seabed areas with similar characteristics but a few hundred metres away from the cable. The power generation data from the Cross Sound cable company will be correlated with the cable EMF measurements to assess the variability in EMF with cable transmission. These data will be important for calibrating the model and ensuring the modeling reflects the actual environment. These data will be stored and saved in a digital format for post-processing and replication.

### **2.3 Summary of EMF and field data to be collected**

EMF is measured by current density via a flux gate magnetometer and conductivity or direct measurement of electric field by the three-axial electrode sensors discussed above. Measurements include:

- Ambient EMF – Both magnetic and electric fields
  - the Earth's magnetic field and variations (ionosphere) will be established
  - tidal induced (Motional induced Voltage)
  - magnitude and orientation of EMF generated by any identified distant sources
- Measurements
  - sources of magnetic fields (on-site magnetometers)
  - sources of electric fields (on-site three-axial electrode systems)
  - frequency content of induced fields from electric devices will be established
  - magnitude, orientation and geometry
  - intensity of field/magnetic flux density

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- local ambient E-fields in relation to cable route(s)
- stray E-fields outside the periphery of the area
  
- Cable related EMF
  - emission along cable (DC)
  - induced E-field along cable (AC)
  - decay with distance from cable (perpendicular to cable DC and AC)

Other co-variables to measure/determine:

- Cable design, material and characteristics
- System design of turbines and power plant
- Applied voltage/currents
- Power production of individual turbines as well as total production of plant
- Current velocity
- Timing of switch on/off
- Time series of transmission and determination of variability (concurrent with field measurements of EMF)
- Sediment properties (affect EMF-propagation)
- Water conductivity and temperature

#### **2.4 Detailed Approach to ROV Surveys**

*Pre-Dive and Launch:* Before the ROV is deployed, the pilot and deck crew executes a series of checks. These checks ensure proper operation of all ROV functions including lights, thrusters, cameras, tilt and sonar systems. Upon completion of the pre-dive checks, the ROV will be launched. The Saab Seaeye Falcon is fitted with a stainless steel lock latch mechanism that is disengaged by a tag line, allowing for efficient and safe launch and recovery operations via a A-frame or davit. The deck crew maintains constant communication with the ROV control shack to pay out or recover tether. This communication is critical to reduce the risk of tether snags and damage to the ROV.

*Underwater Inspections:* The ROV pilot will navigate to the cable using the Innovatum cable tracker. Once over the cable, the ROV will be flown at an approximate speed of 0.3 knots over the cable as the sensor gathers data. The altimeter included in the Innovatum package will allow the pilot to maintain a constant distance off the bottom to increase the quality of

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the survey data. Limited data will be reviewed in real time as the survey progresses to verify all equipment is working properly. A USBL tracking system will be used to track the position of the ROV allowing the survey vessel to move along the cable at the correct speed. The tracking system will also be used to document the end of a day's survey operations to ensure no gaps are formed and minimal overlap occurs. The Swedish EMF sensor will be towed on a sled 3 m behind the ROV.

*Recovery and Post Dive:* Upon completion of inspections and surveys, the ROV will be recovered to the surface. As with launch procedures, communication is critical between the deck and ROV control van. Tether is recovered as the ROV ascends and when at the surface, the lock latch is used to recover the vehicle. The vehicle is visually inspected and stowed or prepared for the next dive.

### **3. Electromagnetic Field Measurements**

The electromagnetic field (EM-fields) will be mapped for the Cross Sound and Neptune cables. Co-PI Sigray will perform high-resolution measurements which will be used in the study of behavior change of three EM-sensitive marine species, and for comparison with the Meridian EM-field measurements performed by Meridian Ocean Services. Sigray will use the Stockholm-Electro-Magnetic-Low-Noise Apparatus (SEMLA), which consists of a three-axial fluxgate magnetometer and a three-axial electrode system mounted on a sledge-like structure (Figure 5) The wet weight of this unit is approximately 70 kg and the size 1 x 1 x 1 m. The SEMLA's external surface is made out of plastic to avoid disturbing the electric field, and the entire system is constructed of non-magnetic material to avoid disturbing the magnetic field. The SEMLA will be deployed from our research vessel using an A-frame. In water, it will be handed over to the RIB. The wet part of the SEMLA is connected to an electronics unit via a sensor cable (Figure 6). The electronics unit will be located in a wooden box of size 1 x 0.6 x 0.5 m (Figure 7). The sensor system is powered by a 12 V battery, which has to be recharged every evening. FOI will supply all equipment except the batteries and the chargers. The singular deployment rope is attached to the red ropes on the sensor platform (Figure 5), which will be equipped with a hard shell buoy that will be used to stretch the ropes to avoid entanglement. A surface buoy will be attached to the deployment rope for retrieving the sensor platform (see Figure 6).

#### **3.1 Ships and RIB**

In this document the ship (Shanna Rose) is a vessel with an A-frame that can handle 100 kg. A 24' RIB will be used to tend the SEMLA for the EMF-measurements. Due to the weight and momentum of the SEMLA it should be deployed and retrieved by the Shanna Rose. After initial deployment the deployment rope is transferred to the RIB.

#### **3.2 Risks related to EM measurements**

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There is a risk that the SEMLA can be broken while performing the EMF measurements. The sensor platform may tilt on the seabed while being pulled. This risk is estimated to be small to moderate. To prevent this tilting from happening, a surface buoy is attached that will dip into the water when the SEMLA tilts. The risk of damage to the power cables is negligible since the sensor system weight is low in water. In addition, the SEMLA will be deployed and retrieved by personnel handling the sensor cable by hand to minimize stress. If the sensor cable did snap, then the sensor system will be retrieved using the connection to the surface buoy. If the sensor system is entangled in for example cobbles and not recoverable, then divers will be used for retrieval. Our crew will include certified research divers and appropriate dive gear will be on board the Shanna Rose.

### **3.3 Other Risks**

Risks related to deck gear use, A-frame and over-the-side operations will be discussed and mitigated by the responsible people on-board (captain and chief scientist). The EMF sensor platform has been used before and there is considerable experience on how to deploy the SEMLA. The electrical system that will be placed in the RIB is powered by 12 Volt batteries. There is a small risk that the electronic equipment placed in the RIB could become damp or wet and then the data acquisition could be disrupted. This risk will be minimized by not operating in rough conditions.

### **3.4 Equipment to be supplied by URI**

Two 12V auto batteries and two battery chargers will be supplied and maintained by URI.

### **3.5 Measurement overview**

*Prime Area 1 Cross Sound Cable (the location of the behavioral study)*

Prerequisite: The location of the cable is known and has been pinpointed by the ROV survey. The area has been chosen to be the prime candidate for experiments on animals. The seabed should be flat and free from obstacles.

1. The SEMLA is positioned on top of the cable (Figure 8). The positioning will be done using the ROV. Data are recorded for several cycles of power changes (at least 3 hours). The measurement is ended with the SEMLA being towed from its position on the cable to a new position away from the cable. OBJECTIVE: To record temporal changes and to record induced electric fields.
2. The SEMLA is suspended over the seabed by lifting it using the RIB. The distance over the cable is established using the ROV. The RIB is positioned upstream and the engines are turned off. The RIB drifts over the cable while the SEMLA is recording the EMF. This measurement is repeated three times (Figure 9). OBJECTIVE: To record spatial changes of the magnetic field and to compare results with ROV measurements and model results.

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3. The SEMLA is deployed on the seabed upstream (approximately 20-50 m from the cable) the RIB slowly tows the SEMLA over the cable while recording the EMF (Figure 10). This measurement is repeated three times. OBJECTIVE: To record spatial changes for modeling purposes and for mapping of the EMF prior to the experiments with animals.

#### *Area 2 The Neptune cable*

1. The SEMLA is suspended over the sea-bed by lifting it using the RIB. The distance over the cable is established using the ROV. The RIB is positioned upstream and engines are turned off. The RIB drifts over the cable while recording the EMF. This measurement is repeated three times. OBJECTIVE: To record spatial changes of the magnetic field and to compare results with ROV measurements.
2. The SEMLA is deployed on the seabed upstream (approximately 20 m from the cable) the RIB slowly tows the SEMLA over the cable while recording the EMF. This measurement is repeated three times. OBJECTIVE: To record spatial changes for modeling purposes.

#### *Area 3 The Neptune cable*

The measurement at Area 2 is repeated.

#### *Area 4 Cross Sound Cable (area where the depth of the cable below the seabed is known to be shallow (near to New Haven Harbor))*

Prerequisite: The location of the cable is known and has been pinpointed by the ROV.

The same measurements as done in Area 1 are repeated.

#### *Area 5 Cross Sound Cable*

Prerequisite: The location of the cable is known and has been pinpointed by the ROV.

The same measurements as done in Area 1 are repeated.

### **3.6 Type 1: Temporal measurement**

The battery and the electronic unit are lifted into the RIB's working area. The sensor cable from the deployed system is lifted into the RIB from the ship. The RIB is positioned near to the ship's A-frame (Figure 11). The SEMLA is deployed from the ship and kept suspended in the water column. The deployment rope is transferred to the RIB and it takes control of the

SEMLA keeping it suspended. The RIB is positioned near to the cable. If possible the RIB is tied to an anchored surface buoy. The ROV is used to adjust the position on the seabed as near to the cable as possible, and the goal is to put it on top of the cable (Figure 8). The SEMLA will record data for at least 3 hours.

### **3.7 Type 2: Spatial suspended measurement**

The battery and the electronic unit are lifted into the RIB. The sensor cable from the deployed system is lifted on to the RIB from the ship. The RIB is positioned near to the ship's A-frame (Figure 11). The SEMLA is deployed from the ship and kept suspended in the water column. The deployment rope is transferred to the RIB and it takes control of the SEMLA while keeping it suspended. The RIB is positioned 20-50 m upstream of the cable. The ROV is used to adjust the depth to 0.5 m above the seabed. The RIB drifts at least 20 m downstream relative to the cable (Figure 9).

### **3.8 Type 3: Sledging 3**

The battery and the electronic unit are lifted into the RIB. The sensor cable from the deployed system is lifted into the RIB from the ship. The RIB is positioned near to the ship's A-frame. The SEMLA is deployed from the ship and kept suspended in the water column (Figure 11). The deployment rope is transferred to the RIB and it takes control of the SEMLA while keeping it suspended. The RIB is positioned 50 m upstream. The SEMLA is deployed on to the seabed. The magnetometer is used to keep track of the bearing of the SEMLA. The RIB drifts slowly downstream and the cable is deployed until approximately 50 m of cable is deployed over board. By holding on to the cable while deploying it will be possible to keep the RIB in place with aft pointing downstream. When 50 m of sensor cable is deployed the RIB is turned around with the cable stretching aft of the RIB. The RIB uses the engine to slowly tow the sledge over the cable (Figure 10). The SEMLA is pulled vertically by lifting it with the deployment rope. If possible the RIB brings the SEMLA back to the first position, then the maneuver is repeated. If it is not possible, then the SEMLA is lifted by the ship's A-frame, and the procedure is repeated.

## **4. Optional Additional Survey of the Neptune Cable**

Our scope of work currently assumes a transit day from Long Island Sound down the East River to the Neptune Cable area and one day of ROV survey on the Neptune Cable and one day of SEMLA studies. One day of survey would characterize about 4 miles of the cable. For modeling purposes it is desirable to have additional data on the higher capacity Neptune Cable. We estimate a fully loaded per day cost of \$9935/day for additional studies. Our work schedule would allow for up to an additional 5 days of survey work on the Neptune Cable. We estimate that we could survey about 35-45% of the total length of the cable dependent on tidal currents and ship traffic. We propose to BOEM to do some additional

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ROV survey and SEMLA studies while we are in the study area. The length of time for any additional survey of the Neptue Cable will be determined by consultation with BOEM.

## **5. Determination of the Effect of EMF on Marine Species**

### **5.1. Introduction**

Our understanding of how marine organisms interact with either natural magnetic or electric fields is poor, but our knowledge relating to anthropogenic sources (e.g. subsea cables) is worse. Current reviews on the topic (Normandeau, et al., 2011) show that there are published cases of EM-sensitive animals responding to EMF sources in the marine environment (e.g. European eel and salmonid movement response to subsea cables, both HVDC and HVAC: Westerberg, 1999; Westerberg and Begout-Anras, 2000; Westerberg and Lagenfelt, 2008). The most convincing studies are those that have attempted to address a specific research question or hypothesis focused on improving the scientific evidence base of marine organisms and their interaction with EMF. This is the approach we propose to take in our research.

The basis of the proposed project is to conduct studies that are specifically aimed at quantify the EMF associated with an HVDC cable (the Cross Sound cable, Long Island) and whether there is any significant response by electromagnetically (EM) sensitive animals to the EMFs emitted.

It is important that the field-based research collects primary data that are appropriate in relation to the biological relevance of the emissions. This biological assessment needs to be considered at two scales; the first is that the emissions may be associated with evidence for an effect or a response (e.g. temporary diversion response from the path of migration by eels on encounter with subsea cables). The second relates specifically to whether the effect actually constitutes a biologically significant impact (i.e. a predictable response that has potential consequences for the species population). Hence, it is necessary to recognize the difference between an effect and an impact when considering how the current evidence base is interpreted. In environmental impact assessment terms this represents the difference between a major or minor impact and whether mitigation should be considered or proposed, caveated by the level of certainty associated with the assessment.

### **5.2. Field Studies Designed to Statistically Detect Effects of EMF on Marine Species**

A potential problem for studies of the interaction between mobile animals and an HVDC transmission cable, like the Cross Sound Cable, is the distribution and abundance of already depleted (i.e. overfished) natural populations in the study area. For example American lobster populations are currently very low in western Long Island Sound. For this reason an approach that utilizes capture, tagging and recapture is unlikely to produce statistically

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significant results. Our proposed general solution to this problem is an experimental approach using a novel design for monitoring enclosures that can be populated with animals and deployed at selected sites along and across the transmission cable.

Prior to the study the scientific review committee will assess the project design to ensure that the net enclosure approach will obtain the scientifically rigorous information required to answer the primary research question of:

- Do EMFs from HVDC cables have a likely impact on marine species movement?

The study will use state-of-the-art acoustic telemetry technology supplied by Hydroacoustic Technology Inc. (HTI), Seattle, WA 98105 USA. The telemetry system will detect the real-time movements in 3-D of individually identifiable animals within an enclosure in relation to an energized section of sub-sea electricity cable. A second enclosure study in a comparable area away from the energized cable will be used as a reference.

#### 5.2.1 *Acoustic telemetry technology*

An Acoustic Tag Receiver HTI Model 290-8 along with six (6) hydrophones, cables and a dedicated computer with installed software will comprise the data collection system. The 290-series system with three or more hydrophones deployed in a line-of-sight array can be combined to measure 2D or 3D positions and provide real-time tag track display during data collection. Detection on one hydrophone confirms the presence of an acoustic tag, but to be accurately positioned in 3-D a tag must be detected by at least four hydrophones (or three hydrophones for two-dimensional (x-y) tracking). As an acoustic tag passes through the hydrophone array, the difference in the arrival time of each pulse is used to triangulate the exact location of the tag, similar to the principle used by Global Position Systems (GPS). In this way, a movement path for each tagged animal will be mapped and can be presented in a three-dimensional display, with an estimated error of between 15-25cm in three dimensions. The system will allow us to determine periods of movement within the water column and time spent resting on the substratum as well as 3-D determination of the actual response at a fine scale.

We will use field-programable tags, which will report their positions once every few seconds in line with the time-scale and resulting position resolution required for the study objectives. For accurate 3-D positions, the ratio between X/Y distances with depth (Z) is ideally 1:1 which we will aim to achieve. However, if the practicalities of constructing and moving the enclosures mean that we may deviate from 1:1, then we will still get good results as the hydrophones can be placed up to a 1:5 ratio with good results. The highest precision position estimates occur when the tags are fully located within the area defined by the hydrophone array. We have taken this factor into account in the positioning of the hydrophones onto the enclosure extremes (Figure 12). Tags can be positioned outside the

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array up to about half the horizontal distance between hydrophones, but the precision will be reduced.

### 5.2.2 *Acoustic Tags*

HTI Model 795LG tags will be used. These tags can provide over 50,000 unique code IDs, and up to 500 tags can be tracked in the same volume simultaneously. For determining appropriate tag size, we followed this recommendation "rule of thumb" of tag weight less than or equal to 5% of animal weight. As an example, for the Model 795LG, this formula converts to a minimum fish size of 90 g. With these tags the Tag ID, ping rate, output power, and signal encoding are all field-programmable with a turnkey system that enables field programming of the tags, sets up the data collection system and will allow us to initially analyze our data in the field.

We will also have a small tag detector, the Model 492-B, that provides a quick "sniff" test that is used just prior to tag release to verify current tag state (activated or in sleep mode).

The data collection is recorded on a field-type computer that is configured for system set-up and testing. In addition, this same computer, along with the Acoustic Tag/Mark Tags software will provide us with a complete data analysis package, with ongoing technical support from HTI.

### 5.2.3 *Experimental Enclosure*

The basic characteristics of the enclosure are:

- A choice chamber – akin to a mouse in a maze
- Easily deployed and recovered
- Multiple site use to enable experimental design to be set up
- Block sections for transport – can be put together at boat side (approx. 3m/10 ft side blocks with 1m height and 5-7m/5-20ft middle chamber with 3m/10ft height minimum)
- Symmetrical shape to allow same use both ends to reduce potential for net/equipment confounding effect
- Short ends increase likelihood of animals moving and encountering the large choice chamber and hence the EMF from the cable (if located on the cable)
- Central chamber allows animals some choice of direction to go – larger choice chamber with greater height over cable axis to capture any depth behavior (z dimension) as well as x and y axis
- Material for construction will be polyethylene piping and joints and nylon web fishing net (8-9cm), with sand/concrete put into the piping to add sufficient weight to sink the structure
- Materials have been sourced and construction will begin during April/May.
- Testing within Narragansett Bay at Meridian's test facilities will enable fine tuning of the enclosure construction and deployment

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- HTI acoustic tracking system hydrophones attached at six points on extremes of enclosure. Cable to the surface where data will be logged onto the field computer set up in a waterproof casing attached to some surface floats.
- Go-Pro camera to record behavior concurrently for verification
- Mesh sides large enough to see through but small enough to retain species (bottom of net will be larger mesh to ensure sea bed is not kept separate (i.e. Fine mesh bottom would be physical separation from sea bed))
- Trap doors either end of each section to allow animals to be put in and removed

Figure 12 shows a plan view of experimental pen that has been designed. Tagged animal(s) shown as X will first be put in a randomly selected end section of one of the arms. The three sections of the enclosure will then be connected together at the sea surface along side of the Shana Rose. The enclosure will then be lowered by winch to the seabed near to the axis of the subsea cable. The project ROV will locate the enclosure directly over the cable using the on board magnetometer and video cameras.

Once located on the seabed over the axis of the subsea cable the animal(s) will be able to move along the arm forward towards the choice chamber (shown by the arrow). Once at the choice chamber the arrow shows the basic directions that the animal(s) can move, 1- Towards the cable, or 2- left or right, all these options represent choices that the animal can take. The hydrophones are to be mounted as close to a cube formation as possible with four hydrophones attached to the enclosure, with two at the top and two near the seabed of the choice chamber section and then one at the far end of each of the arm sections to provide 3-D position fixing for all tagged animals. The animal(s) may stay on the same side of the cable, move up and down it or move over it to get to the other side. A camera will obtain additional behavioral footage of the responses, which will be used to back up the plotted responses coming from the tags.

Once the enclosures have been constructed in April/May they will be assessed over a period of two to three weeks at Meridian's test site within Narragansett Bay, RI, for sturdiness and potential problems such as movement, gaps, effects of tidal regime and fouling. In addition daily baseline measurements of environmental variables will be taken.

#### 5.2.4 *Study animals*

We have made arrangements to source study animals from local stocks via our fisheries colleagues in Rhode Island and Connecticut. For all species we will take morphometric data length, weight and sex within a species to ensure we account for co-variation in the analysis.

The lobster and skate are both benthic species which are most likely to come into contact with the EMF from a buried cable. The HTI ultrasonic tags are relatively small and in discussions with HTI we propose to use the most appropriate for the size of animal and the

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requirements we have in terms of battery life and attachment of tags. All species are more active during dawn and dusk (crepuscular period) and the nighttime (nocturnal period), hence the recording of activity of the animals will necessarily be conducted over a minimum of a 24-hour period.

Once the fish have been tagged the tags will be tested. After the test period the animals will be put into the enclosures and deployed from the research vessel. We propose to put five (5) animals into the enclosure at any one time. These animals will represent a replicate and hence allow the data recording system to obtain data on individual movement and also group related movement. By having more than one animal we are also increasing the likelihood of animals behaving in a normal way as they are often found in loose groups or aggregations. This number will ensure that there are sufficient animals within the enclosure without introducing too many individuals which might result in density dependent confounding factors. We will undertake more than one replication of the experiment per site using similar numbers of different animals from our tagged stock, and we plan to use up to five sites along the cable. These sites will be chosen based on the benthic habitat characteristics being similar and EMF being measured within each of the sites (see Section 3).

In order to determine the number of replicates and hence the number of animals we undertook a standard power analysis to determine the effect of sample size on the potential statistical validity of the results. We have estimated that we would need somewhere around 10 replicates with 5 animals. Based on experience of enclosure studies and also evidence from free ranging animals responding to EMFs we assumed that up to 30-40% of the individual animals would respond to the EMF. We also assumed a 10-20% similarity in response variable at random in the reference enclosure studies. Using 50-70 tagged animals to illustrate (the costs of 50 animals have been factored into the experimental study budget) we ascertained that the statistical power would vary as shown in table below:

% response	Sample size (n)		
	50	60	70
10 v 40	94.6%	97.5%	98.9%
10 v 30	71.1%	78.9%	84.9%
20 v 40	59%	67%	73.8%
20 v 30	21%	24%	27.5%

### 5.2.5 Co-variables

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Tidal information for the local area is available from local sources.

We will attach a current meter and CTD sonde to the cages to ensure we can take into account co-variation.

Seabed characterization and classification according to the predominant habitat type (e.g. U.S. Geological Survey, Coastal and Marine Geology Program and NOAA CMECS) have been accessed and benthic habitat maps are being produced by URI.

#### 5.2.6 *Experiments*

We suggest that a minimum of five repeats of the experiment are undertaken for each species. Each repeat will use up to 5 individuals of a given species which will encounter the EMF from the same cable. A second enclosure deployment will hold the same number of animals but will be away from the cable approximately 100-200m away so that the seabed characteristics are comparable but the EMF from the cable will be well below background and hence regarded as non-detectable. The movement of these animals will be recorded in exactly the same way as those in the cable-related enclosure but using an imaginary line down the centre of the enclosure as the reference point to judge their activity against. The studies will be stratified into day and night.

Repeat experiments will move the study enclosures to the other parts of the cable identified from the initial cable survey by Meridian/URI and FOI and follow the same protocol outlined above. The enclosures will be swapped so that both are used for the cable and the control at some stage, thereby negating any enclosure effects, which although unlikely need to be taken into consideration in the analysis. This swapping of the equipment is regarded as more scientifically robust as the results will not just be associated with one mesocosm and its siting. It will ensure that the project results have wider relevance to the understanding of animal response to sub-sea cables.

Considering the seasonal availability and movements of the animals and the expectation that Long Island Sound may well become low oxygen or even anoxic for a few weeks in August/September we propose that we run the field experiments in blocks (see revised Gantt chart). The first block will be in June/July where we will concentrate on the initial testing and deployment of the full experimental system and use skates as the first focal species. The second block will be July/August where we expect to have a reduce deployment and recovery time following the lessons learnt from the first block. We will conduct the study on the lobster which we understand will be more available in the waters further north in the Long-Island Sound. In the third block we will focus on the eels. The enclosures will have to be adapted with finer mesh to ensure the eels are contained within the enclosure. We propose to conduct the eel study during March/April 2016, which gives us time not only to adapt the enclosures but also obtain the eels during their periods of

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movement. We will also have conducted the main analysis of the other two species during the fall and winter of 2015/2016 hence we will be able to analyse the eel data efficiently once we finish the field experiments.

### 5.2.7 Results – Assessing the significance of observed responses

Our interpretation of the behavioral data will objectively analyze the following:

- Response of animals encountering the cable when EMF is present.
- Duration of any response.
- 3-D spatial use of the enclosure by animals when the cable is present, including any area restricted use.
- 3-D spatial use of the enclosure by animals when the cable is not present, including any area restricted use.
- Rate and path of movement in relation to emitted EMF.
- Depth related movement.
- Interaction between individuals (intraspecific) will also be assessed.
- Any differences in the above analyses will also assess the influence of day and night.

The results will be interpreted in light of the above measured variables. The significance of any difference attributable to the presence of EMF will be assessed in relation to the time and potential energy costs (or benefits) to the fish of responding to the EMF. These aspects are recognized as of ecological significance. Any species specific responses will be assessed in terms of the typical life style of the species. Furthermore, an evaluation of the limitations of the data obtained will be included. The whole assessment will also feed into the consideration of monitoring programs for subsea cables.

## 5.3 Project Data Analysis and Results

An inherent property of animal movement data is that successive records are not independent. For example, the position that an animal moves to will depend on the position that it has moved from and this dependency is greater the shorter the time between position recordings. Such dependence between data is known as autocorrelation and a number of studies have made suggestions of how to reduce the dependency of the data to allow normal statistical analysis to be undertaken (Schoener 1981; Swihart & Slade 1985). However, the suggested methods reduce the sample size and can also seriously alter the biological significance of the data. Animals typically move non-randomly hence any analysis should aim to take this into account (de Solla et al 1999).

In terms of study proposed here, the effect of the previous position on the next position of an animal is regarded as of fundamental importance to the activity data obtained as we are

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interested in the effect of a fixed environmental stimulus, the electrical cable. Co-PI Gill and colleagues have recently been developing a geospatial analytical approach that standardizes the inter position time interval to increase the accuracy and precision of the position fixes. The high resolution HTI tracking system will locate the animals positions at regular, short time intervals, hence we can standardized the time interval between fixes by dividing the distance covered by the time taken to move from one position to the next.

### 5.3.1 *A note on determining impact*

No single study will be able to determine the impact of EMF on marine animals however by recording the response of numerous individuals at the time of migration and movement the results will enable some extrapolation. The approach we will take is that short-term behavioral responses to a disturbance, such as EMF, may become biologically significant if the animals are exposed for sustained periods of time or react to multiple encounters with the EMF (*sensu* Boehlert & Gill 2010). Key to the interpretation of the biological consequences of a disturbance is specifying what constitutes a meaningful response, both at the individual and the population level, e.g. the effects of a disturbance on an animal's vital rates, such as survival linked to food location or ability to breed. We will use our liaison with the fishing community to understand local population status and consider the life history aspects of these relatively well know species. In addition we will classify our interpretation in terms of level of certainty as either low, medium or high.

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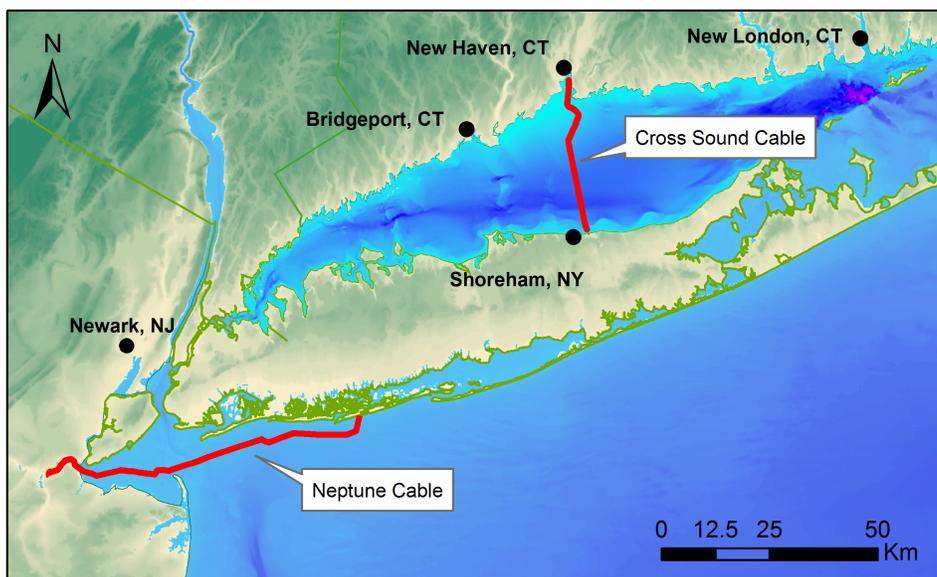


Figure 1. Locations of the Cross Sound and Neptune cables. Cables are shown in red.

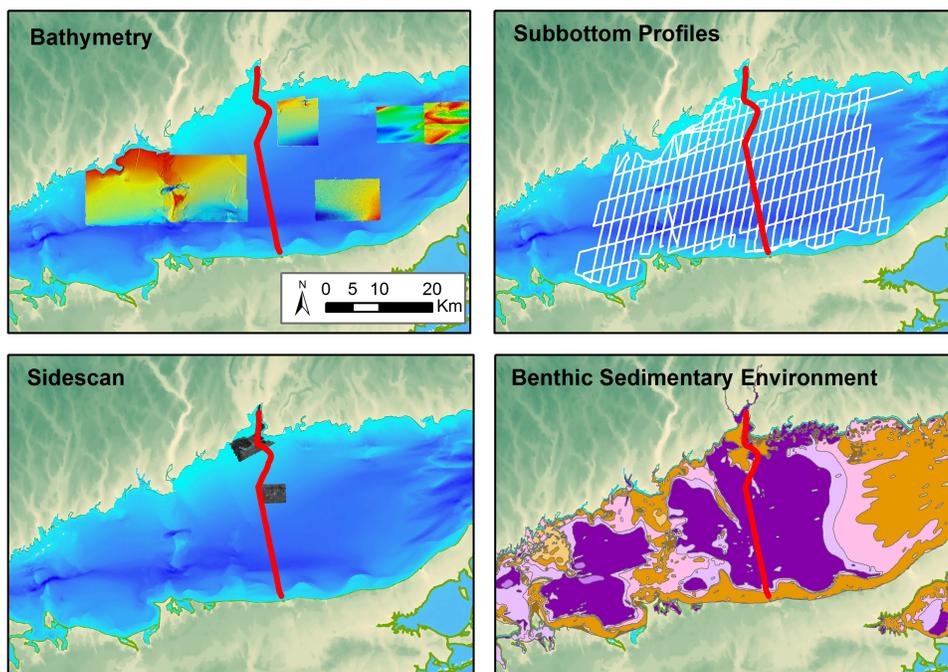


Figure 2. Examples of publicly available data in the Cross Sound Cable area that will be leveraged for as supporting data for survey operations.

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Figure 3. URI Sabb Falcon ROV and Meridian Ocean Services Innovatum 3 cable and pipeline tracker.



Figure 4. Two views of the URI research vessel "Shanna Rose."

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Figure 5. The sensors mounted on a sledge. This unit will be deployed on to the seabed and connected with a sensor cable to the “dry” electronics that will be situated on either the ship, or the RIB.

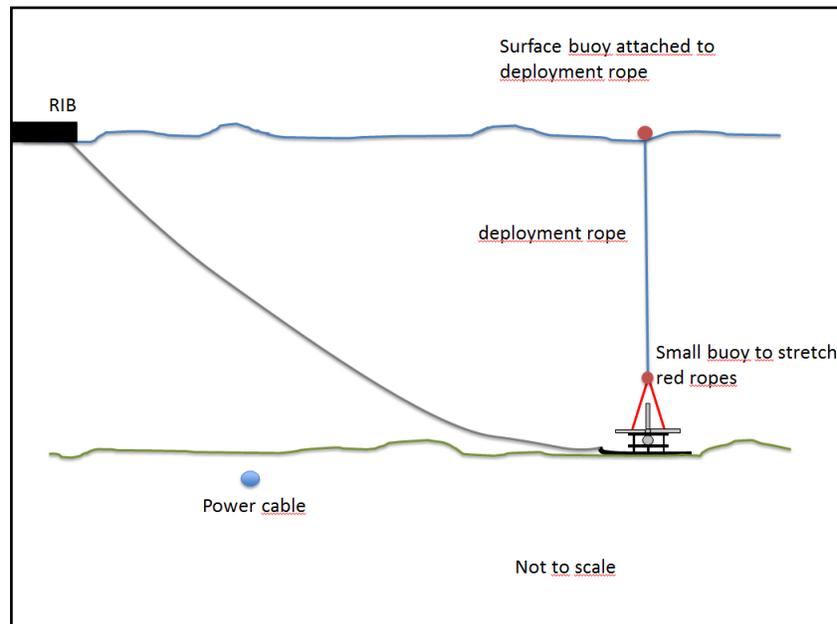


Figure 6. Diagram of the components of the SEMLA.

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Figure 7. The wooden box that contains the electronics unit and recording instruments. Missing in the picture is the cable, which connects the “dry electronic” and the sub-surface sledge shown in Fig. 5.

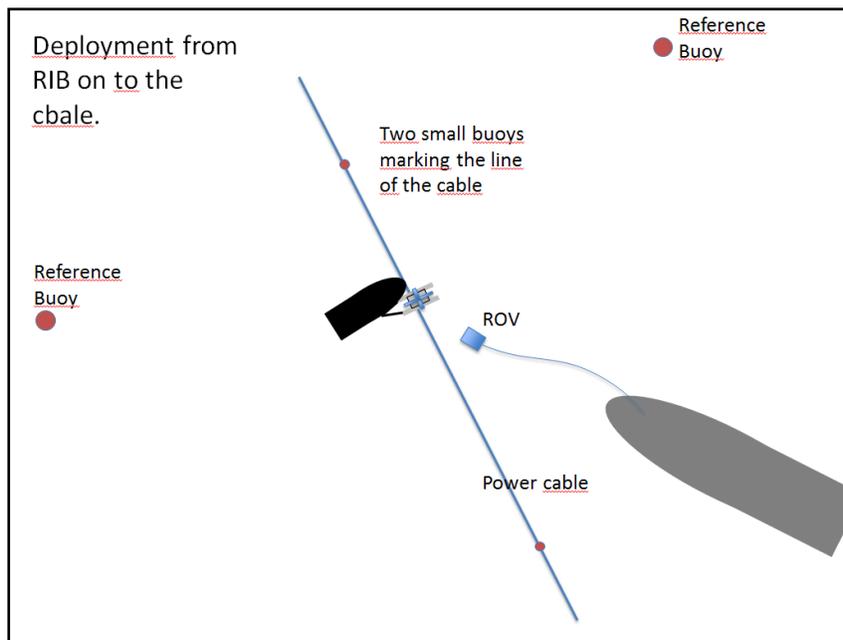


Figure 8. The deployment of the SEMLA on top of the cable. The ROV is used to control the position to be as close to the cable as possible.

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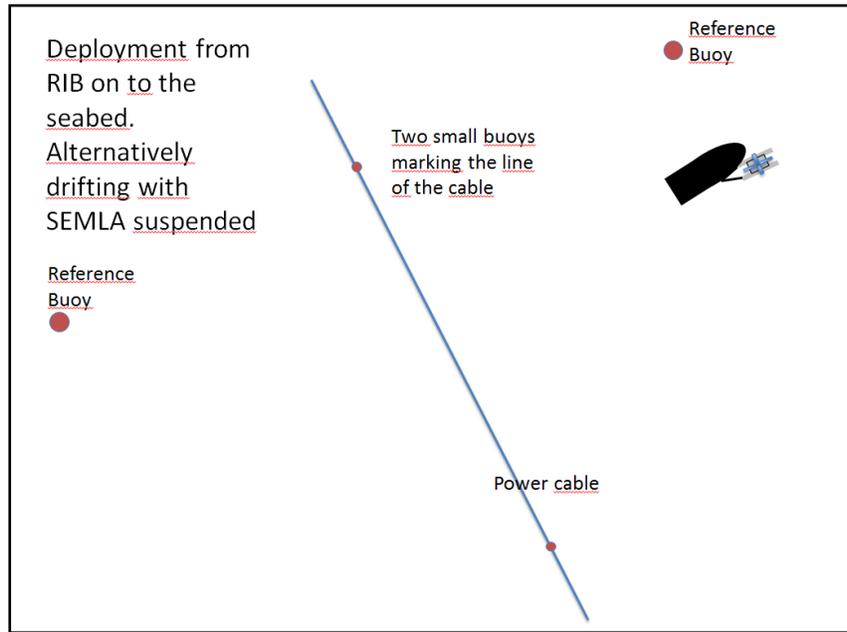


Figure 9. This sketch shows the position at deployment of the SEMLA before sledging and the configuration when drifting over the cable with the SEMLA suspended in the water column.

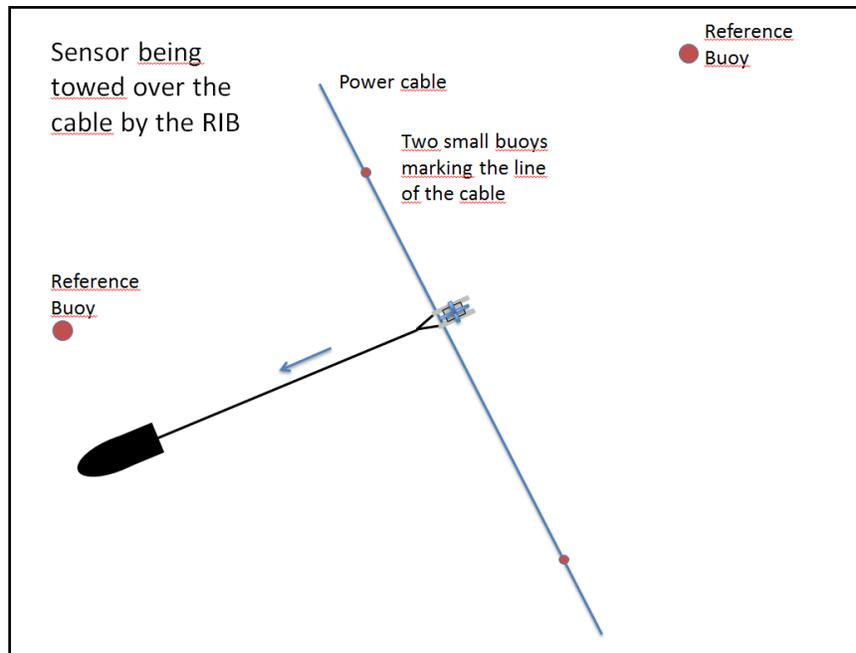


Figure 10. After being deployed on the seabed the SEMLA is towed over the cable by the RIB.

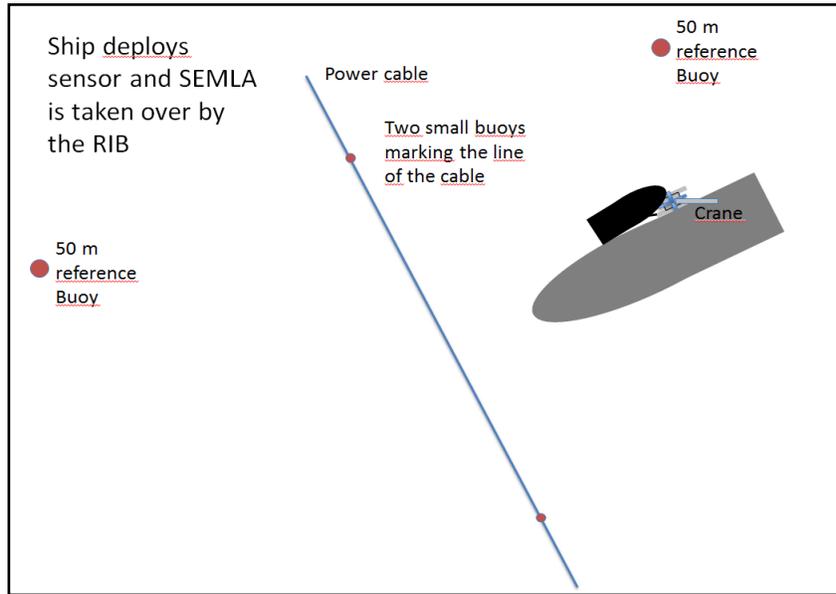


Figure 11. The over-board lifting is done from the ship to transfer the SEMLA to the RIB.

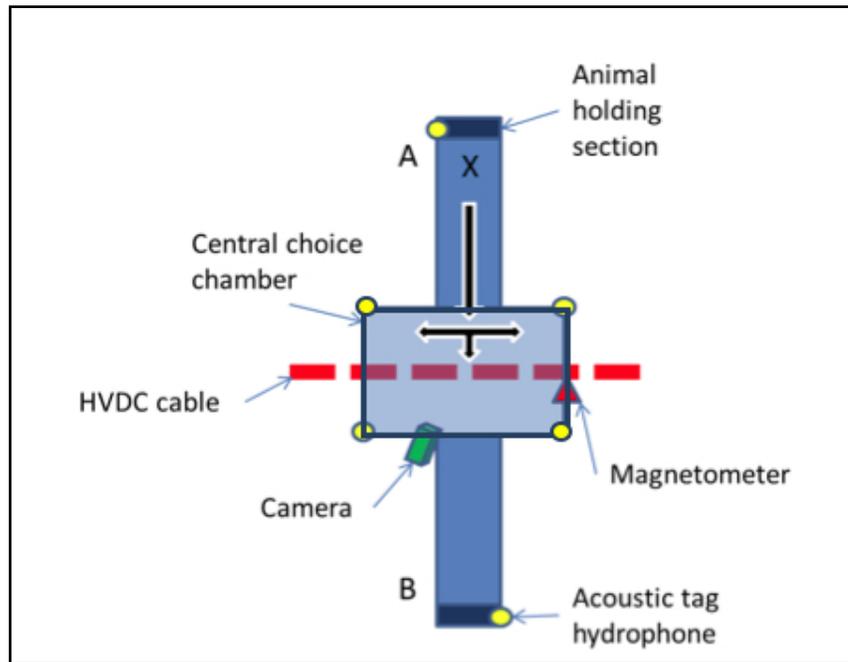


Figure 12. Plan view of experimental enclosure.

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## Response to comments on the field plan

**Reviewer:** Mary Boatman

**Comment:** "More detail needs to be provided on the experimental field plan (pages 13-16) with particular emphasis on statistical experimental design and analysis. The plan does not adequately describe how the different factors in the experiment (e.g. species, site, near/away from cable) will be accounted for and whether any interactions will be examined. In addition, it is not clear what the specific response variable(s) are. The discussion of replicated (Page 15) does not seem suitable, as it is not clear what the treatment combinations are. The [following] text also suggests that two enclosures are being used. If so, it may be necessary include possible differences in the enclosure within the experimental design: "We suggest that a minimum of five repeats of the experiment are undertaken for each species. Each repeat will use 3-5 individuals of a given species that will encounter the EMF from the same cable. A second enclosure deployment will hold the same number of animals but will be away from the cable approximately 100-200m away so that the seabed characteristics are comparable but the EMF from the cable will be well below background and hence regarded as non-detectable."

**Response:** *The magnetic field will be mapped out by the SEMLA before the biological study starts. The magnetic field will be linearly dependent on the current in the cable. The observed magnetic fields will be related to the current in the cable. It will thus be possible to establish the magnetic fields generated by the cable even if the SEMLA is not used. To decrease the uncertainty we will use an autonomous magnetic field sensor to track the changes of the current in the cable.*

*We are planning to use two cages as this should expedite the fieldwork during good field conditions. The cages will be used both on and off the cables as we are interested to see whether the same animals respond differently. The easiest way to do this is to move the cages and the animals onto the cable site if they have been on the non-cable site and vice versa. So if there is any enclosure related effects we can assess for that. It could also be argued that using only one cage is limited as any response could be because of a quirk of that enclosure hence using two is better.*

*In terms of the experimental design, we are using a randomized approach in terms of the cages being placed on cable or off cable and the animals will be assigned randomly too. Also, we need to factor in the sequence of encounter, hence there will some animals that have encountered the cable first and then a non-cable and others that encounter the cable after being away from it. These will be nested levels within the analysis (i.e. cable 1<sup>st</sup> then non-cable or non-cable 1<sup>st</sup> and then cable).*

*Furthermore, as we will know individuals, time of day (incorporating some day and night), and tidal cycle then look to categorize the responses by these variables nested within an overall hierarchical analysis design. By doing this we can then assess the interaction between variables, although the statistical power for looking at these interactions will reduce with the greater number of levels within the hierarchy for a given number of animals.*

*Considering replication we originally stated that we would do a minimum of 5 repeats per site and cover up to 5 sites. Note that a site includes an on-cable and an off-cable experiment as one replicate. Taking into account the comments of the science panel we will reduce the number of sites to two: one where we have determined a high EMF (following the initial cable surveys) and one that is representative of the average EMF along the cable. Depending on the measured*

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*variation in EMF along the sections of cable that we survey and time available, we may include a third site to cover the range of EMF, although we favor more repeats at fewer sites.*

*Within each enclosure there will be 3-5 animals. We will have data on each individual but as they will be together we will have to look at a group as the replicate, rather than the individual animal. However our analysis will be able to look at each individual animal also.*

*The response variables will be as outlined on page 16. We add a bit more detail here:*

- *3-D spatial patterns within the enclosure by animals when the cable is present, including any area restricted use (i.e. movement path, direction, location through time).*
- *3-D spatial patterns within the enclosure by animals when the cable is not present, including any area restricted use.*
- *Rate of movement in relation to EMF or no-EMF (i.e. 3D distance v time)*
- *Path of movement in relation to EMF or no-EMF.*
- *Depth related movement as a function of distance to cable (imaginary cable line).*
- *Interaction between individuals (intraspecific) will also be assessed (i.e. closeness to each other and correlated behavior through time).*
- *The above variables considered by day and night.*

*The response of animals is to be analysed and compared on encountering the cable, when EMF is present and not present. The duration of any response as well as both the 2D and 3D position will be determined to assess the section of the enclosures that the animals are found within (i.e. area restricted or all over) in relation to distance from cable (in 3D). We are scheduled to conduct background tests with the tags, animals and enclosures in Narragansett Bay before deploying them on site at the Cross Sound cable.*

**Comment:** We have reviewed the draft field plan and have no substantive comments. It looks well thought out. I do have one minor comment, should you consider that Cross Sound Cable conducts maintenance in the spring and turns the power off. This could be a good control, but also an issue if looking for a response. I believe this should be mentioned in the field plan.

**Response:** *The SEMLA is at GSO URI and will be available to measure during periods when the Cross Sound Cable is powered off. URI staff have been trained in the use of the SEMLA.*

*We have planned the 2<sup>nd</sup> field season earlier next year, so could investigate the possibility of conducting more detailed studies at that time with lobsters. We could also look more in depth at the day/night question (or other interactions) with a greater number of animals. But it will depend on animal availability and prioritization of the animal species studied.*

## **Reviewer 2: April 22 email from "one of Mary's reviewers"**

**Comment:** "I'm not sure what they are going to get out of 24 miles, especially if the pieces are not done in one continuous run or if pieces are done on different days. It would be interesting to see diurnal/nocturnal variation out of the cables, since one of the species of interest, lobster, are nocturnal. Can you make the diurnal/nocturnal part of the additional work?"

**Response:** *After additional consideration, we agree that mapping the entire cable does not make sense because the logistics of the enclosure experiments dictate that they be done closer to one end of the cable or the other. We know that the cable is shallower at the northern end (New Haven area), and for this reason the EMFs will likely be higher than at the southern end. We therefore now intend to map only the northern 10 miles of the cable and pick our sites within this section of the cable. The diurnal/nocturnal consideration may not be relevant for the magnetic fields because the cable apparently runs at full capacity 24/7 during the summer. The environmental EMF is proportional to the current in the cable. The indication from the cable company is that the current does not vary much during summer but we will know that from our logger and from the log of the cable operations.*

*We agree the day/night aspect has been factored in to a degree from the outset of the study planning. However a case could be made to focus on this specifically in alternative studies next year as focussing on a specific aspect such as day /night then the power of the analysis will increase and aspect such as size of animal, sex or some other influential variable could be included.*

### Reviewer 3: Christopher Lowe

**Overall comment:** "Projects like this are badly needed to address key questions surround biological impacts of underwater power cables. Unfortunately, these questions are very difficult to answer based on limited available physical and biological data, and particularly challenging to measure in the field. Nevertheless, the PIs have provided a realistic experimental design considering the logistical constraints. Due to the inherent complexities and challenges of measuring resulting EMFs from HVAC and HVDC cables underwater and under varying environmental condition and varying current loads, making predictive modeling even more challenging, especially for behaviourally-relevant conditions. I understand that including all relevant information is difficult in the field survey design draft; however, I have a number of questions that may have well been addressed, just not in these documents."

#### Specific questions and comments:

##### Section 2.2

**Comment:** "There is no mention about how much power distribution varies through either cable over time. It is stated that power generation data supplied by the Cross Sound cable company will be correlated with measured EMF from along the cable. How much does this power distribution vary over seasons, diel, hourly periods? When will field measurements of EMFs occur relative to these known periods of power distribution?"

**Response:** *Unfortunately the power distribution does not vary that much during the months during which we will do our surveys. We will be doing our studies at peak or near peak distribution and in theory will see "maximum" biological effects if there are any. We will provide data on seasonal, diel, and hourly variations as part of our study."*

### **Section 2.3**

**Comment:** "Maybe I missed it, but I don't recall seeing any information about how shallow surveys will be conducted? Will they be done up to the shoreline? Also, what about simultaneous measures of salinity and temperature? I assume these may vary depending on depth, and these will likely change field strength measurements in the more dynamic parts of the Sound. These areas may be of particular importance as they form important migratory pathways of some of these animals."

**Response:** *We intend to survey the north end of the cable up to the shoreline. It is possible to do so by surveying the shallows at high tide. However the cable runs underneath the navigation channel in New Haven harbor and it will not be possible to do the enclosure studies in the navigation channel. We anticipate that we will do these studies in 30-60' of water outside of New Haven harbor in the northern part of LIS. We intend to monitor temperature, salinity and oxygen levels using an In Situ sonde mounted above the enclosure. We will also monitor current velocities using a pole mounted ADCP located on our support vessel.*

**Comment:** The methods described to measure EMF and other metrics of field strengths all appear rigorous and useful for modeling. Obviously, the cable survey measurements will vary with tidal flow. Since a continuous survey will take almost 3 days, are there plans to run these surveys during full or new moon periods to capture time of low and high tidal flow rate?

**Response:** *Logistically running ROV surveys at times of maximum tidal flow is not ideal and may not even be possible. We will do what we can but trying to capture high flows is not part of our plan.*

### **Section 3.5 Prime area 1, #1**

**Comment:** Data will be recorded for several cycles of power changes... what are the estimated magnitude of those power changes? Will it matter where along the cable these measurements are made? What is the water depth at these sampling locations?

**Response:** *Burial depth varying along the northern end of the cable and we anticipate that the maximum variation in EMF will be observed at shallow burial depths. The point of the ROV survey is to pinpoint these areas. We anticipate that these areas will be located in 30-70" of water.*

### **Section 3.6**

**Comment:** I'm not sure I understand how this measurement will be made based on the description. The ROV will be used to adjust the position of the SEMLA on the seabed, but preferable place it on top of the cable? I take it the cables are buried? How deep? Also, the SEMLA will be held stationary over the buried cable for 3 hrs? Won't it be difficult to maintain position if there is a surface float with any wind or sea conditions? Are any of these measurements to be made at diver accessible depths (<130 ft)? If so, why not have divers position and weight the SEMLA with sand bags to hold it on station?

**Response:** *The actual depth is unknown but at laying it was planned to be a depth of ~2 m. We know that this depth was not attained at locations along the northern end of the cable. To maintain position depends on tidal current. From our experience in using the SEMLA at the Belgium wind farms it was not a problem to keep it on the seabed. The tidal current was about 1 m/s. The surface float is a small 2 liter float that marks the position of the SEMLA and is used to pull up the sensor system. It should not affect the SEMLA. One option is to slide it on top of the cable (maximum field) with the support vessel and stop when the maximum field is measured. This can be achieved by testing on site.. A second option is to slowly slide it while optically monitoring with the ROV. The position of the maximum field can be marked out with the ROV. Our principal objective is to measure any time variation of the magnetic field as well as the hourly switching of the current inducing electric field, hence we just need to ensure the SEMLA is within a meter of the cable axis. We may use a similar approach to position the enclosures on the cable.*

### **Section 3.7**

**Comment:** It sounds like the ROV will be along for each drift to help the SEMLA maintain the correct depth over the cable area? How far away will the ROV from the SEMLA during measurement? There's a lot of metal and e-fields coming off the ROV.

**Response:** *This statement is correct. The ROV will be used to adjust the depth so that the SMELA goes safely along the seabed. The ROV will also be used to optically estimate the distance between the SEMLA and the seabed at the cable. The actual measurement, drifting or stationary, will be done without the ROV. If for some reason the ROV will be needed while measuring, a test will be performed where the SEMLA is placed on the seabed and the ROV will slowly approach. It will be possible to measure the influence of the ROV and establish the "safe" distance.*

### **Section 5.0**

**Comment:** PIs are aware of many of the challenges and pitfalls associated with making behavioral measurements in the field and value of adequate controls. However, there are a number of issues that may need further consideration or explanation.

It's unclear at what depths these behavioral cage trials will take place? Other than a shaded relief map of the Sound (fig 1 & 2), there are no actual depths of operation provided. In the case of lobster and skate, migratory paths are likely to be greatly influenced by benthic sedimentary composition. In addition, these migratory corridors also tend to be depth specific. Is there any local knowledge of habitat use patterns of these species that may be used to make cage trials more realistic? It would help to know where in the Sound these trials will take place, particularly in reference to benthic habitat and depth.

**Response:** *The depths are around 10-20m depending on the tide. We agree that migratory corridors are potentially important but we didn't make it explicit that we do need to consider these in the discussions about where we will do the studies. Initial liaison with the fisheries community in the area has not revealed any specific migratory corridors in the area that we are to do the studies (i.e. the Cross Sound Cable path coming from New Haven. There is some heterogeneity in the sediment types across the sound but we will be focussing mainly on the sandy/silty areas that we*

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*know lobsters and skates are found moving over in the area (or have been historically when numbers were greater in the case of lobsters). Information from the fisheries community indicates that skates are found all over Long Island Sound. We are also avoiding deeper waters as anoxic conditions that are known to occur in Long Island sound are more likely in deeper waters.*

### **Section 5.2.1**

I'm a little sceptical that the HTI system will render 15-25 cm positional resolution for 2D or 3D positioning. Since this trilateration system typically operates at a ~300 kHz (really designed for freshwater systems) signal output is greatly reduced in SW significantly reducing range. According the diagram in Fig. 12, the hydrophones will be positioned inside the cage (mesh), but without clear line of sight for each. Is the meshing of the cage woven nylon? If so, the mesh material of the cage can trap air and occlude acoustic signals, thereby potential lowering 1) the number of simultaneous detections needed to derive a position, and 2) potentially bias positional accuracy in the main cage compared to the arms. Assuming there is significant attenuation from the cage compartments, what is the minimum positional resolution needed to make accurate animal position to field strength estimates? If the criteria for impact are simply defined as the proportion of animals found to not cross the cable, and the positional accuracy is more like 1-3 m, then you won't be able to tell if the tagged individual has crossed the cable or not. Similar cage experiments using this HTI system have been done in an open subsurface seaped; however, the hydrophones had clear line of sight across a 25 m x 15 m (Rillahan et al. 2009). The proposed cage design may pose detection issues that limit the efficacy of the HTI system. With that said, it shouldn't be hard to measure the actual positional accuracy throughout the experiment cages.

**Response:** *We agree that these positional aspects are very important and understand the questioning of the suggested accuracy. However, we are in close discussion with HTI and we are awaiting confirmation of their predicted accuracy. They have algorithms that they use to predict the accuracy depending on the system set up. The system needs at least 4 hydrophones in clear line of sight for best accuracy. We have looked at the best dimensions for the enclosures with regards to 3-D positioning and have redesigned them such that they represent a cuboid rather than a central chamber with two arms. This means that we will be able to get the most accurate positioning of the animals from the start of the trials and throughout their deployment. We will be doing tests prior to the studies where we will create an accuracy map within the enclosure by placing static tags around in the cage. We will also deploy a tag onto the position of the cable during the tests to ensure we get a measurement of the positional accuracy variability during each experiment trial.*

### **Section 5.2.2**

**Comment:** What are the power output options available for these tags? Because of their higher freq. operation range, power will be an issue even across a 25 m span. Also, for analysis sake I would recommend using all the same size transmitters and output power. If not, range, detection efficiency, and positional accuracy will need to be determined for each trial.

**Response:** *We agree. The tags will all be the same and we will go with the recommendation by HTI for our study design, which we are awaiting. As the cage is not that large they do not see any issue as they normally provide systems that have to operate over a much greater range.*

### **Section 5.2.3**

**Comment:** Why not place GoPro cameras (downward facing) equally spaced throughout the main cage and use the mesh bottom as an additional movement calibration system to compare with acoustic telemetry tracking? While this can only be done during the day and assuming good visibility, it may provide another calibrated movement metric.

Again, it's not clear if the cable is visible from the surface or whether it is completely buried. I would assume it is buried since your control site will just have bare sand/mud/cobble? This is important since many benthic organisms use benthic relief as sign posts for migration and orientation, which may have nothing to do with EMF detection or avoidance.

If the cable is buried, how will the cage be positioned in order to contain movements relative to the cable? Why not mark the path of the cable with a few acoustic transmitters placed on the seafloor? This way, assuming you have good positional accuracy, you'll have a comparable cable position reference relative to tagged animals.

What depths will the enclosures be deployed? It must be in diver depth since that will be how animals will be introduced to the enclosures? Are we talking 5 m or 30 m depth?

**Response:** *We agree about the GoPro cameras. We will add cameras and use them facing downwards. Obviously this will only work with good visibility but we should get some valid data to complement the tagging results.*

*The cable is buried, as far as we are aware. The survey will confirm this. We may also see seabed features consistent with the location of the cable (i.e. depressions in seabed, raised seabed, colonisation patterns of benthic organisms). Using control sites with similar features to the cable sites aims at ensuring we will be recording EMF responses rather than benthic features. We will use the bathymetric assessment to confirm the site similarity.*

*Tagging the cable is a good idea and we will have a tag along the line of the cable attached to the cage. We will use a magnetometer and ROV positioning to ensure we are along the line of the cable.*

*We are not intending to use divers because they will add considerable expense and logistical complexity to the already complex logistics. We will put the animals into the cages at the surface and then lower down the cages.*

### **Section 5.2.4**

**Comment:** How long will individuals be acclimated to the enclosure before experimentation? It would seem that animals first released in the enclosures would first explore the boundaries of the enclosure looking for an exit or will try to hide in or associate with folds in the netting. High

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variability among individuals may make it difficult to separate out artifacts related to stress responses. A 24 hr test period seems satisfactory in accounting for diel differences in movement behavior and may help deal with parsing out stress related movements. This is why acclimation period may be important.

The sample size looks sufficient, but this will really depend on how well these 3 species behavior. However, for another taggable-size backup species, I would recommend *Mustelus canis*. They are more mobile than skate and more likely to provide 3D information on EMF influence. Since they are larger, they can carry a pressure-sensing transmitter, which will provide greater accuracy than 3D positioned receivers over that narrow depth range.

**Response:** *We agree that acclimation is important. During our test period we will look at this for the animals being tested. 24 hrs appears sensible as based on a recent review (Stoner, 2012) in most cases it is considered that biochemical and physiological measures of stress never last more than 24 hours. Also there is a good link to behavioural measures of stress. So we may well be able to reduce the acclimation time through some initial testing that we will conduct involving handling using indices of reflex (such as a scale of strength of aggressive response to handling, appendage responsiveness, tail flicking). The animals will be held in containment tanks for several days prior to the studies so initial capture and handling stresses should reduce.*

*We will also apply the visual based reflex index to each individual when they first go into the enclosures and when they come out so that we can identify particular individuals that may have high levels of stress and we can make a decision whether to replace or not. We will have reserve animals in containment to cover this eventuality.*

*In terms of the alternative species we agree that *Mustelus canis* is potentially a good backup for determining 3D response. However, we have conducted previous work with a comparable *Squalus* species and found that even cages larger than the ones we propose here, were too small to obtain reliable position fixes owing to the greater natural movement of the individuals. With a benthic species we increase the likelihood of the individuals encountering the highest EMF, although they will be less active than more free swimming species and we assume that our cages will have less of an influence on their movement.*

#### **Section 5.2.5**

**Comment:** Will the current meter and sonde be inside the enclosure? This will be necessary to account for net enclosure effects on tidal flow.

**Response:** *We have inexpensive Seahorse current meters that will be placed inside the enclosure in order to record the current acting inside as a potential confounding factor.*

#### **Section 5.2.6**

**Comment:** I like the block design approach to account for seasonal effects and the use of local knowledge for choosing what species to trial when.

At how many different locations and depths will trials occur? Depth may be important factor in terms of migratory path. Fishing data may be useful in knowing what depths and habitat types might provide the best test locations along the cable.

**Response:** *We agree that using fishing/fisheries info is important in the consideration of the right sites to use and we have already used some of this information. We will be reducing the number of sites and will look to keep depth within the migratory corridors, which are considered to be above 30m, and comparable between sites to reduce the potential for depth related effects. As mentioned above we do not have any local knowledge that suggests there are specific migratory routes within the Long Island Sound that we need to be concerned too much about.*

### **Section 5.3**

**Comment:** So what state-space modeling approach will be used to interpolate between measurements? This will make knowing positional accuracy more important particularly in terms of response to EMFs. The biggest challenge I see will be determining whether the telemetry system can resolve a skate or lobster immobile on the seafloor. Jitter in trilateration positioning can result in 1-2 m movements of a stationary tag. This error will need to be factored into the state-space model along with inter-interval detections.

**Response:** *Taking the second point first. We are confident that we can have sub-meter accuracy and are aiming for sub-half meter or less, this has been discussed with the acoustic tag company and reflects their opinion too. As the enclosures are relatively small and we will be using a clear cubic arrangement of the hydrophones the detection probability should be high. In Rillahan et al's. 2009 study, which is the only study we can find comparable, they had detection probability in the high 80's% or better at short time intervals of a few seconds. We will also have two fixed point tags on the enclosure, so we will be able to obtain a simultaneous measure of positional error.*

*When considering the analysis, there will be a coarse level analysis of spatial distribution of the groups of individuals particularly comparing between controls and treatments. In this case we will be using the overall distribution of the animals in an enclosure, repeated with different animals to enable an analysis of independent data (i.e. different groups of animals compared with each other categorised as either on-cable or control).*

*In terms of individual behavioural patterns, we will use our current approach of looking for emergent properties within individuals through sub-sampling discrete periods of movement that can enable a contrast of, for example, near-far to cable on versus no cable. By doing this discrete sampling we will be removing the potential influence of autocorrelation for this analysis of behavioural patterns.*

*In terms of state-space modelling we have not specifically defined the approach as we do not yet know if we will be able to define distinct behavioural states (e.g. foraging versus resting). The data we will obtain will be fine scale in both time and space hence we may be able to see differences in state, such as faster movement aligned along the cable v slow movement away from the cable. However, if the results provide only an indication of change in depth or longer association with the cable than other parts of the enclosure then determining well defined states may be a step too far.*

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*We do however anticipate analysing the data in a hierarchical manner and also assessing the autocorrelation within the data of individuals. If the autocorrelation analysis shows that the previous behaviour has little influence on the subsequent behaviour then we could look at differences in state. The advantage of using a SSM approach is in the extrapolation of the individual data to potential population outcomes. The science of this extrapolation is in its infancy and it generally relates to free ranging animals that have been tagged and then using the data to extrapolate to the population distribution, for example. How appropriate it will be for a cage experiment is not known but something that we will consider in the analysis.*

#### Reviewer 4: Håkan Westerberg

**General Comment:** The expertise of the project staff is broad and collectively they cover most aspects that are relevant for the project. The technical resources and special equipment are also of a high standard.

There is limited technical background information about the cable in the project proposal or the field survey description. It is a HVDC cable with a bundled return cable, but no description about what this bundling means physically, which will determine what to expect about the EMF field. It says nowhere if the cable is buried or laid on the sediment surface. According to information from ABB the cable is burrowed, but it is not clear if this is only at exposed part or the whole route. This information is important for the planning of the sledging operation and the placement of the experimental enclosure.

It is not mentioned in the proposal if institutional or national guideline for the use of experimental animal is followed or permission for tagging has been granted by an ethical committee.

**Response:** *Cable information. The information that we have is that the cable is buried all the way, which is expected given the sedimentary nature of the seabed in the Sound. By surveying with the ROV we will be able to confirm whether there are any places along the surveyed length of the cable where the cable is not buried and on the seabed. Photos have been added from the Neptune cable showing the bundle and the cable configuration.*

*The study is under the jurisdiction of the URI animal welfare and ethics committee. Tagging will follow national protocols for external tagging of animals and with reference to best practice from the tag suppliers.*

**Comment:** There is a question regarding the role of the Scientific Review Board, which is said to also act as a Project Steering Team. What this means in practice is not clear to me.

**Response:** *Mary, we view this as a legitimate question, but we need BOEM's input on the answer.*

**Comment on EMF measurements:** The program for EMF characterization seems on the whole both ambitious and well planned. The SEMLA instrument is described as having a very high sensitivity, but there is no information about what this sensitivity is in relation to the expected noise level caused by

natural fluctuations of conductivity around the electrodes. It is not clear what the real measurement threshold will be in a turbulent estuary as Long Island sound, with large salinity variation.

**Response:** *The electrodes are protected from direct influence of water motion. The sensitivity when drifting was measured during the studies that we undertook at the Belgium wind farms. The observed rms-variation (broadband) of the fields were 0.8  $\mu\text{V}/\text{m}$  and 0.14  $\mu\text{T}$ , respectively. Sliding or static on the seabed it is expected to be better. The expected magnetic fields at full power, i.e. during the summer, are in the range of 20  $\mu\text{T}$  based on the bundled cable separated by 0.2 m, and 1000 A current. This is far higher than the background and comparable to the Earth's magnetic field. The main purpose of the experiment is to measure B-fields since these are present all the time. At every hour the current is regulated and there will be an induced E-field present for a short time; the SEMLA is expected to detect these. We will use carbon fiber electrodes that are protected inside a water permeable protection. The carbon fiber by its nature will high-pass filter the signal with a threshold frequency of 0.01 Hz. We will thus not be disturbed by DC offsetting, which often is the case with Ag-AgCl electrodes.*

**Comment:** There are other points that are unclear in the description e.g. how the sediment properties will be measured and how to keep track of the local variation in the Earth's magnetic field. This must be done at the spatial and temporal scale of the measurements, which, as far as I can see, is not trivial.

**Response:** *The variation of the cable-induced magnetic fields are expected to be higher than the local variations. We will map bottom types using a Teledyne-Benthos C3D interferometric sonar system and groundtruth using the ROV.*

**Comment:** The operation in connection with the EMF measurements with SEMLA is described in great detail, but it is unclear why this has to be made from the RIB rather than the "Shanna Rose", when SEMLA anyway has to be handled by her? In either case I should suggest that the instrument should be put in a starting position downstream of the stretch to be measured and that the boat which is going to make the measurement instead of drifting or towing the sledge should be moored to a fixed, anchored buoy upstream; from where the instrument can be winched in a controlled fashion. This would ensure easy repeatability both for the bottom and suspended transects and probably decrease the risk of snagging and damaging the gear.

**Response:** *The argument for using the smaller support vessel is for the drifting where the influence of the ship structure has to be as low as possible. The Shanna Rose might disturb the magnetic field. The sledging operation is being discussed with the boat crews and might be done in the way described by the reviewer. The suggestion by the reviewer could work and we will keep it in mind. Note that we have decided to use a 22" C-Hawk fiberglass hull vessel rather than the aluminium hull RIB as the support vessel because it proved easier to do the SEMLA transfers with these vessel and it has more space for crew and gear as well as an enclosed cabin for electronics gear/computers.*

**Comment:** In section 3.8 it is mentioned that the magnetometer will be used to keep track of the bearing of the SEMLA. Is that possible when the presence of the cable is supposed to alter the Earth's EMF?

**Response:** *Both the drifting and the sledging will start over 50m away from the cable. In terms of the magnetometer tracking the SEMLA, the crucial moment for the sledging is when placing the SEMLA on to the seabed. The orientation of the SEMLA can be monitored by looking at the magnetometer recording. We want to avoid flipping the SEMLA by monitoring the x, y and z components of the B-fields. When drifting this has no relevance. When placing it on the cable we will either sledge it (then the magnetometer will be used to make sure that it is not tilted) or place it by monitoring its orientation with the ROV.*

**Comment:** There is no discussion of the practical difficulties connected to the tidal currents, which will have about one knot amplitude. This may restrict the opportunity to use full days effectively. Another disturbance is commercial vessels in this heavily trafficked area. This probably will be an even more important problem for the animal study.

**Response:** *The tide at the Belgium wind farm was in the same range and there was no problem with drifting or sledging. That is why we will use a support vessel; to be able to work with the tide and not against it. We will operate from the support vessel since tidal force can be dealt with.*

*We will deploy the cages for multiple hours that will include the tidal cycle. The minimum time for deployment will be 12 hours to get some coverage of day/night but likely it will be a bit longer. We will have tidal records and will look at any correlation between tidal state and animal movement.*

*The enclosure studies will be conducted away from the main traffic lane, however, during the day we will also record any passing vessels in terms of time of day and estimated distance away. We can then look at any correlation with animal position in relation to vessel presence.*

**Comment regarding animal studies:** I have no detailed knowledge of the local biology and fishery of Long Island sound. I presume that the three species selected are characteristic for the area and of commercial value. This is certainly the case for lobster, but if the relatively flat area between Shoreham and New Haven is a lobster habitat is unclear. At least it seems unlikely that skates and lobster will occupy the same areas. The eel are probably restricted to relative a shallow region, say above 20-30 m, which means a rather small fraction of the cable route.

**Response:** *All three species are valuable either commercially or from a conservation perspective or both. The area has historically been fished for all three species too. With Skates and lobsters being commercially fished in Long island Sound itself and eels fished in the estuaries all along the Sound, which they move through to get to/from the estuaries.*

**Comment:** In section 5.3.1 the problem of determining impact is discussed. There is in principle an increasing management relevance of impacts going from the individual level (behaviour alteration, fitness loss, loss of habitat) to impacts on the population level (affecting migration, spawning sites) to the species level (loss of subpopulation, extinction) and ultimately to the ecological level (interactions in the foodweb, including human use). It should have been valuable if there had been a

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deeper analysis of what the possible effects of the cable could be for the chosen species, put into relation to other alternative choices. The sturgeon which is on the red list and probably is electro-sensitive, striped bass which is the most important sport fishing target and the anadromic shad could be considered.

**Response:** *We agree that other species could be considered. However, given the scope and direction of the study the three species were chosen because of their presence in the area and their wider commercial importance, they were also defined in the initial stages of the RFP. We believe that should there be significant findings from this research that indicate a wider potential influence then subsequent studies should be conducted which would then include other species, such as those suggested. Furthermore, species such as Sturgeon have protected status hence it would require a higher level of permissions and licencing in order to work on them. The effort to do this has not been factored into the project resource plan and looking at species that are easier to obtain and work with is better justified in the context of the objectives of the research.*

*We would very much like to be able to extrapolate any findings up the levels from individual to population but as knowledge is so poor just determining if there is a predictable response with multiple individuals is about as far as we can go with the present study. The use of multiple individuals and the individual analysis mean that we will look for emergent properties that will be indicative of a response across individuals that will have relevance at the population level. If State space models are appropriate to the data we obtain then we can assess and apply the most appropriate to extrapolate to population level effects, under a set of well-defined assumptions.*

**Comment:** The proposed method with an experimental enclosure has been used by the team earlier. The maze concept is good in that it allows a large number of replicates and statistical analysis, but has the drawback that the animals are confined in a relatively small enclosure, which could affect natural behaviour. In particular any migration or homing behaviour will be disrupted. As this is the kind of behavior where a magnetic sense is thought to come into play this is an evident restriction when the purpose is to study the effect of an altered geomagnetic field due to the cable.

**Response:** *We agree that the enclosures may have some influence on the migratory behaviour. We have redesigned the enclosures in light of obtaining the best potential 3-D positional fix and also to reduce potential cage effects of having individual contained and not moving. The newer cuboid design allows freer movement from the beginning.*

*In terms of the skates, we believe that disrupted natural behaviour will be less of a potential issue as they are electroreceptive and are likely to be responding to local cues (for feeding or orientation) rather than geomagnetic properties.*

*The lobsters, whilst principally magnetoreceptive have a benthic habit so we are assuming that by studying them during the period when they normally migrate inshore and along the coast and acclimating them to the handling and enclosure-type setting that they will be less likely to be behaviourally disrupted.*

*The eels are more of a risk as they should be free swimming during migration. We will conduct the eel studies in the most appropriate depth of water that is <20m of water. Also with the multiple*

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*individuals and repetition we have look towards increasing the chances of some individuals responding. The biggest potential issue relates to the time of year that the eels migrate back to sea is around October to December, which makes field work highly contingent on the weather and associated sea state.*

**Comment:** The use of several animals in the experimental enclosure. Lobsters are highly aggressive when put together like this, and as a minimum the claws must be tied to avoid that they kill each other. To which extent this will confound the result versus the EMF is unclear. I don't know about skates but as for eels they are not normally aggregating.

**Response:** *We agree that there needs to be consideration of this and we have already done so to some extent. We are looking at putting 3-5 individuals. Any more we believe will increase potential for aggression and other density dependent effects. We could use single individuals however there is also a danger that singles will not move at all. With the presence of one or two others we are aiming to stimulate some kind of movement and that the animals may want to get away from each other and hence move towards the cable. If we use some different sized individuals then the likelihood of movement away from each other will be greater. Also the redesigned cages mean that the individuals will not be contained together, which should reduce the potential for conflict. This then will allow us to use lobsters without their claws tied which we believe may just add another factor to the behavioural response. In terms of Skates they have a tendency to aggregate anyway so we do not see any particular issue.*

**Comment:** The proposal says that different study sites along the cable will be chosen to have similar benthic habitat characteristics. I would think that more information should be obtained by choosing different habitats, or if the purpose is to get many replicates, why move around?

**Response:** *Based on comments from others we will reduce the number of sites. We will chose the most appropriate sites partly based on habitat characteristics and the species, as we don't have to use exactly the same sites for each species. We want to use more than one site to remove the potential for site effects, and also to look at places where the EMF is different intensity.*

*Regarding the second enclosure, placed off the cable as a control, it is important not only that the seabed characteristics are similar but that the orientation is the same. Current direction will probably be the major factor determining how the experimental animals move.*

*We agree that the enclosures need to be in the same orientation.*

**Comment:** This raises another point. Many animals can be stationary for long periods. A lobster may well stay for days where it is released. It could be worth considering introducing some attractant in the maze. This could be bait in the side chamber opposite from where the animal is released (provided that the maze is oriented against the current) or a light or sound source. This may induce a more directed behaviour and give a more distinct display of any EMF effect.

**Response:** *This is a good point. We will either put bait or we may have a light for cameras that could act as an attractant.*

**Comment:** I believe the setup of the eel study will be the most difficult. This will now be made outside the migration season. Migrating silver eels move off bottom, often close to the surface with occasional excursions down. Little is known about yellow eel behaviour at those scales and what to expect, so interpretation of the observations will be difficult.

**Response:** *We agree that this is the study that is the most difficult. We have moved the dates to suit the migratory time too, although the best time to look at migration would appear to be during the poorer weather periods.*

#### Reviewer 5: Jeremy Collie

**General comment:** This is a strong project team comprising experts with a good understanding of electromagnetic fields (EMF) and their effects on marine animals. The draft field plan is well documented and includes contingencies and assessments of risks. The field plan is ambitious, not so much in its scope, but in the number of “moving parts” that need to work together. To the extent possible, these parts should be tested separately to ensure that they will work together.

**Comment regarding measurement of EMF:** Given that the Cross-Sound Cable is already in place, it seems that its type, configuration, and materials are already known (HVDC Cable Details.pdf). Are other co-variables listed on page 5 also known? I understand that modeling the EMF from this cable is part of the project, but it seems that first-order estimates could be made to bound the range of possible outcomes.

**Response:** *An estimate was made based on a separation of 0.2 m and a burial depth of 4 feet. The maximum field is estimate to be about 20  $\mu$ T. We will be measuring or using secondary data to cover the co-variables listed on page 5.*

**Comment:** I understand that the SMARTRAK will be used to track the cable. It is not clear which of the measurements listed in Section 2.3 it will make and record? In other words, which EMF measurements will be made continuously along the cable and which will be measured at specific locations with the high-resolution sensor (SEMLA)?

**Response:** *The drifting over the cable will be done at up to five locations along the cable. The sledging will be done at the selected experimental areas as well as the temporal study of the fields.*

**Comment:** How will the SEMLA navigate to find and stay over the cable? Is this done real-time through the SEMLA sensor cable, or with the aid of the ROV? The protocol for deploying and transferring the SEMLA to the RIB is well thought out. What is the desired altitude of the SEMLA when drifting? Can it be fitted with an altimeter or camera to measure its altitude independently of the ROV? How will EMF decay be quantified when the sensor is stopped at sample points (Page 2)?

**Response:** *In principle the SEMLA will be used in real time to find the strongest B field. The ROV will also locate the axis of the cable to within 1 foot and mark it with a beacon. The current in the cable is regulated every hour so the magnetic field will not change. The altitude is as near to the*

*seabed as possible without damaging the SEMLA. This will be done using the ROV. The drifting over the cable will be at about 1 m from the seabed. At each site this will be done at different depths to map out the field as a function of distance to the seabed.*

**Comment:** I am wary of having multiple lines in the water at the same time given the tides and boat traffic in Long Island Sound. What is the risk of tangling the ROV tether with the SEMLA sensor cable or deployment rope? I think that the ROV would want to approach from downstream, so that it could retreat in the event of unforeseen circumstances.

*Response: We agree that this is a good point. The arrangement of boats and lines in the water is being planned and tested in field conditions, prior to the actual surveys. Part of the time will be spent during the tests practicing to avoid entangling and the potential for damage of the equipment. However, the plan is to handle the SEMLA from the support vessel and the ROV from the Shanna Rose in order to separate cables and ropes.*

**Comments regarding the determination of EMF effects on marine species:** Some aspects of the field design were not clear to me, and might benefit from additional description or clarification.

In the final paragraph of Page 11, “the ratio of X/Y distance with depth (Z) is ideally 1:1 which we will aim to achieve.” Does this relate to the deployment of hydrophones along the horizontal and vertical axes?

**Response:** *Based on advice from HTI the best accuracy would be gained by the hydrophones forming a cube (i.e. ration of 1:1:1, x,y,z). We will aim to get as close to this as possible and have redesigned the enclosures, which still give some constraints to the locating of the hydrophones on the enclosure. We have obtained further advice from HTI on what different dimension arrangements would mean in terms of accuracy and they will work with us to ensure that the equipment provides the best outputs in terms of positioning.*

**Comment:** How will the acoustic tags be attached to the animals? Implanting? Glued to lobsters? Have the IUCAC forms been completed and approved? I think that testing of the enclosures in Narragansett Bay will be critical to their success. Ideally the entire set up should be tested with tagged animals, hydrophones, and cameras to find out how the experimental animals react and behave in the enclosures. Will the camera use ambient light?

**Response:** *The tagging is planned to be external, either through attachment to standard tags, such as dart or Petersen disc –type tags or glued in the case of lobsters. Approval is being conducted through URI.*

*We are awaiting approval our application at this time. We agree about the testing and we plan to do this and replicate as much of the experiment as possible to learn the most we can. We need to carefully consider whether we need to use a light for the cameras, but we do believe that it could act as an attractant so we are not planning to use lights.*

**Comment:** With respect to the statistical power table, the expected response must scale with the strength of the EMF. Is it possible to estimate this before the experiments to fine-tune the experimental design?

**Response:** *The expected response is difficult to determine, as this study has not been done before. Also, the response is not necessarily expected to scale with strength as at lower levels we may get an attraction whereas higher levels there may be an aversion. The knowledge base is so poor that we have to use our best approximation. The power table is really to show that if we get a difference it will be more easily detected if the control response is much less variable between individuals. We hope that it will be then our statistical power will be much better. But it may not be so we need to include an estimate of power in our final analysis to provide the level of confidence in the results.*

**Comment:** Section 5.2.7 lists the behavioral data that will be collected. Section 5.3 explains that animal movement data are inherently autocorrelated such that the number of independent observations is less than the total number of observations. Therefore the methods of analysis need to account for the effect of the previous position on the next position. I guess this is a sort of Markovian or state-dependent process, but it is not clear how this will be achieved beyond the fact that location of the animals will be measured at regular intervals.

**Response:** *As highlighted earlier the data will be collected on a coarse (group) basis and then a finer scale individual basis. For the latter we will sub-sample the data to give discrete behavioural sequences that are independent. Whether this will be a first or second order Markov process (i.e. the behaviour of position 'x' is dependent on the previous position (1<sup>st</sup> order) or on the 2 previous positions) is something that our emergent property analysis takes into account to ensure that we are sub-sampling appropriately.*

**Comment:** How will the on and off-cable data be compared to test for EMF effects? I realize that this is the field plan and that data analysis will follow the field work. Even so, it is useful to think through the entire process to anticipate any required modifications of the experimental design.

**Response:** *The movement parameters (i.e. direction, rate/speed of movement and 3D position) or individuals within an enclosure will be assessed for changes through time and as a function of distance to the cable. This is why we have designed the cages to cover a relatively large expanse of area/volume away from the cable axis. We anticipate any major change in behaviour to be related to the distance from cable axis. We will also look at more coarse scale measures such as group distribution within the cages through the course of the experiment by comparing the control animals with the experimental treatment (on cable).*

**Comment:** I agree with the proposed sequence of experimental animals: skates, lobsters, and eels, as each new species will be increasingly challenging.

**Response:** *We initially ordered the experiments in terms of difficulty, but in response to the comment about trying to study organisms in the appropriate migratory season, we have moved the eel experiment to late this fall.*

## **Appendix 2: Dive Plan**

**University of Rhode Island**  
**Dive Operations & Accident Management Plan**

**DIVE OPERATION OVERVIEW**

**Location of Fieldwork:** Long Island Sound outside of New Haven Harbor, New Haven, CT

**Local Dive Safety Officer/POC:** Anya Hanson/203-258-4479

**Dates of research dives:** TBD – late July 2016; August, 2016; September 2016

**Scientific Dive Team:** (First two divers listed will alternate as Lead Diver)

<b><u>Diver Name</u></b>	<b><u>Diving Program</u></b> <b><u>Email Address</u></b>
David Robinson*+	URI dsrobinson@uri.edu
Joe Mangiafico*++	URI josephmangiafico15@gmail.com
Tabitha Jacobs#	URI tjacobs@nessf.org
Ryan Patrylak#	URI ryanpatrylak@gmail.com
Hillary Kenyon#	URI Hilary.kenyon@gmail.com

*\*Lead Diver will ensure that oxygen unit, first aid kit, dive flag, and cell phone are on-site*

*+Will be present at start of field program and periodically as needed for rest of program*

*++ Will be Second Diver when Robinson is present and Lead Diver when Robinson is absent; will be present for entire field program*

*# Will be Second Diver or Stand-by Safety Diver during diving ops and present as available during field program*

*Three divers will be on site each day – Lead Diver, Second Diver, and Stand-by/Safety Diver. The Lead Diver's communications/strength line will be tended from the dive platform by a dedicated tender.*

**Location of research dives (describe local sites):**

Shallow (ca. 30 ft deep) coastal waters of Long Island Sound just outside of New Haven Harbor, New Haven, CT (see attached map)

**Approximate number of proposed dives:**

We anticipate making 2 dives per day (morning and afternoon) x 2 divers = 4 dives per day

**Estimated maximum depths and bottom times anticipated:**

30 ft; approximately 60 minutes or less per dive

**URI Diving Equipment:**

oxygen unit

**Special Equipment Required** (*being provided by King Lab*):

- OTS Guardian full-face masks (to be used only by divers certified in their use – i.e., David Robinson or Joe Mangiafico when they are acting as Lead Diver) with hard-wire communications to be tended by topside personnel briefed/trained in the operation prior to tending
- 30 cu ft pony bottle redundant supplemental air supply on Lead Diver and Second Diver

**Other Equipment, Boats, etc.:**

- R/V *Shanna Rose* – 42 ft URI research vessel with USCG-licensed captain serving as dive platform

**Any hazardous conditions anticipated and means for addressing them:**

- *sunburn, dehydration, warm air temps*: temperature-appropriate clothing; sun and thermal protection will be worn out of the water as needed; water and cool non-caffeinated/non-alcoholic drinks will be available to keep field team well-hydrated and cool; dive platform has full cabin and enclosed on-deck and below-decks work space to avoid sun over-exposure
- *passing storms*: weather forecasts will be reviewed in the morning by the Lead Diver and vessel captain before daily field deployment and hourly throughout the day; in the event thunder is heard or lightning seen, work will be postponed and shelter sought; work will not resume until 30 minutes after last thunder clap is heard/lightning seen
- *slips, trips and falls*: prior to field deployment of the project, the field team will be briefed by the vessel captain regarding vessel operations, potential hazards, field team will be shown the locations of first aid kits and fire extinguishers onboard, and reminded to move slowly and deliberately while transferring equipment, moving about on board, and entering/exiting the water
- *lifting/transfer of heavy scuba tanks, weight belts and other equipment*: field team personnel will wear protective footwear, lift with their legs, and avoid dropping or banging of scuba tanks, weight belts and other equipment on vessel deck. All equipment will be secured on board the vessel prior to transiting to and from the dive site
- *over-exertion swimming in currents, disorientation due to low visibility, entanglement in enclosure*: (see Scope of Work below)

**Scope of Work (describe what you are doing):**

A large (16.5 ft long-x-12.5 ft wide-x-8.5 ft tall) wood-frame and fishnet-paneled enclosure equipped with underwater video, acoustic tracking instruments and acoustic-tagged marine animals (five lobsters, five skates and five American eels all at different times) is being deployed onto the seabed of Long Island Sound by URI-GSO at two sites. One site is over a buried submarine electric cable located just outside of New Haven Harbor, New Haven, CT, in 30 fsw or less, the other is a site of similar characteristics and depth, but away from the cable (approx. 600-900 ft). The goal of the study is to determine what, if any, affects the cable's electro-magnetic field (EMF) has on the behavior of the different species of marine animals as determined through the tracking of the individual animals' movements in 3D space within the enclosure. The study requires five individuals of a focal species to be deployed and recovered from inside of the enclosure at the beginning and end of each species' observation period (approx. 18- 24 hrs). The most expeditious and safe method for doing this is by fixing the enclosure in place at the site for several days and use a scientific diver to release and recover the animals from within the enclosure via a built in access panel on the side of the enclosure. While diving in an overhead environment with entanglement

risks posed by cables and ropes that are affixed to the top of the enclosure is obviously inherently hazardous, by using a 4-x-4 ft side-door entrance to access the enclosure and with the appropriate level of careful planning and preparation, the inherent hazards can be addressed and managed so that the release and recover tasks may be accomplished safely. This type of diving operation was conducted safely during a similar study undertaken in Scottish waters by UK members of the URI-GSO project team. The dive protocols proposed are as follows:

1) The operator of the dive platform will establish a 3-pt anchor position directly over or immediately adjacent to the project location/dive site. A secure, buoyed downline to the enclosure is then established for the divers to use for their descents and ascents to and from the project. **IT IS ESSENTIAL THAT THE POSITIONS OF BOTH THE DIVE PLATFORM AND ENCLOSURE REMAIN STATIONARY THROUGHOUT DIVE OPERATIONS OR SERIOUS INJURY OR DEATH COULD OCCUR TO THE DIVERS.**

2) Diving operations will only be conducted at slack-tide and with a minimum underwater visibility of 3 ft.

3) Diving operations will be conducted on scuba. The diver entering the enclosure will be either me (David Robinson), the Lead Diver, or Joe Mangiafico, who will serve as Lead Diver when Robinson is not on site. The Lead Diver only will be rigged with a Guardian full-face mask fitted with an umbilical consisting of a 250 ft long ½-inch diameter nylon strength member clipped to a metal clip on the Lead Diver's BCD (both Robinson and Mangiafico are certified FFM divers). The BCD will be equipped with a sharp knife and two pairs of emergency shears for cutting line or netting in the case of unanticipated entanglement in the enclosure. Both the Lead Diver and the Second Diver will be equipped a redundant air supply consisting of a 30-cu ft pony bottle. The umbilical's strength member will have an integral diver-surface hard-wire communications line, as well as an attached self-lit video line to a topside monitor, that will be tended by topside personnel from the dive platform. The Dive Team's Second Diver will tend the Lead Diver's umbilical from immediately outside the enclosure at its door while the Lead Diver is working within the enclosure.

4) Prior to diving, each diver will perform a pre-dive equipment check. Each diver's starting air pressure will be recorded at the surface. The dive team will enter and exit from the same place together. The dive team will inform topside personnel that they are ready to enter the water. Topside personnel will check that the entry area is clear and give the divers the ok to enter the water. The dive team's water entry time will be recorded by topside personnel in the dive log. Communications and video operations checks will be performed at the surface prior to descent. The Lead Diver will inform topside personnel when the dive team is ready to descend to the project. The Lead diver will initiate the descent down the buoyed line going to the project. Topside personnel will record in the dive log the time that the dive team begins its descent.

5) The dive team will descend to the project together. Upon reaching the bottom, they will confirm with each other and with topside personnel tending the Lead Diver that they are ok, whether or not currents and visibility conditions are acceptable for diving, and whether or not they are ready to continue with the operation. Topside personnel will confirm and ask the dive team to either continue with or to terminate the planned dive.

6) The dive team will locate and open the 1-x-1 m enclosure's door that is on the side of the enclosure, ensuring beforehand that none of the experiment animals are in proximity of the door and that none is likely to escape when the door is opened.

7) The Lead Diver will inform the Second Diver that he is ready to enter the enclosure and then enter the

enclosure. The Lead Diver's umbilical will be tended by the Second Diver who will remain outside of the enclosure. Light tension in the Lead Diver's umbilical will be maintained at all times by the Second Diver and by topside personnel during the diving operation to minimize the likelihood of its fouling.

8) The Second Diver will partially close the door to the enclosure to help reduce the likelihood of the experiment animals escaping during their release or recovery. The enclosure door will be either kept open slightly or fashioned in such a way so that it doesn't close tightly enough to prevent free movement of the Lead Diver's umbilical. The Lead Diver's umbilical's path to the Second Diver will provide the Lead Diver with a directional reference and help guide him back to the enclosure's door and the way out of enclosure upon completion of the release or recovery task.

9) The Lead Diver will recover or deploy experimental animals from within the enclosure. Skates, eels and lobsters will be released from a nylon mesh bag. Skates and lobsters will be recovered using a net or by hand and placed into a nylon mesh bag. Eels will be recovered from within the enclosure using a low-powered suction dredge hose that will be deployed to the bottom prior to the dive via a travel-line attached to the buoyed descent/ascent line and brought into the enclosure with the Lead Diver. Recovered eels will be retained in a detachable nylon mesh bag on the exhaust end of the dredge that will be removed by the Lead Diver from the end of the dredge once all of the eels have been recovered.

10) Upon completion of the release or recovery operations, the Lead Diver (still inside of the enclosure) will tell the Topside tender to begin taking up slack in the umbilical and signal to the Second Diver with two quick line-pulls to do the same. The Lead Diver will follow his umbilical back to the door in the enclosure and signal to the Second Diver to open the door. The Lead Diver will hand the Second Diver the mesh bag with the recovered animals in it. The Lead Diver will then remove dredge from the inside the enclosure. Lead diver will exit enclosure with the dredge. The Second Diver will then hand the Lead Diver a second mesh bag with the next set of animals so that they can be released within the enclosure. The Lead Diver will re-enter the enclosure to release the second set of animals. The Lead diver will exit the enclosure. The Second Diver will hand the mesh bag with the recovered animals back to the Lead Diver, and then will close and secure the enclosure door.

11) The Lead Diver will inform topside personnel that the dive team has completed its tasks, that he has exited the enclosure, and that the divers are preparing to ascend back to the surface. The Buddy team will leave the bottom and ascend to the surface together following the buoyed descent/ascent line. The Lead Diver will inform topside personnel when the dive team has left the bottom and begun their ascent. Topside personnel will record this time in the dive log.

12) The dive team will inform Topside personnel that they have reached the surface, are ok, and are ready for assistance passing up the mesh bag with the animals to the dive platform and for exiting the water. Topside personnel will assist the dive team in exiting the water and will record their water exit time in the dive log book. Surface interval time will be monitored and recorded in the dive log book. Maximum allowable dive time for the day's second dive will be calculated and recorded in the dive log book based on the previous dive time and depth and surface interval time prior to making second dive of the day.

## **EMERGENCY MANAGEMENT PLAN**

### **Primary Response**

1. Diver will be removed from water and stabilized
2. Make appropriate contact with victim or rescuers as required

3. Establish (A)irway, (B)reathing, (C)irculation as required
4. Further stabilize the victim
5. Administer 100% oxygen, if appropriate (in cases of decompression illness, or near-drowning)
6. Activate Emergency Medical System (EMS) for transport to nearest medical treatment facility (see map for nearest hospital). Call DAN to assist and track progress of evacuation. Explain the circumstances of the dive incident to the evacuation teams, medics and physicians
7. Call appropriate Emergency Contacts to follow-through with primary response and prepare for evacuation
8. Notify URI DSO or designee
9. Complete and submit Incident Report Form

## EMERGENCY CONTACT INFORMATION

- Nearest emergency medical facility/phone #: **Call 911; Yale-New Haven Hospital 20 York Street, New Haven, CT (11 mins/2.7 miles away) (see attached map)**
- Name of Emergency Transporter/Method of Transport/Transporter Phone #: **Call 911**
  - **Address where R/V *Shanna Rose* docked: 50 Mill Street, New Haven, CT (see attached map)**
- Nearest hyperbaric chamber location/contact information:

### CT

#### **Recompression Chamber, USN Submarine Base, Groton, CT**

Group Two Duty Chamber telephone numbers: 860-694-3676 or 860-694-3929

Duty Medical Officer at Sub Base Chamber: 860-694-2075 Pager: 860/332-4352

**Directions to the USN Sub-Base:** The recompression chamber at the Groton Sub-Base is approximately 50 miles from New Haven, CT; travel time is approximately 55 minutes. Take route 95N, and get off at exit 86. Travel north on route 12. The main entrance into the Sub-Base is on your left, approximately two miles on route 12.

### RI

#### **Wound Recovery and Hyperbaric Medicine Center**

15 Health Lane, Building 2-D

Warwick, Rhode Island

Contact Information: Ricardo Duran @ 401-736-4646

Hours: Monday through Friday 8:00 am to 4:30 pm

24-hour emergency hyperbaric oxygen (HBO) therapy service available

#### **Divers Alert Network (DAN) Contact Information:**

**DAN Diving Emergencies - +1-919-684-4326 or +1-919-684-9111**

**DAN *TravelAssist* for Non-Diving Emergencies - 1-800-326-3822**

**DAN Non-Emergency Diving Questions and all other DAN services +1-919-684-2948**

#### **URI Emergency Contact Information:**

**URI Dive Safety Officer:** Anya Hanson, 203-258-4479

**Local Diving Safety Officer:** Anya Hanson, 203-258-4479

#### **Divers' Emergency Contacts:**

<u>Diver Name</u>	<u>Affiliation</u>	<u>Emergency Contact</u>	<u>Relationship</u>	<u>Emergency Phone</u>	<u>DAN#</u>
David Robinson	URI	Hayley Robinson	Spouse	401-575-1778	1330186
Joe Mangiafico	URI	Salvatore Mangiafico	Father	860-276-7614	281340
Tabitha Jacobs	URI	Paula Jacobs	Mother	860-303-4998	2357016
Ryan Patrylak	URI	Nathan Patrylak	Brother	860-942-0017	2017438
Hillary Kenyon	URI	Patricia Kenyon	Mother	202-848-4612	2414748

**DIRECTIONS**

**URI-GSO TO**

**R/V *SHANNA ROSE* DOCKING LOCATION  
(50 MILL STREET, NEW HAVEN, CT)**

## University of Rhode Island Bay Campus

215 South Ferry Road, Narragansett, RI 02882

### Get on I-95 S in Richmond from RI-138 W

29 min (16.3 mi)

- ↑ 1. Head west on S Ferry Rd toward Tarzwell Dr  


---

0.8 mi
- ↑ 2. Continue onto Bridgetown Rd  


---

1.4 mi
- ↑ 3. Continue onto RI-138 W  


---

14.0 mi
- ↗ 4. Turn right to merge onto I-95 S toward Westerly  


---

0.2 mi

### Follow I-95 S to Hamilton St in New Haven. Take the I-91 N exit from I-95 S

1 h 4 min (71.2 mi)

- ↗ 5. Merge onto I-95 S  
i Entering Connecticut  


---

70.6 mi
- ↘ 6. Take the I-91 N exit  


---

0.4 mi
- ➡ 7. Keep right to continue on Exit 2  


---

0.2 mi

### Take Chapel St to Mill St

3 min (0.7 mi)

- ➡ 8. Turn right onto Hamilton St  


---

0.1 mi
- ↶ 9. Turn left onto Chapel St  


---

0.5 mi
- ↶ 10. Turn left onto Mill St  
i Destination will be on the left  

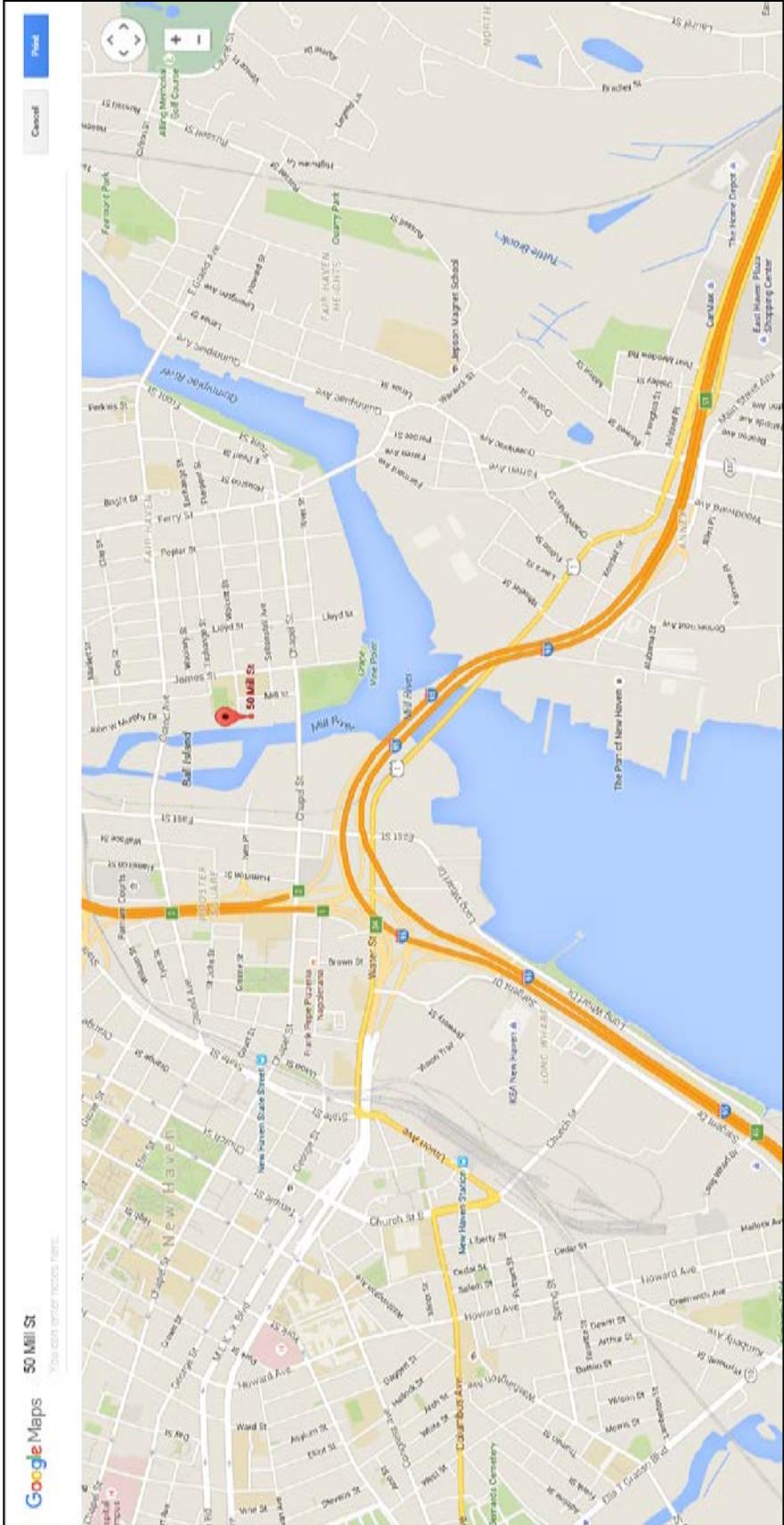

---

0.1 mi

## 50 Mill St

New Haven, CT 06513

These directions are for planning purposes only. You may find that construction projects, traffic, weather, or other events may cause conditions to differ from the map results, and you should plan your route accordingly. You must obey all signs or notices regarding your route.



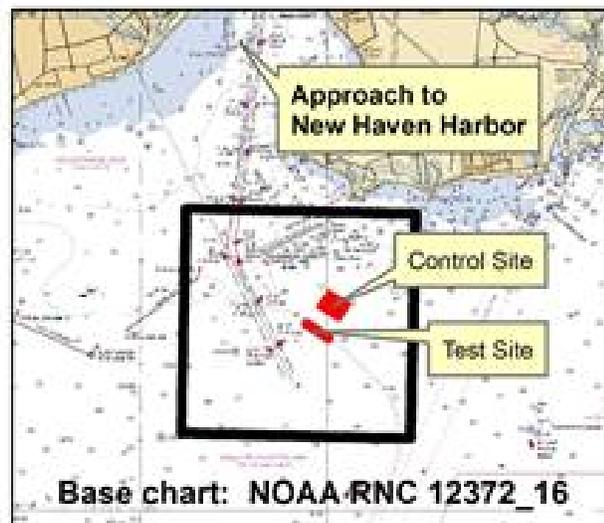
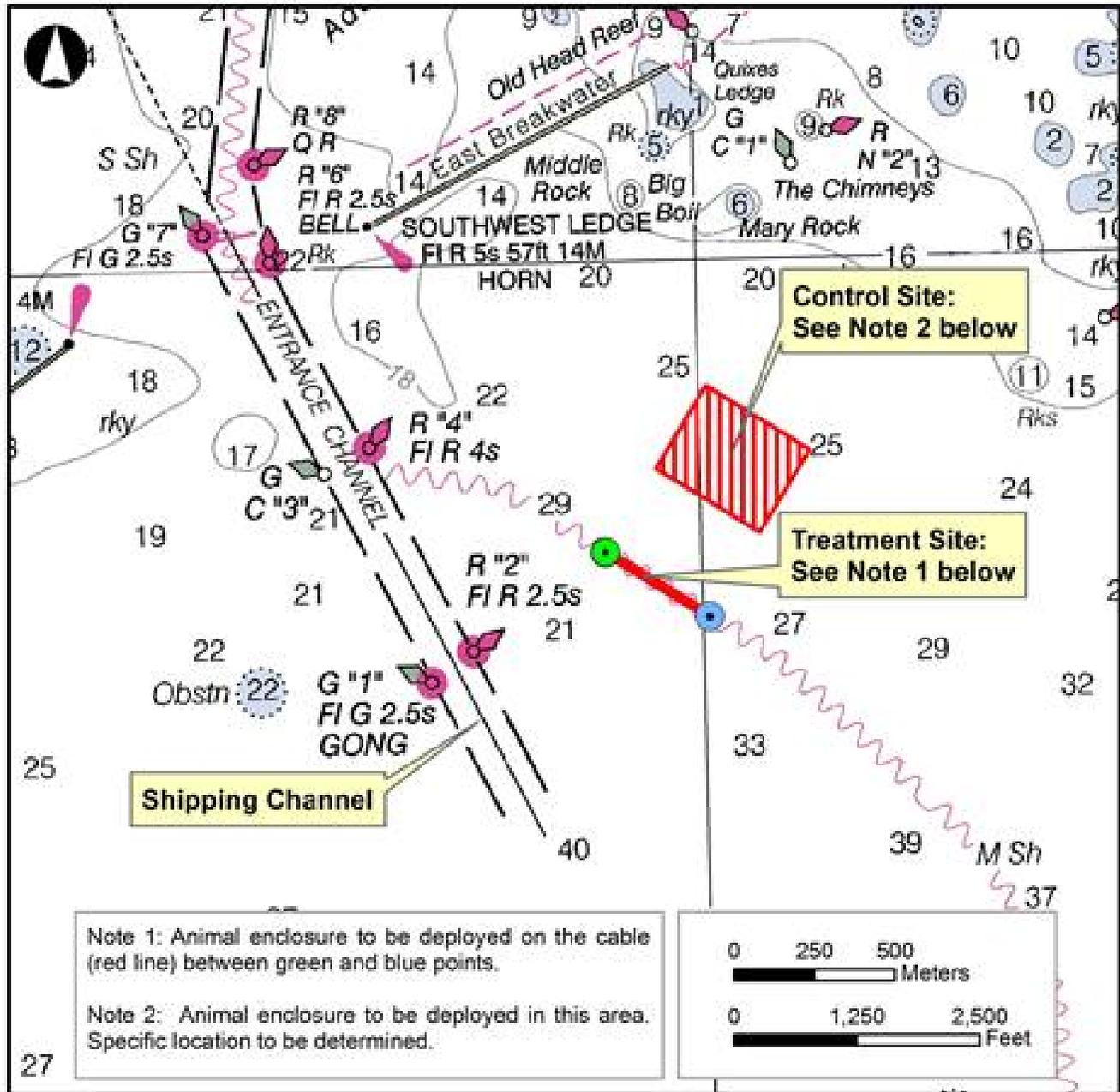
Google Maps 50 Mill St

Your current location here.

Cancel Print

## **DIVE SITE LOCATION**

Proposed Study Areas for Animal Enclosure Experiments  
 Graduate School of Oceanography/University of Rhode Island



**Legend**

- Distance from shipping channel: 1640.4 ft (500 m)  
Latitude: 41.225230 Longitude: -72.903587
- Distance from shipping channel: 2296.6 ft (700 m)  
Latitude: 41.223374 Longitude: -72.899783
- ▨ Corner Points of Deployment Site:

Latitude	Longitude
41.227974	-72.895951
41.225892	-72.897865
41.227542	-72.901648
41.225824	-72.899734

**DIRECTIONS FROM 50 MILL STREET TO YALE-NEW HAVEN HOSPITAL**

## 50 Mill St

New Haven, CT 06513

### Take Chapel St to Water St

- 
- ↑ 1. Head south on Mill St toward Saltonstall Ave 3 min (0.7 mi)
- 
- ↘ 2. Turn right onto Chapel St 0.1 mi
- 
- ↙ 3. Turn left at the 1st cross street onto East St 0.3 mi
- 
- 0.2 mi

### Continue on Water St. Take Union Ave to Howard Ave

- 
- ↘ 4. Turn right onto Water St 7 min (1.6 mi)
- 
- ↙ 5. Turn left onto Union Ave 0.7 mi
- 
- ↘ 6. Sharp right onto Church St S 0.4 mi
- 
- ↙ 7. Turn left onto Columbus Ave 0.2 mi
- 
- 0.3 mi

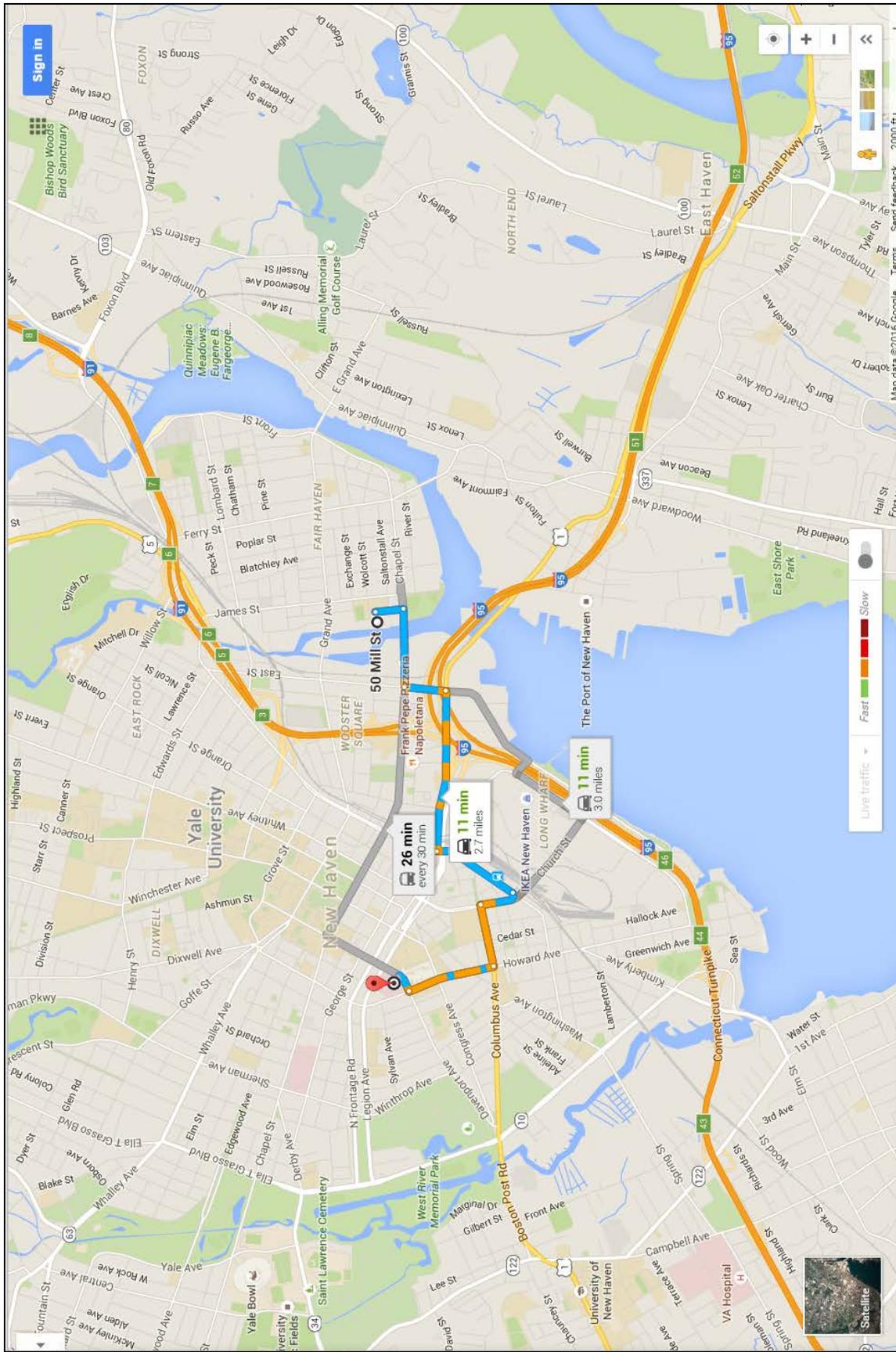
### Continue on Howard Ave. Drive to York St

- 
- ↘ 8. Turn right onto Howard Ave 3 min (0.5 mi)
- 
- ↘ 9. Turn right onto York St 0.4 mi
-  Destination will be on the left
- 
- 449 ft

## Yale-New Haven Hospital

20 York Street, New Haven, CT 06510

These directions are for planning purposes only. You may find that construction projects, traffic, weather, or other events may cause conditions to differ from the map results, and you should plan your route accordingly. You must obey all signs or notices regarding your route.



## **Appendix 3: IACUC Documentation**

The University of Rhode Island (URI) Institutional Animal Care and Use Committee (IACUC) serves as the IACUC for the URI. The use of animals is essential to the teaching, outreach, and research missions of URI. Significant benefits to the health and welfare of both animals and humans have resulted from animal use in research, and continued use is crucial to future advancements. Those who utilize animals in teaching and research are morally and legally obligated to care for them properly and use them humanely. Each faculty member, staff member, or student involved in the use of animals is directly responsible for promoting and protecting their welfare within the instructional, research, and outreach programs of URI. The IACUC is responsible for overseeing the provisions for the care and well-being of animals used for research and educational purposes at the University and serves the public by ensuring compliance with all legal and ethical standards regarding the use of vertebrate animals in research and teaching at URI.

### **Instructions** **Research requiring Registration**

Use this form to register research involving vertebrate animals. Animal use may not proceed until authorization from the IACUC.

### **Form Submittal**

Submit via IRBNet the following:

- This Protocol Document. **Please try to limit your answers to the space provided.** Upload separate document if you believe additional information is valuable to the committee (refer to specific questions you are addressing).
- Any attachments
- CITI certificates for all key personnel (no more than 3 years old)
- Relevant thesis, dissertation, or grant proposals
- Signed Proposal Approval, if part of a thesis/dissertation
- Student Assurance form, if graduate student will be using project data to complete a thesis/dissertation

### **Adobe Forms**

- Check that you have installed the latest version of Adobe Acrobat or Reader. The link to install Adobe Reader is: <http://get.adobe.com/reader>.
- Download the Protocol, Mac and iOS Users, open the file using Adobe Reader rather than the Preview function built into your Mac OS. Windows users, open the file using Adobe Acrobat or Reader rather than using a web browser.
- Save the form once you have entered your information.

### **Training**

All faculty, staff, and students listed on the Protocol must complete the on-line training course at [www.CITIprogram.org](http://www.CITIprogram.org). Register as a new user and choose URI as your institution. Complete Course: Investigators, Staff and Students, Basic Course (Working with the IACUC) and courses specific to the species of animals as described in Section 3 of this Protocol Form. The IACUC will alert you if other training modules are also required.

### **Occupational Health**

All personnel (staff and students) working with animals in research and teaching environments are required to participate in the [URI Animal Users Health and Safety Program \(AUHSP\)](#) prior to working with animals. IACUC approvals will not be granted until everyone listed on the protocol has completed the occupational health requirements. For more information about requirements by species of animal, see the [IACUC Policy on Occupational Health and Safety](#). For most work, listed personnel must:

- Complete and submit an [Occupational Health and Wellness Survey](#) (except those working with fish, amphibians and/or reptiles, or with limited or no animal contact). If personnel have completed in last year, they do not need to submit again. **Do not submit survey via IRBNet. Submit via instructions available on the form.**
- Review training materials available on the [AUHSP website](#) and submit completed/signed training acknowledgement form and health survey (if required) to [researchintegrity@etal.uri.edu](mailto:researchintegrity@etal.uri.edu)

### **Reference Materials**

- USDA/APHIS Animal Welfare Act, [www.aphis.usda.gov/wps/portal/aphis/ourfocus/animalwelfare](http://www.aphis.usda.gov/wps/portal/aphis/ourfocus/animalwelfare)
- The NIH Office of Laboratory Animal Welfare (OLAW), PHS Policy on Humane Care and Use of Laboratory Animals, [grants.nih.gov/grants/olaw/references/phspol.htm](http://grants.nih.gov/grants/olaw/references/phspol.htm) and What Investigators Need to Know About the Use of Animals, [grants.nih.gov/grants/olaw/investigatorsneed2know.pdf](http://grants.nih.gov/grants/olaw/investigatorsneed2know.pdf)

### **IACUC Review and Approval Cycle**

- IACUC approvals involving USDA covered species require annual renewals (to complete, submit an annual renewal form).
- All Protocols must be resubmitted and reviewed every 3 years
- Refer to the IACUC meeting schedule on the URI Research Integrity [website](#) for submission deadlines. **Please submit materials at least three weeks prior to meeting dates.**
- Allow at least 4-6 weeks for protocol review, depending on the complexity of the project.

## IACUC Protocol/Three Year Renewal Completion Checklist

The checklist provided is an optional tool for researchers that clearly defines the requirements for IACUC project submission. Use this to make sure all of the required documents are being uploaded to IRBNet and all personnel associated with your project receive the necessary training.

- Completed New Protocol & 3 Year Renewal Protocol Form. **Please try to limit your answers to the space provided.**
- Upload separate document if you believe additional information is valuable to the committee (refer to specific questions you are addressing).
  - Any attachments relevant to your protocol
  - CITI certificates for all key personnel (no more than 3 years old)
  - Relevant thesis, dissertation, or grant proposals
  - Signed Proposal Approval, if part of a thesis/dissertation
  - Student Assurance form, if graduate student will be using project data to complete a thesis/dissertation
  - Review Animal Users Health and Safety Brochure
  - Review the Allergy Prevention documentation
  - Review animal-specific Occupational Health and Safety training materials
  - Complete the Occupational Health and Wellness Survey (if required) and mail as indicated on the last page of the form. **Do not submit the survey via IRBNet.**
  - Sign the Occupational Health and Wellness Training Acknowledgement form and submit as indicated on the form. **Do not submit the training acknowledgment form via IRBNet.**
  - \*\*If using the **laboratory animal facilities** (e.g., Fogarty, Morrill, Woodward, CLAF, or the Wild Rodent Room), all new users (staff or students) must attend a mandatory facility orientation and tour

**Facility orientation sessions will be offered at the beginning of each month. Participants must email the animal care staff at [ori\\_carestaff@etal.uri.edu](mailto:carestaff@etal.uri.edu) to ensure a spot in the training.**

**NOTE: Animal facility access will not be granted until personnel have been added to the protocol, have completed the Occupational Health Program, and have completed their facility orientation training.**

### Questions?

- Contact the Office of Research Integrity at 401-874-4328 or email: [researchintegrity@etal.uri.edu](mailto:researchintegrity@etal.uri.edu)
- For training materials on IRBNet or the Animal Care and Use Policy, refer to the Office of Research Integrity [website](#)

**Section 1 - Administrative Information**

**REMINDER FOR MAC USERS:** Complete form in Adobe Reader, not the Preview function in MAC OS. Using the Preview function will disable parts of the form.

a. Principal Investigator

b. College / Department

c. Email

d. Phone Number

Check all the responsibilities that apply:  Training Certificate(s) Uploaded  Animal Husbandry  Administer anesthesia  
 Perform surgery  Perform euthanasia  Draw blood/perform injection

e. Project Title

f. Type of Application  New Protocol  Three-Year Renewal  
If renewal, list Protocol Number

g. Anticipated Research Start Date  Anticipated Research End Date

**Funding**

h. Is this project funded or being submitted for possible funding?  Yes  No  
If yes, submit an electronic copy of the grant proposal as part of the IRBNet package

Funding Source  If the project is funded, is the project PHS funded?  Yes  No

Grant/Contract Title

Grant/Contract ID #:  Proposal Submission Date:

**Permits**

i. Will you be conducting any activities for which a permit is required?  Yes  No  
If yes, submit an electronic copy of the local, state or international collection permit as part of the IRBNet package

**Collaboration**

j. Does this project involve collaboration with another institution?  Yes  No  
If yes, submit an electronic copy of IACUC approval from the other institution as part of the IRBNet package

**Use of Animals in Teaching**

k. Does this project involve use of animals in teaching?  Yes  No  
If yes, list instructor, department, course number and title, and years and semesters course will be taught.

Students working with live animals must, as part of a course, complete CITI training. Instructors are responsible for retaining CITI certifications.

**Section 2 - Personnel**

List all personnel associated with the project

a. Co-Investigator

Name  Department   
 Email  Phone Number

Check all the responsibilities that apply:  Training Certificate(s) Uploaded  Animal Husbandry  Administer anaesthesia  
 Perform surgery  Perform euthanasia  Draw blood/perform injection

b. Student Researcher(s)

Name  Name   
 Email  Email

Check all the responsibilities that apply:  Training Certificate(s) Uploaded  Animal Husbandry  Administer anaesthesia  
 Perform surgery  Perform euthanasia  Draw blood/perform injection

Will this project be used as a thesis or dissertation proposal, directed research, independent study or research paper?  Yes  No

If yes, submit an electronic copy of that proposal/paper as part of the IRBnet package

c. Other Personnel

Name	Position	Responsibilities					
		Training Certificate(s) Uploaded	Animal Husbandry	Administer anaesthesia	Draw blood/perform injection	Perform surgery	Perform euthanasia
Zoe L Hutchison	Post-Doc	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	BSc in Marine Biology, MSc in Aquatic Resource Management, PhD in Marine Science						
	<input type="text"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	<input type="text"/>						
	<input type="text"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	<input type="text"/>						
	<input type="text"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	<input type="text"/>						
	<input type="text"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	<input type="text"/>						
	<input type="text"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Qualifications	<input type="text"/>						

If additional staff are working on this protocol, submit a Personnel Attachment as part of the IRBNet package.

### Section 3 - Training

All personnel actively involved with animal components of the project must be listed in Section 2. All personnel listed on this protocol must complete CITI training modules for animal care and use at [www.citiprogram.org](http://www.citiprogram.org).

All listed personnel are required to complete the Investigators, Staff and Students, Basic Course (Working with the IACUC) **AND** the appropriate species specific training and the post procedure care training (depending on the species utilized in the protocol).

Completion certificates (completion dates within the past three years) are required to be uploaded for all personnel as part of the submission package.

Available modules are listed below. **Check off each of the modules that pertain to your research.**

- Investigators, Staff and Students, Basic Course (Working with the IACUC)
- Post-Procedure Care of Mice and Rats in Research: Reducing Pain and Distress
- Working with Amphibians in a Research Setting
- Working with Mice in Research Settings
- Working with Rats in Research Settings
- Working with Hamsters in Research Settings
- Working with Gerbils in Research Settings
- Working with Guinea Pigs in Research Settings
- Working with Rabbits in Research Settings
- Working With Swine in Research Settings
- Working With Fish in Research Settings
- Working With Reptiles in Research Settings
- Working With Cattle in Agricultural Research Settings
- Wildlife Research

**Students working with live animals as part of a course, must complete CITI training. Instructors are responsible for retaining applications.**

I certify that all listed personnel have completed the required training modules and all applicable certificates are included as part of the submission package.

I certify that all listed personnel have the appropriate experience and have been trained in all listed animal procedures.

#### Section 4 - Animal Care and Use

- a. **Nontechnical description of the project and its potential value.** Describe overall purpose, goals, and significance (e.g., importance to the advancement of scientific knowledge, potential benefits for amelioration of disease) of your project. **Write in layman's terms and limit your response to the space provided.**

The Bureau of Ocean Energy Management (BOEM) has funded URI to do a study of possible effects caused by EMF associated with DC underwater power transmission cables on marine organisms. In some cases EMF can be an attractant to certain marine organisms (sharks and skates) and in other cases may be a deterrent to behavior, e.g. migration. In this study we plan to study animal behavior caused by EMF in the natural marine environment by placing organisms in an enclosure and deploying the enclosure on top of the DC Cross Sound Cable that runs between New Haven, CT and Long Island, NY. The animals will each have a small acoustic tag affixed to them, the enclosure will have an array of hydrophones mounted on it to track the tags, and we will also have several GoPro cameras tracking the animals to validate our acoustic tracking. The enclosure will have several sensors associated with it including a magnetometer to monitor EMF, a sonde to monitor temperature, salinity, pH, and oxygen level, and a current meter will monitor bottom current velocity.

This study will help determine if the behavior of these animals (skates and eels, which are of commercial importance), are affected by EMF. Ultimately, this research will be used to help inform responsible management of the marine renewable energy sector as it develops in the USA and in the broader context, globally.

- b. Describe the rationale for using animals in this research and the appropriateness of the species to be used.

In order to assess animal behavior in this context, live animal specimens must be used. Elasmobranchs are known to respond to electrical fields akin to the signals that their prey produce however their response to EMF from power cables in situ has not been assessed. Little skate are considered a good model species for this family. There is some evidence that eels altered their migratory path in response to underwater power cables however this was not assessed in a controlled manner. In this sense eels are suspected to respond to EMF such as that of the Cross Sound power cable but also represents a model species for migratory organisms.

- c. Justify the number of animals to be used according to accepted statistical principles or other scientific rationale. Power and sample size calculating tools are available at <http://statpages.org/#Power>.

Based on a standard power analysis to determine the effect of sample size on the potential statistical validity of the results, we have estimated that we would need 10 replicates with 5 animals. Based on experience of enclosure studies and also evidence from free ranging animals responding to EMFs we assumed that up to 30-40% of the individual animals would respond to the EMF with 10-20% similarity in response.

- d. Activities involving animals must not unnecessarily duplicate previous experiments. Duplication of previous experiments?

Yes  
 No

If yes, please justify

N/A

## Section 5 - Experimental Design

- a. **Describe procedures that will be performed (use scientific terminology if necessary).** Provide concise description of the experimental design (including treatment groups and appropriate controls), endpoints of the experiments, and the procedure conducted on the animals. Include lab methods only as pertinent to understanding the animal usage and welfare. **Use the additional space provided on the following page if necessary.**

An overview of the experimental design is detailed in the attached document called "Detail for the Coast Guard". This document has some figures which help explain the experimental design and further details such as the location of the field experiments.

In brief, we have built an enclosure which is 5 x 3 x 2.5 m (l x w x d). The enclosure structure is made of wood and has fishing net covered PVC panels attached which will secure animals inside the enclosure. The enclosure also houses an array of six hydrophones which will be used to listen to the precise position of acoustically tagged animals. The enclosure will be deployed on top of a buried cable which will emit a measured electromagnetic field. This will be the treatment site. The enclosure, with the same animals will also be deployed at a control site where there is no buried cable but the bathymetry, depth and seabed type is similar. The deployment at the treatment site and the control site will represent one true replicate. In each replicate, the sequence of the treatment followed by the control or control followed by treatment site will be alternated. There will be no more than five tagged animals in the enclosure at any one time and only one species will be worked with at one time.

There are no concerns regarding abnormal behaviour of the animals in the enclosure since it is 5 x 3 x 2.5 m and 5 animals in this area is a lower density than would be considered normal for animal husbandry. The animals will interact with each other but there will be ample space for 5 animals. In addition, the animals will have been introduced to each other and similar group living conditions in the aquarium.

Between 5 and 10 true replicates will be obtained per animal giving a maximum of 50 experimental specimens of each species. Allowing for spare specimens and the logistical constraints on field studies we specified a maximum of 60 animals.

For each individual animal, the duration of the experiment will be 48 hours. That will be 24 hours at the control site and 24 hours at the treatment site. These will not necessarily be back to back and could be separated by <1-5 days. The experimental period is expected to be a minimum of 11 days per set of animals (i.e. 11 days for skates, 11 days for eels). This may be extended to allow for weather days and other logistical constraints but that would not affect the total number of days in the experimental enclosure.

Prior to the experiment the animals will be tagged with a small acoustic tag supplied by HTI Sonar. Please see the document titled "Supporting Information for Section 5" Figure 1 for a scaled image of the tag. These tags have specifically been designed for being attached to fish in a non-invasive manner. Further details of tagging for each species are provided below. Importantly, the tags are small in comparison to the skates and eels (we have reduced the size of the tags to optimize the animal/tag ratio) and will be streamlined to the animals such that there is minimal disturbance to normal behavior. The ratio was optimised both in terms of length and weight. They are the smallest tag available that was suitable for the project. Larger tags are used for the lobsters but smaller ones were specifically sourced for the skates and eels. Additionally, tags will be attached for a short period of time and will be retrieved immediately after the data has been collected.

We do not intend to sedate or anaesthetize the animals during tagging procedures.

### Skates:

There are a number of suggestions but we need to do some pilot trials to determine the best method of acoustic tag attachment and retention. Initially, we intend to attach the tag by surgical glue directly to the spines on the back of a skate. However this is a new method and the success rate is unknown. There is some suggestion that the mucous produced by the skates might prevent adhesion. A veterinary surgical glue will be used which is designed for wound closure so no adverse reaction to the glue would occur. It is inert to the animals and naturally degrades after several days by which time the tags will have been removed. The glue can also be removed by gentle rubbing with petroleum jelly.

We expect that attachment would be to the spines and the skin, the area was selected since it is a site with less mucous production. We acknowledge that this may not work but if it does it would be quick and efficient including of minimal stress to the animal. We will test this method for efficacy in the aquarium.

A second option is to use Petersen discs inserted through the wing musculature of the skates (see Figure 2 for an example of a tag attached to a flatfish using a Petersen disc that we used in a previous project), which is akin to e

**5a. Experimental Design cont.**

**Eels:**

HTI, the company that are supplying the acoustic tags and tracking equipment have been working on another project with eels and have recommended a saddle which is inserted through the dorsal musculature of the eel and then the acoustic tag is glued or cable tied to the top of the saddle. Please see Figure 3 for an example of an eel saddle. Satellite tags are much larger than the tags we are using. We propose to use the main musculature attachment with a saddle piece across the dorsal fin of the eel which will then allow us to glue the tag above the dorsal midline. Should the saddle prove to be inappropriate then there are several other tag attachment methods we could consider for eels (Jellyman & Tsykamoto, Westerberg, Okland-Westerberg methods), which have been assessed in terms of their attachment longevity and short term behavioral response to the attachment method. Since we are only conducting short term assessments of eel behavior we will in all circumstances aim to reduce any discomfort to the animals. Literature suggests that behaviors indicating discomfort substantially reduce after 3 hours in the aforementioned methods.

The saddle attachment described above is most akin to the Oakland method. Alternatives are the Jellyman and Tsukamoto method which would use three plastic discs. One plastic disc on either side of the muscle would be secured in place using wire and attached to a third disk on the dorsal of the animal to which the tag would be secured. It is similar to the saddle but has a three-point anchorage on the animal with equal tag drag distribution – the tag and discs would still be streamlined to the animal. Another alternative is the Westerberg method which incorporates a three-point anchor system of wire loops on the eel skin. Effectively the tag is held in place by one point but there are two backups should the first fail. Finally, the Oakland-Westerberg method is a single anchor point using a T-bar under the skin for attaching the tag. Each of these methods are used on eels with much larger satellite tags which float above the animal imparting an amount of drag on the animal. The attachment of the much smaller HTI tag would be fixed to the saddle, not floating above the animal and hence be much easier to attach and less of a discomfort for the animal.

**General:**

There will be a minimum of 24 hours between tagging and use in the experimental enclosure to allow the animal to get used to the tag. The animals will be observed during that time for normal/abnormal behaviour which if it occurs we expect will be manifest in the first few hours after tagging based on experience and other published tagging studies. If required (indicated by abnormal behaviour) the time for acclimatisation to the tag would be increased. Due to constraints of weather and other logistical considerations for the project there is every possibility that the time between tagging and experimentation will be increased. During this time, normal husbandry procedures will resume. Food supplied will be high quality fish (e.g. herring, squid) sourced from the local fish supplier and fit for human consumption. An appropriate quantity of fish for the number of animals will be cut into small pieces and added to the water. Animals will be watched to see that they eat (or not, which will be recorded). After ample time (2-3 hours) to allow feeding, the remaining food will be removed from the tank to prevent fouling of the water. This feeding procedure is outlined in section 13c and was devised after consultation with Dr Rebeka Merson. Note that Dr Rebeka Merson supplements the fish food but since our period of animal husbandry is much shorter this is not required. Animals will not be fed 24 hours prior to transportation to reduce the build-up of waste during transportation.

Drs Andrew Gill and Zoe Hutchison have tagging experience. Zoe has most experience with the current HTI tags and surgical glue whereas Andrew has most experience with the Petersen discs and eel saddles. Zoe and Andrew will work together to tag the animals. Currently, Andrew will remain in the UK as an advisory but can be present if deemed necessary. Andrew has 25 years of experience as a fish biologist and tagging fish including surgical implanting of tags into the body cavity of cod and hammerhead sharks, external tagging of skates, catsharks, dogfish, dover sole, and porcupine pufferfish. Zoe has been working with the HTI tags and lobsters for the last 6 months and previously has 5 years' experience as a behavioural marine biologist. Andrew and Zoe both have experience of post tagging behavioural monitoring procedures and handling and transport to field sites both road and boat based transporting.

**5b. If submitting a three year renewal** - Describe any changes from your protocol's most recent approval (original or last renewal), including any amended information between approvals. This will give the IACUC a full description of how your protocol has changed from the last full board review. ***If this is your original protocol submission, skip this question.***

N/A

**Section 6 - Animal Information**

a. Animal Inventory

Common and Species Name/Strain	Source	Animal Use Classification					Total # of Animals per Year	Total # of Animals For Project (planned for next 3 years)
		<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E		
Little Skate; <i>Leucoraja erinacea</i>	GSO Trawl or Deep Water Wind as available	<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E	50-60	1 year only
American eel; <i>Anguilla rostrata</i>	Trap caught in local estuary	<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E	50-60	1 year only
		<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E		
		<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E		
		<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E		
		<input type="checkbox"/> A	<input type="checkbox"/> B	<input type="checkbox"/> C	<input type="checkbox"/> D	<input type="checkbox"/> E		

**Pain/Distress Category: USDA Category under which animal use falls. The URI Attending Veterinarian must be consulted for any animals in Category D or E.**

**Category A** - No live animal contact. This includes field observations and the use of cadavers or carcasses (this is a URI category, not a USDA category)  
**Category B** - Animal use activities that involve only breeding, conditioning, or holding.  
**Category C** - No/minimal pain, distress, or discomfort is associated with the protocol and no pain relieving drugs or treatments are necessary. This includes routine procedures such as blood sampling, short-term restraint, injections, and euthanasia and also includes post euthanasia procedures such as tissue harvesting.  
**Category D** - (Relieved Pain) Pain, distress, or discomfort is associated with the protocol, and pain-relieving drugs, anesthesia, or treatments are provided as part of the protocol.  
**Category E** - (Unrelieved Pain) Pain, distress, or discomfort is associated with the protocol but pain relieving drugs or treatment are withheld because their use would interfere with the scientific objectives.

b. Are any of the animals on this protocol species covered by the USDA Animal Welfare Act?  Yes  No

The USDA Animal Welfare Act covers all warm blooded animals except:  
 (1) birds, rats of the genus *Rattus*, and mice of the genus *Mus*, bred for use in research,  
 (2) horses not used for research purposes, and  
 (3) other farm animals, such as, but not limited to livestock or poultry, used or intended for use as food or fiber, or livestock or poultry used or intended for use for improving animal nutrition, breeding, management, or production efficiency, or for improving the quality of food or fiber.

**Section 7 - Pain and/or Discomfort**

If animals will be exposed to procedures that cause more than momentary or slight pain or distress (e.g., animals listed in Category D or E in Section 6), indicate below the anesthetics, analgesics, or tranquilizers to be used.

a. Use of Anesthetics, Analgesics, or Tranquilizers.

Species	Specific Drug(s)	Dose per Kg Body Weight	Route of Administration	Frequency of Administration
N/A				

b. Describe procedure for monitoring animals exposure to drug?

N/A

c. Describe procedures involving pain or distress:

There may be mild, brief distress associated with the attachment of the tag however this will be minimized by careful handling.

d. If you will perform painful or distressful procedures that will NOT be alleviated (i.e., **Category E**), please provide a scientific justification:

N/A

e. Describe method or means to determine that receiving pain or distress would interfere with results:

All animals will be monitored for behavioral responses to tag attachment. It is well recognized that abnormal behavior due to tag attachment will reduce rapidly as the animal acclimatizes to the tag and can be visually assessed. We will hold the animals, post-tagging for a minimum of 24 hours in the aquarium at URI to ensure the animals will have ample time to recover prior to any further handling.

f. If you expect any unanticipated effects (including pain and distress) of your procedures or stimuli on the animals (e.g. weight loss, fever, poor appearance, neurological deficits or behavioral abnormalities), please describe in the space below. Describe the conditions, complications and criteria (e.g. 20% weight loss, maximum tumor size, vocalizing, and lack of grooming) that would lead to contacting the attending veterinarian or euthanasia of an animal before the expected completion of the experiment.

An injured animal would be isolated from others and the ability to recover assessed based on the severity of the injury. If recovery was an option then the animal would be looked after in isolation if required, to provide the best chance of recovery. Advice would be sought from Dr Roxanne Smolowitz at Roger Williams University or the GSO/IACUC attending vet, Gordon Brackee. Should the animal need to be euthanized, the protocol outlined in Section 15b would be followed which has been updated to include cervical transection as a secondary confirmation of euthanization. Once the animal is confirmed dead or if an animal was to unexpectedly die, the carcass would be disposed of by placing it in a bag and putting in in the trash thereby preventing its entry to the food chain.

**Note:** if any unanticipated effects not described below occur during the course of the study, a complete description of those effects and any action taken in response to them must be communicated to the **Attending Veterinarian** and the **Research Integrity Office** immediately. The **Event Reporting Form** must be submitted to the Office of Research Integrity within 72 hours.

### Section 8 - Animal Husbandry

a. Preferred location of animal housing (include building and room #): Room 205, Marine Science Research Facility, Graduate School of Oceanography

b. Will your protocol require any of the following specific housing or husbandry conditions that deviate from normal Animal Facility SOPs for feeding and housing?

- |  |   |   |
|--|---|---|
| <input type="checkbox"/> Sterile cages     | <input type="checkbox"/> Special bedding  | <input type="checkbox"/> Food regulation  |
| <input type="checkbox"/> Wire bottom cages | <input type="checkbox"/> No bedding       | <input type="checkbox"/> Water regulation |
| <input type="checkbox"/> No enrichment     | <input type="checkbox"/> Social isolation | <input type="checkbox"/> Special diet     |
| <input type="checkbox"/> Other             |   |   |

If yes to water or food regulation, refer to [IACUC Food and Water Regulation for Laboratory Animals Policy](#)

For any condition checked above, please describe (include the length of time required for each condition) and provide a scientific justification:

N/A

### Maintenance Outside Animal Facility Housing

Complete this section if animals will be maintained in a laboratory or other area not designated for housing of laboratory animals for more than 24 consecutive hours (12 hours for USDA covered species).

c. Provide location and describe facilities that will be used to house the animals: During experimentation, the animals will be housed in the enclosure which will be deployed at the treatment and control site in New Haven Sound.

d. Provide justification for the need to move animals outside animal facilities: The experimental design incorporates a field study in order to assess the effect of the electromagnetic field emitted by an installed and active underwater power cable which is buried in the seabed therefore it cannot be conducted in the aquarium.

e. Describe transportation to be used and who will transport animals: A small group of 5-7 animals will be transported in an aerated, temperature controlled holding tank(150 L cooler)by road and to the deployment site by boat. Water exchanges will occur as requiredto prevent metabolite build up, in the event of delay.Travel time is estimated at approximately 2-3 hours to site, in total.During summer temperatures floating ice packs may also be used to help maintain a low temperature. Inside the coolers there will be battery operated air pumps for aeration.

f. Will animals be returned to original animal facility?  Yes  No

### Section 9 - Alternatives

The Animal Welfare Act Regulations, Section 2.31 and USDA (Policy #11 and #12 ) require that a written narrative be provided by the Principle Investigator (PI) to determine whether or not alternatives exist to procedures which may cause pain or distress in animals used for teaching or research. In addition, if alternatives exist but are not used, the PI must justify why this is the case. Alternatives have been broadly defined to include: procedures that reduce the number of animals used (e.g., special statistical designs, sharing animals/specimens with several projects, etc.); refinements that decrease the pain or distress experienced by the animal; and methods that replace animals with non-animal alternatives or employ the use of animals with a lower taxonomic status.

a. If your protocol includes any procedures to *reduce* or *refine*, please describe briefly.

N/A

b. If any alternatives (*reducing, refining, or replacing*) are available, and they are not being used, explain what they are and why they are not being used.

N/A

c. If no alternatives (*reducing, refining, or replacing*) are available, please explain why.

N/A

d. If you have listed animals in **Pain Categories D or E**, and no alternatives are available, you must explain the basis for this assertion. An electronic literature search constitutes part of the basis for this assertion, please provide search details utilizing two pertinent sources. **Remember to not include the word "alternative" when conducting your search.**

Databases	Date of Search	Years Covered	Key Words or Search Strategy
N/A			
N/A			

**Suggested resources for literature sources:**  
[Animal Welfare Information Center - Alternatives](#)  
 and  
[Consideration of Alternatives to Painful/Distressful Procedures](#)

e. The literature search yielded the following information (attach separate sheet if needed)

N/A

f. If you have listed animals in **Pain Categories D or E**, and no alternatives are available, please list one or more experts whom the IACUC may contact who are familiar with the experimental procedures you are using and might render an opinion regarding the appropriate use of animals for these studies. URI faculty would be appropriate.

N/A

**Section 10 - Other Procedures**

Answer the following questions regarding blood collection, restraining animals and animal stress.

a. Blood collection?

Yes  No

If **yes**, refer to [IACUC policy of Blood Collection](#)

Volume of Blood Draw	Frequency and Number of Samples	Collection Site
N/A		

b. Restraining animals with mechanical device?

Yes  No

If yes, describe the type of restraint (e.g., rabbit plastic restrainer, tethering)?

N/A

If yes, what is the duration of restraint (e.g., 1 to 2 hours, overnight)?

N/A

If yes, provide a scientific justification for the restraint.

N/A

c. Subjecting animals to conditioning or environmental stress?

Yes  No

If yes, describe method and duration of exposure

N/A

### Section 11 - Surgical Procedures

Complete this section if surgical procedures will be performed on live animals. By providing this information, you are justifying the use of the animal model you have selected, supporting your justification for the use of animals for your project and ensuring that no alternatives exist to procedures that cause pain or distress and that these studies have not been previously conducted. The information is to include: the databases searched (2 or more), the date of the search and years covered by the search, and the key words or search strategy used.

a. Are surgical procedures included in this protocol?  Yes  No

b. If yes, please indicate whether the surgical procedure is non-survival (animals will not recover from anesthesia) or survival (animals will recover from anesthesia)  Non-Survival  Survival Number of animals:

c. Multiple survival surgery?  Yes  No

If yes, justify the multiple surgeries based on scientific necessity. Indicate the specific surgical procedure and the time interval between the procedures.

N/A

d. Briefly describe the surgical procedure(s)

N/A

e. Briefly describe the post-operative care (e.g., length of recovery time following anesthesia).

N/A

f. Where will the surgery be performed (Building/ Room Number)?

N/A

**Section 12 - Hazardous Materials**

Complete this section if any hazardous materials will be introduced into live animals.

When using hazardous materials in the laboratory, but not with live animals (e.g., formalin fixative) ensure that appropriate SOPs are in place to minimize risk of exposure. For information on SOPs, please contact URI [Environmental Health and Safety \(EHS\)](#).

a. Will hazardous materials be introduced into live animals?       Yes     No

b. If yes, what materials will be used with live animals?

Radioactive materials                       Chemicals/carcinogens

Infectious agents                                 rDNA (e.g., plasmids)

Human or nonhuman primate tissues or cell lines

Adjuvants (Freund's or Titer Max Gold)

c. If you checked "yes" to infectious agents, rDNA, or human or nonhuman primate materials, **Institutional Biosafety Committee approval is required.**

IBC Approval Number or Review Status (e.g., pending, approved)

N/A
-----

d. If you checked "yes" to any material above, describe:

Number of Animals	Agent	Dose per Kg Body Weight	Route of Administration	Frequency of Administration
N/A				

e. List the specific health risks to humans and animals from possible exposure to these agents and precautions to be taken to protect people and animals.

N/A
-----

### Section 13 - Aquatic Species

Complete this section when aquatic species (fish, amphibians, and aquatic reptiles) are to be used.

- a. Provide details of tank(s) or enclosures and the cleaning schedule:
- A 10 ft diameter circular tank has been designated in the aquarium for this project. The water depth is 3 ft . The tanks will be for short term husbandry only but will be cleaned 1-2 times per week as required to prevent algal build up and remove uneaten food, therefore preventing fouling of the water.
- Skates will be provided with clean sand on the bottom of the tank which they will interact with and move around the tank often producing a clearing at the tank perimeter.
- Eels will be held in the same tank described above but at a different time to the skates. The tank outflow will be modified such that eels cannot escape.
- b. Describe maintenance of water quality (e.g., filtered, frequency of change, temperature, pH, removal of metabolites).
- The water supply is drawn from Narragansett Bay from intake pipes along the side of the pier. The water collects in two 12 ft diameter, 8 ft deep settling tanks which is then pumped through 3ft diameter sand filters. The water is nominally filtered to 30 um. The water reaching the tank we are using is supplied with ambient seawater at approximately 9 degrees Celsius. There will be a continuous flow which will reduce metabolites and an air stone. The seawater parameters will be monitored daily using a sonde which will provide readings of temperature, salinity, pH, oxygen, conductivity and ammonia.
- c. Describe routine animal care procedures (e.g., feeding schedule, checking for health of animals).
- Animals will be held under an artificial day-night cycle which reflects the natural light regime. Animals will be fed a minimum of twice per week on a prepared ration of quality food (squid/herring from the local fish mongers). The health of animals will be checked during feeding and during any other periods of animal handling. Notes that animal husbandry will be for short periods, i.e. weeks not months. Should ill-health occur at any time, the sick individuals will be isolated and expert advice sought.
- d. Describe any hazard (biological, chemical or physical) associated with the maintenance and care of aquatic species and emergency procedures pertinent to the safety of aquatic species and personnel who care for them.
- Eels often bite when handled therefore gloves will be worn when handling eels.

## Section 14- Field Studies and Animal Collection

Complete this section if field studies involving wild animals will be conducted or animals will from collected in the wild. Ensure that permit from appropriate wildlife agency is uploaded to IRBNet as part of this submission.

a. Describe method of capture. Describe safety and protective measures for personnel involved.	<p>Skates will be collected from the Graduate School of Oceanography (GSO) trawl. These trawls are much shorter than standard fishing trawls and have provided researchers at the GSO Marine Science Research Facility with healthy specimens in the past. The trawl uses a standard sampling protocol; the capture gear is a 2 seam, 3 inch mesh, otter trawl (39 foot head rope) towed at 2 knots for 30 minutes. <i>Alternatively, Deep Water Wind is currently conducting a fisheries monitoring project that is supervised by Dave Beutel of CRMC and uses the same methodology as the URI fish trawl. Dave Beutel will liaise with the fishermen doing the Deep Water Wind project.</i></p> <p>Eels will be captured using a standard size and shape eel pot (approximately 90 cm x 25 cm x 25 cm). The pot is designed to capture the eels alive and in good condition. <i>The eels will be collected by John King and Dave Beutel of CRMC. The time that fish will be held in the aquarium will be dependent on the frequency and success of collection. Success is not predictable but once appropriate numbers have been obtained, they may be held in the aquarium for 2-4 weeks. It is preferred that the fish are held for less time in the aquarium so that they are still behaving naturally during the experiment.</i></p>
b. Describe procedures to ensure the well being of the animals after capture and during transportation to and from research site (if applicable).	<p>After capture, eels and skates will be transferred to a temperature controlled aerated holding tank and transported to the URI aquarium. The time spent in the portable tank will be minimized and specimens will be transferred to large holding tanks in the URI Aquarium as soon as possible (i.e. within a few hours of capture). Animals will be assessed for indications of good health on transferal. Animals will be fed regularly and water quality parameters of temperature, salinity, ammonia and pH monitored will be closely monitored, as will behaviors which are used to indicate acclimatization to their new environment.</p>
c. Describe SOPs used as part of field study (attach if applicable).	<p>Animals will be held in holding tanks as above. Prior to the release of animals into the test enclosure the animals will be inspected for good health, normal behavior and securely attached and working tag attachment.</p> <p>The animals will be placed in the enclosure immediately prior to deployment in order to minimize the amount of time out of water. Once in the water the seawater parameters will be monitored in situ. On retrieval of the enclosure, the animals will be recovered from the enclosure as soon as it is safe to do so and will be returned to the aerated temperature controlled holding tank for transport. Partial water exchanges will occur as required as previously described. Again animals will be monitored for normal behavior and good health.</p>

### Section 15 - Final Disposition

- a. What is the final disposition of the animals in this study?
- Animals will be returned to the colony, herd, flock or appropriate cohort group
  - Animals will remain in a natural setting (i.e., observational study)
  - Animals will be euthanized
  - Death will be the endpoint (without investigator intervention, as opposed to euthanasia)
  - Other Please list:

Complete the following questions if euthanization is the final disposition. Euthanasia must be conducted in accordance with the [Report of the AVMA Panel on Euthanasia](#). Methods not consistent with AVMA Guidelines must be justified scientifically.

- b. Indicate method(s) of euthanasia (include agent, dose and route/ method of administration. Include building and room location where euthanasia will occur).
- In keeping with the AVMA Guidelines euthanization by immersion in a buffered solution of tricane methanesulfonate (MS 222) will be used. MS-222 is usually administered 2-3g/L in a water bath ~~buffered with sodium bicarbonate~~. This method is common to the UK and the USA. The team has conducted such a procedure in the past using MS222 according to UK Home Office licence scheduled procedure. *After treatment with the MS222, a cervical transection using a sharp knife will be conducted to confirm euthanasia.*

- c. Will the study require necropsy on animal carcasses?
- Yes      If yes, describe procedure:
- No

1. Indicate what method(s) will be used to ensure the animal is dead prior to collecting tissues or carcass disposal.
- Animals will be monitored over a 10 minute period for the cessation of vital signs such as opercular, gill slit and/or spiracle movement indicating respiratory arrest after the procedure to confirm death in addition to the absence of a response to physical stimulus. Euthanization will be conducted in a separate small tank using water from the normal fish housing as specified by the AVMA Guidelines and will be monitored for condition where multiple animals are euthanized.

2. Indicate method of disposal of the animal carcasses. See [URI EH&S](#) for more information.
- Following death, the animals having been treated with MS 222 will be disposed of following aquarium regulations ensuring that they do not enter the food web. They will be put in a plastic bag and disposed on with the normal waste regime since they are not hazardous waste.

## Section 16 - Certifications and Endorsements by Principal Investigator

To indicate agreement, check each statement and sign IRBNet package.

- To the best of my knowledge the information provided in this protocol form is complete and accurate and that this application accurately and completely reflects the animal research described in my full grant applications (if applicable) and/or used in my laboratory.
- I am familiar with and agree to abide by the University's policies and procedures for research involving animals, including the URI Program of Veterinarian Care and the Animal Care SOPs.
- I am familiar with and agree to abide by the *Guide for the Care and Use of Laboratory Animals*, The USDA Animal Welfare Act Regulations, and the *Public Health Service Policy on Humane Care and Use of Laboratory Animals*.
- I certify that the activities in this protocol do not unnecessarily duplicate previous experiments.
- I understand that it is my responsibility as the Principal Investigator to ensure that all individuals listed on the protocol have read and understand the procedures described for each species and have received proper training to conduct the described procedures.
- I understand that if I wish to change any procedure or personnel as shown on this protocol, that I will request an IACUC approval by submitting the details of the change(s) as an amendment to the IACUC.
- I acknowledge that I will notify the **Attending Veterinarian (401-742-2855)** and the **Research Integrity Office (401-874-4328)** of any unanticipated outcome, protocol deviation, or adverse events (e.g., any happening not consistent with routine expected outcomes that results in any unexpected animal welfare issues or human health risks) **immediately** and complete the Event Reporting form within 72 hours.
- I understand that any failure to comply with guidelines and requirements of the IACUC may result in suspension of my studies and notification to the funding agency, the PHS and/or the USDA as mandated by law.

Print the form for  
your records

Print Form

OFFICE OF RESEARCH INTEGRITY

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p: 401.874.4328 f: 401.874.4814 [web.uri.edu/researchecondev/office-of-research-integrity](http://web.uri.edu/researchecondev/office-of-research-integrity)

Animal Welfare Assurance #:A3690-01



DATE: June 16, 2016

TO: John King, PhD

FROM: University of Rhode Island IACUC

PROJECT TITLE: [901911-2] Effects of Electromagnetic Fields (EMF) from an Underwater Power Cable on Little Skates and American Eels

IACUC REF #: AN1516-008

SUBMISSION TYPE: Response/Follow-Up

ACTION: MODIFICATIONS REQUIRED

DECISION DATE: June 16, 2016

EXPIRATION DATE:

REVIEW TYPE: Full Committee Review

**Pending Notification:**

Thank you for your submission of Response/Follow-Up materials for this research project. The University of Rhode Island IACUC has determined that the following MODIFICATIONS are REQUIRED in order to secure approval:

Additional information is required prior to approval.

Tagging of the eels without anesthesia/sedation remains questionable and compelling evidence that this can be done without injuring or compromising the animals is required. Eels are quite active and when handled which is not conducive to insertion of a wire through the dorsal musculature as the attachment site for the saddle. Please provide publications where eels were not anesthetized for tag attachment/implantation. The paper the investigators used as a source of information (Økland et al. Animal Biotelemetry 2013, 1:3) used anesthesia it appears. Please provide information to support the tagging of the eels without anesthesia/sedation.

*To submit the required modifications:*

1. *Open your project on IRBNet [901911-2]*
2. *Click "Project History" on the left side of your screen*
3. *Click "Create New Package" in the middle of your screen*
4. *Upload the required documents and a brief memo describing the modifications in this package*
5. *Click "Sign this Package" on the left*
6. *Click "Submit this Package" on the left*

**Research activities in accordance with this submission may not begin until this office has received a response to these conditions and issued final approval.**

This submission has received Full Committee Review based on the applicable federal regulation.

If you have any questions, please contact us by email at [researchintegrity@etal.uri.edu](mailto:researchintegrity@etal.uri.edu) or call 401-874-4328. Please include your project title and reference number in all correspondence with this office.

**PROJECT TITLE:** [901911-1] Effects of Electromagnetic Fields (EMF) from an Underwater Power Cable on Little Skates and American Eels  
**IACUC REF #:** AN1516-008

**Modifications Requested:**

Additional information is required prior to approval.

Tagging of the eels without anesthesia/sedation remains questionable and compelling evidence that this can be done without injuring or compromising the animals is required. Eels are quite active and when handled which is not conducive to insertion of a wire through the dorsal musculature as the attachment site for the saddle. Please provide publications where eels were not anesthetized for tag attachment/implantation. The paper the investigators used as a source of information (Økland et al. Animal Biotelemetry 2013, 1:3) used anesthesia it appears. Please provide information to support the tagging of the eels without anesthesia/sedation.

**Response:**

It is true that Økland et al., (2013) used anaesthesia in the comparison of tagging that was completed however the reason for this was that the saddle and the tag used in these methods was much larger than what we will use. The tag used for the comparative methods by Økland (2013) was 122 mm long. In comparison the tags we have are ~25 mm long. Due to the difference in size, the saddle used in our study will be much smaller and we will use no more than two smaller piercings reducing to one where possible in order to minimise tagging and handling time. Additionally the HTI tag in this study will be more streamlined and will be used for a short period of time in comparison to a pop-up satellite tag which means there will be less drag and less force placed on the tag attachment. Please consider the work of Westerberg et al., (2007) compared to Westerberg et al., (2014) as a supporting example.

Westerberg et al., (Westerberg, Lagenfelt et al. 2007) did not use anaesthesia for the attachment of tags to ~78 cm eels. These tags weighed only 3 g and were attached by a single suture, the attachment process was completed in 1 minute and the animals returned to the water; a simple tagging method. The tag weight was not reported but similar tag weight from the same company measures approximately 35 mm length (<http://www.lotek.com/lat2000-fish.html>). In contrast, Westerberg et al., (2014) tagged ~75 cm eels under anaesthetic. This tagging method refers to Økland et al., (2013). Westerberg et al., (2014) attached pop up satellite tags (again much larger) by a three point attachment at the dorsal fin and acoustic tags implanted by a small incision and single suture. Our tagging method is not quite as simple as Westerberg et al., (2007) but not as complex as that of Westerberg et al., (2014). Although we reference Økland et al., (2013) as a demonstration of different methodologies and importantly their behavioural effects, our tagging method is much more simplistic. Thorstad et al., (2013) further summarises the difference between tag types and their typical size (Figure 1) and details one of the benefits of external tags being that anaesthetic is not always required.



**Figure 1.** Different types of tags for fish movement studies. Note the difference in size of the pop-up satellite tag compared to the acoustic tag. Image from Thorstad et al., 2013.

In support of our suggested protocol not employing the use of anaesthetic are the recommendations from the Environmental Agency in the UK who produce an advisory report on the Monitoring of elver and eel populations; The Eel Manual (Baldwin, Wright et al.). The Eel Manual (uploaded as supplementary material, pg 24) states that anaesthetic should be avoided unless it is necessary. There are considerations for using anaesthetic such as an initial increase in activity (Baldwin, Wright et al.) and physiological responses to the analgesia (e.g. Thiem et al., (2011) and references therein) which may be better avoided in what is a simple procedure. With careful handling of the eels, we will be able to tag them without the use of anaesthetic. This will involve, handling eels with dry hands, covering the eyes of eels to reduce their activity and stress and using an eel trough similar to those displayed in figure 2.

a)



b)



**Figure 2.** An example of an eel trough (a) and an eel tube (b) suitable for measuring eels. An eel trough could be used to measure and tag eels and an eel tube could be modified to provide access to the dorsal for tag attachment. Both can be used with flowing seawater. Images from The Eel Manual, page 21-22; uploaded as supporting information.

## References:

- Baldwin, L., R. Wright, et al. The Eel Manual. Monitoring elver and eel populations. Bristol, UK, Environment Agency: 41.
- Økland, F., E. B. Thorstad, et al. (2013). "Development and testing of attachment methods for pop-up satellite archival transmitters in European eel." Animal Biotelemetry **1**(1): 1-13.
- Thiem, J. D., M. K. Taylor, et al. (2011). "Trends in the reporting of tagging procedures for fish telemetry studies that have used surgical implantation of transmitters: a call for more complete reporting." Reviews in Fish Biology and Fisheries **21**: 117-126.
- Thorstad, E. B., A. H. Rikardsen, et al. (2013). "The Use of Electronic Tags in Fish Research – An Overview of Fish Telemetry Methods." Turkish Journal of Fisheries and Aquatic Sciences **13**: 881-896.
- Westerberg, H., I. Lagenfelt, et al. (2007). "Silver eel migration behaviour in the Baltic." ICES Journal of Marine Science: Journal du Conseil **64**(7): 1457-1462.
- Westerberg, H., N. Sjöberg, et al. (2014). "Behaviour of stocked and naturally recruited European eels during migration." Marine Ecology Progress Series **496**: 145-157.

THE  
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Animal Welfare Assurance #:A3690-01



DATE: July 6, 2016

TO: John King, PhD

FROM: University of Rhode Island IACUC

PROJECT TITLE: [901911-4] Effects of Electromagnetic Fields (EMF) from an Underwater Power Cable on Little Skates and American Eels

IACUC REF #: AN1516-008

SUBMISSION TYPE: Amendment/Modification

ACTION: APPROVED

APPROVAL DATE: July 5, 2016

EXPIRATION DATE: July 5, 2019

REVIEW TYPE: Full Committee Review

Thank you for your submission of Amendment/Modification materials for this research project. The University of Rhode Island IACUC has APPROVED your submission. **This letter serves as official notification of approval for this NEW protocol.**

This submission has received Full Committee Review based on the applicable federal regulation.

The Central Lab Animal Facility (CLAF) is the only approved facility for ordering laboratory animals or transporting animals between facilities at URI. Please refer to the ORI website when you are ready to purchase or transport lab animals.

**Please note that any revision to previously approved materials must be approved by this office prior to initiation.** Please use the appropriate Amendment Form for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office within 24 hours. Please use the appropriate Adverse Event Form for this procedure. Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this project to this office.

Please note that all research records must be retained for a minimum of three years from completion of the project. Approval is valid for up to three years with required Continuing Review by this office on an annual basis for USDA covered species. Please use the Annual Continuing Review Form for this procedure.

If you have any questions, please contact us by email at [researchintegrity@etal.uri.edu](mailto:researchintegrity@etal.uri.edu) or call 401-874-4328. Please include your project title and reference number in all correspondence with this office.

Sincerely,

A handwritten signature in cursive script, appearing to read "T. Myatt".

Ted Myatt  
Director, Office of Research Integrity



### **The Department of the Interior Mission**

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.



### **Bureau of Ocean Energy Management (BOEM)**

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.

### **BOEM Environmental Studies Program**

The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.