Enhanced EMI Models and Systems for Underwater UXO Detection and Discrimination

Project Number: MR-2728

Dr. Fridon Shubitidze
Dartmouth College

In-Progress Review Meeting
February 21, 2018

MR-2728
Enhanced EMI Models and Systems for Underwater UXO Detection and Discrimination

Technology Focus

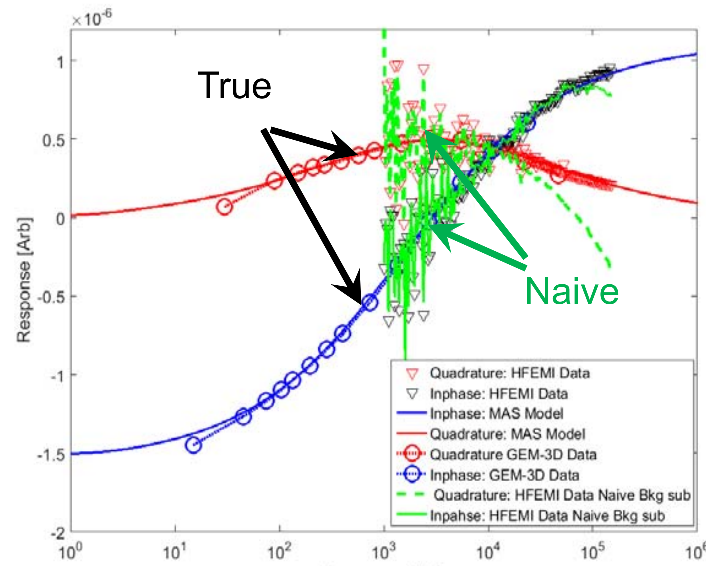
• Develop advanced EMI models and systems to detect, locate and classify Underwater UXO targets.

Research Objectives

- ➢ Understand diffusive propagations of EMI fields in UW environments
- ➢ Mitigate the effects of conducting media on both the primary and secondary EMI fields

Project Progress and Results

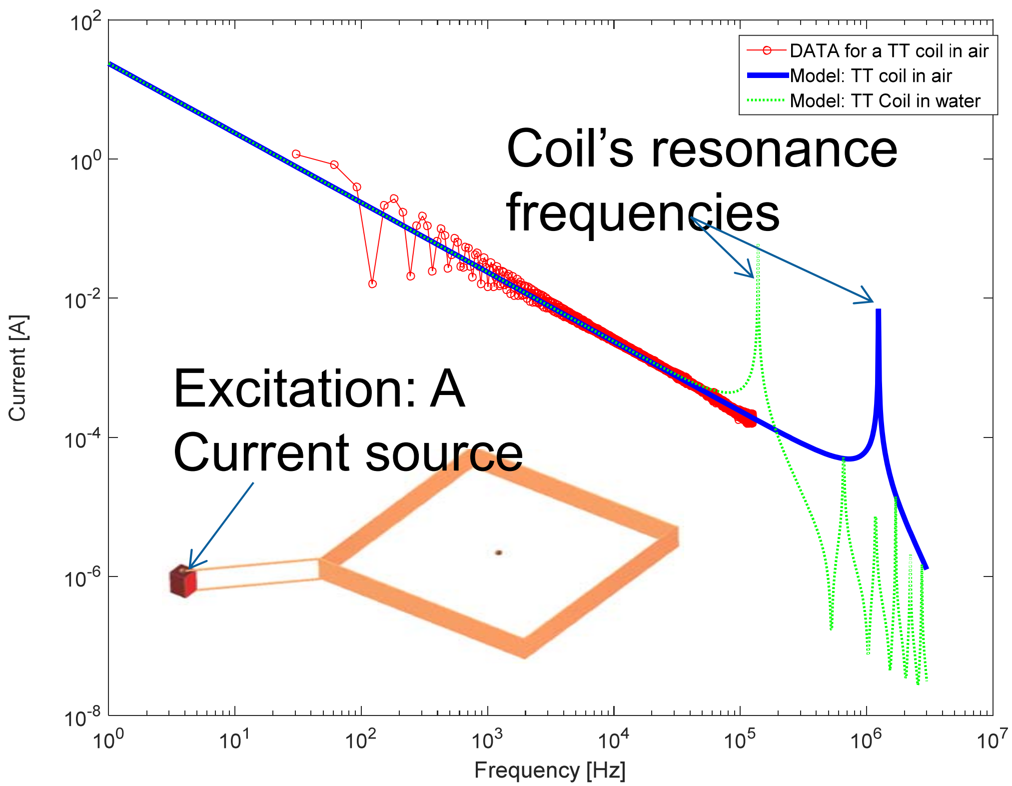
- ➢ EMI signals' and systems' behaviors in UW environments were modeled
- ➢ An experimental setup was built
- ➢ A new scheme was developed for extracting targets true EMI responses
- ➢ The sensitivity of a primary EMI signal with respect to the Air/Water/Sediment boundary has been studied.

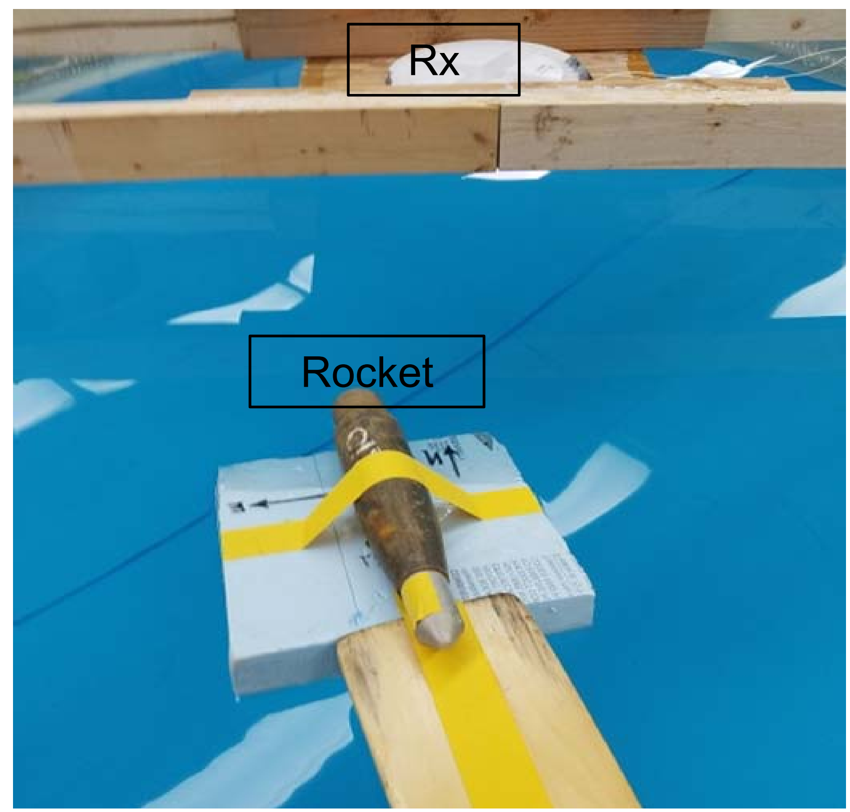


Social Media Content

- **EMI signals and sensors behaviors in UW environments were measured and modeled**
- **A new scheme was developed for extracting targets true EMI responses**

The results will be presented at the SAGEEP-2018 and SPIE-2018 Defense and security conferences and published in proceedings;





Performers

Dr. Fridon Shubitidze

Thayer School of Engineering, Dartmouth College

Specialist in: Advanced forward and inverse EMI Models, EMI sensors and systems design, Classification Algorithms

Dr. Benjamin E. Barrowes

US Army ERDC-CRREL

Specialist in: Electromagnetic phenomenology, EMI sensors

Problem Statement

- Detection and remediation of underwater UXO targets are more expensive than excavating the same targets on land
- Recently, advanced EMI sensors and models have provided excellent performance for detecting and classifying subsurface metallic targets on land

However, direct application of land-based methods to UW scenarios can lead to incorrect interpretations of UW EMI data

Thus, there are needs to develop better EMI models and systems to:

- understand diffusive behaviors of EMI fields in UW environments
- develop enhanced EMI systems and signal processing approaches for UW targets detection and classification

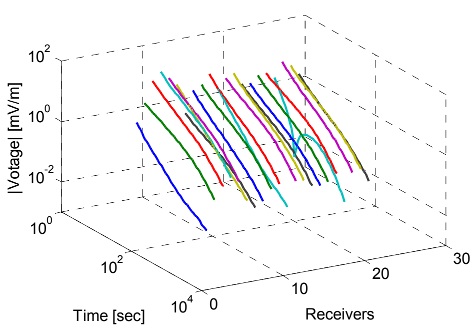
Technical Objectives

- Develop forward and inverse EMI models to accurately account for the underlying physics of EMI fields in UW environments.
- Investigate the behavior of diffusive EMI fields in the air-water-seabed environment.
- Assess and mitigate the effects of conducting media on both the primary and secondary EMI fields.
- Perform a preliminary assessment of the effectiveness of the enhanced models.
- **(Optional)** Research optimal transmitter current waveforms for optimizing a primary EM field strength.

Technical Background

Overview of UXO classification

1. Data Collection



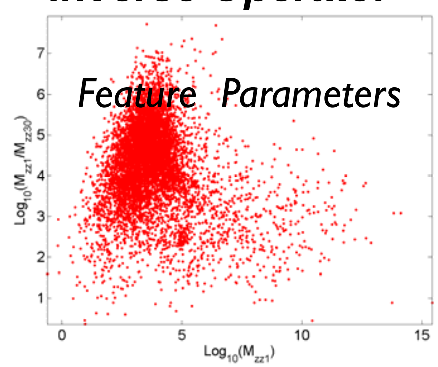
2. Data Inversion

Forward Operator

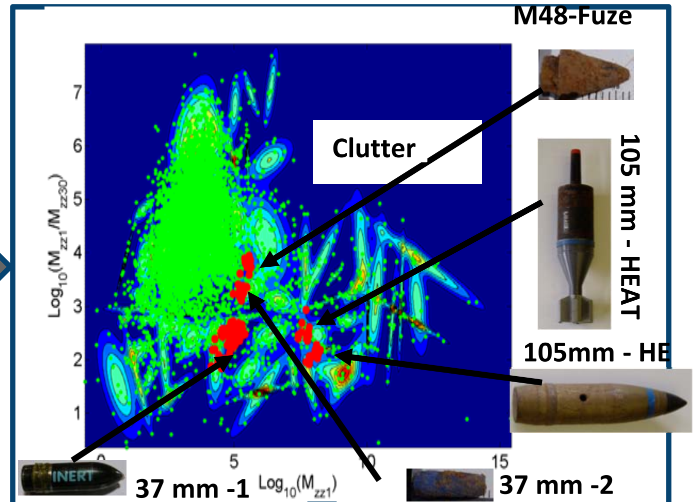
$$d = F[p]$$

$$p = F^{-1}[d]$$

Inverse Operator



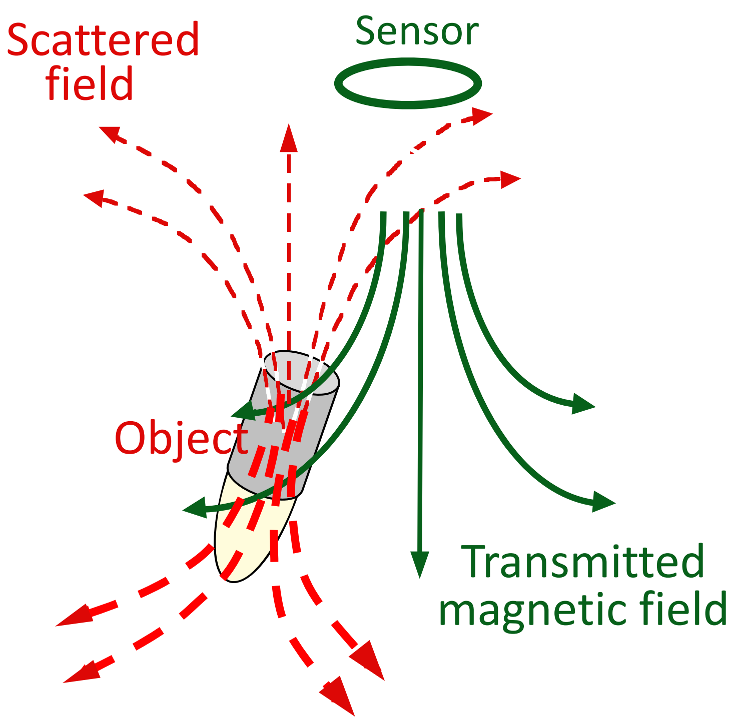
3. Decision



Technical Background

Mathematical formulations: for land based and UW EMI problems

EMI Problem for free space

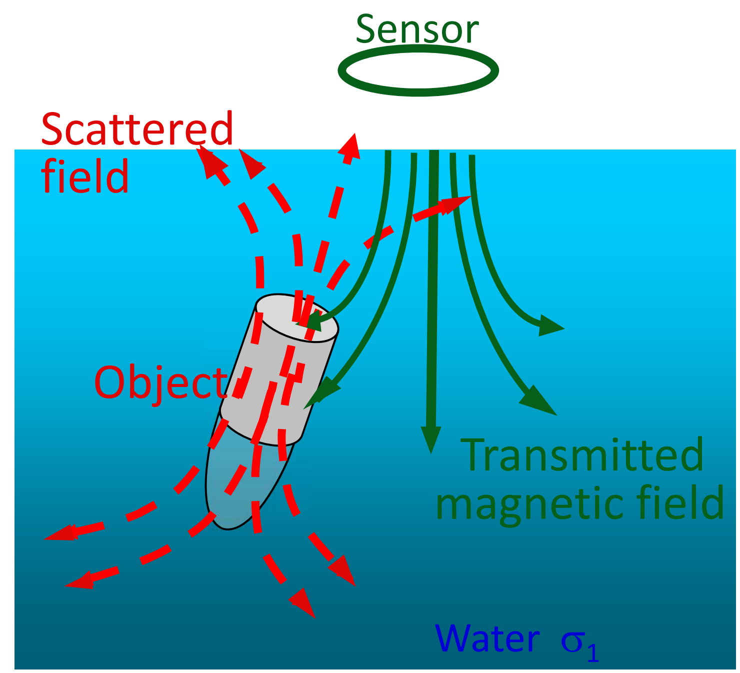


Governing equation: $\begin{cases} \nabla^2 \psi = 0, & \text{outside the object} \\ \nabla^2 \vec{\Pi} + k^2 \vec{\Pi} = 0, & \text{inside the object} \end{cases}$

$k = \sqrt{-i\omega\mu\mu_o\sigma}$

The scattered field is ~$1/R^3$

EMI Problem for UW environment



Governing equation: $\begin{cases} \nabla^2 \vec{\Pi}_1 + k_1^2 \vec{\Pi}_1 = 0, & \text{outside the object} \\ \nabla^2 \vec{\Pi}_2 + k^2 \vec{\Pi}_2 = 0, & \text{inside the object} \end{cases}$

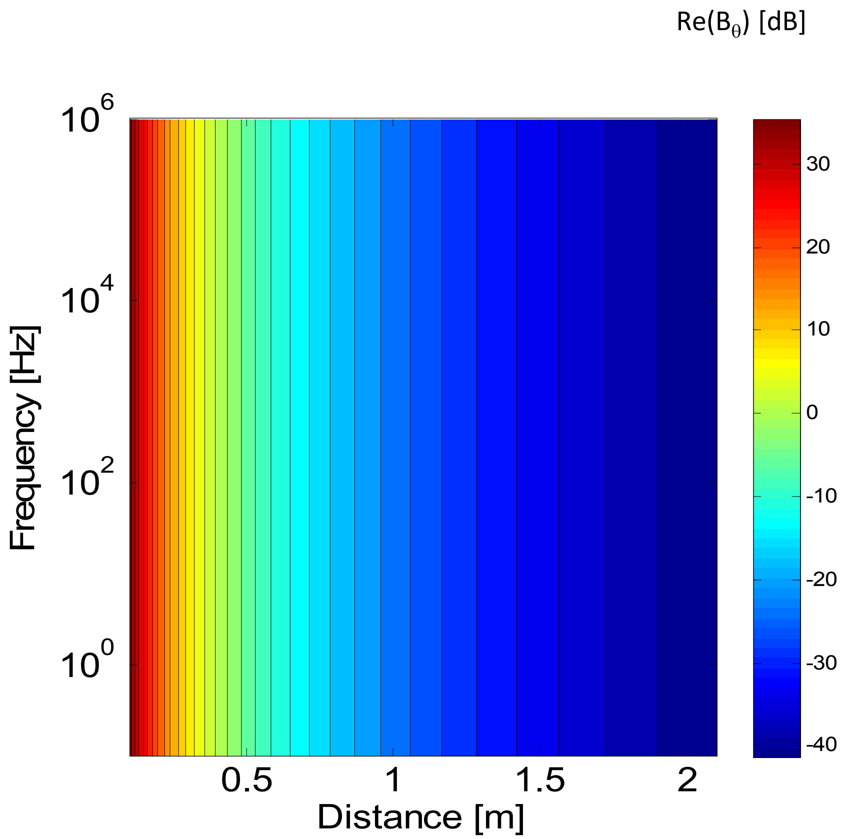
The scattered magnetic field is

$$\mathbf{H} \sim 1/R^3 \; e^{-j\gamma_1 R} \; \mathbf{e}^{-\gamma_1 \mathbf{R}}; \quad \gamma_1 = \sqrt{\omega\sigma_1\mu_1/2}$$

Both the phase and the amplitude change

Technical Background

Magnetic field due to a magnetic dipole in a non-conducting space



$$\mathbf{H}(\mathbf{r},t) = \bar{\bar{\mathbf{G}}}(\mathbf{r},\mathbf{r}_o)\cdot\mathbf{m}(t) = \bar{\bar{\mathbf{G}}}(\mathbf{r},\mathbf{r}_o)\cdot\left[\bar{\bar{\mathbf{M}}}(t)\cdot\mathbf{H}^{pr}(\mathbf{r}_o,\mathbf{r}_{Tx})\right];$$

Where

$$\bar{\bar{\mathbf{G}}}(\mathbf{r},\mathbf{r}_o) = \frac{1}{4\pi R^3}\left(3\hat{\mathbf{R}}(\mathbf{m}\cdot\hat{\mathbf{R}}) - \mathbf{m}\right)$$ Green's dyadic

$$\mathbf{m}(t) = \left[\bar{\bar{\mathbf{M}}}(t)\cdot\mathbf{H}^{pr}(\mathbf{r}_o,\mathbf{r}_{Tx})\right]$$ Dipole moment,

$$\mathbf{H}^{pr}(\mathbf{r}_o,\mathbf{r}_{Tx}) = \frac{1}{4\pi}\int_L \frac{\mathbf{J}\times\mathbf{R}}{R^3}\,dl$$

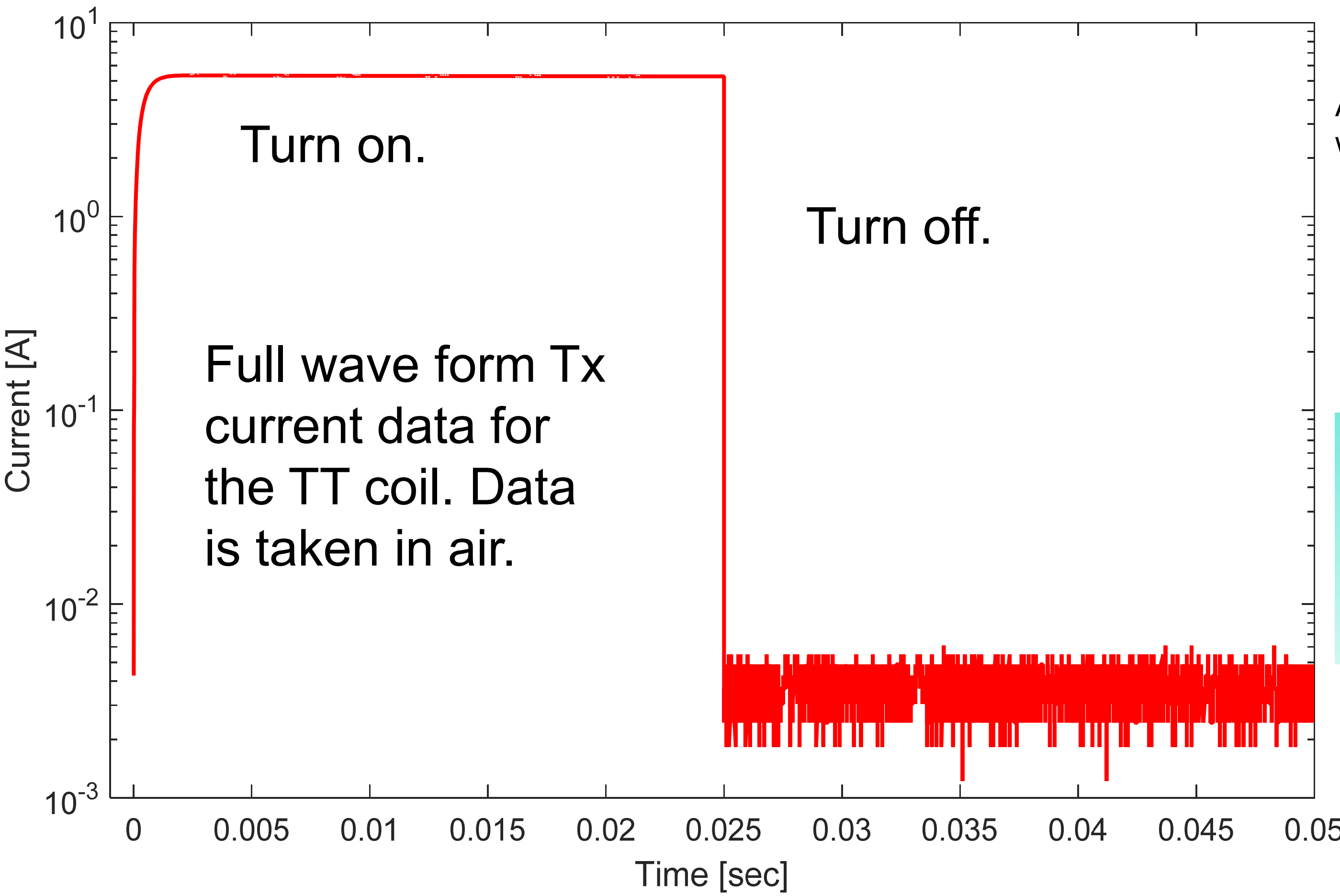
is magnetic field produces by a Tx at $\mathbf{r}_o$ point

$$\mathbf{R} = \mathbf{r} - \mathbf{r}_o;\ \mathrm{R}=|\mathbf{R}|,\ \hat{\mathbf{R}} = \frac{\mathbf{R}}{R}$$

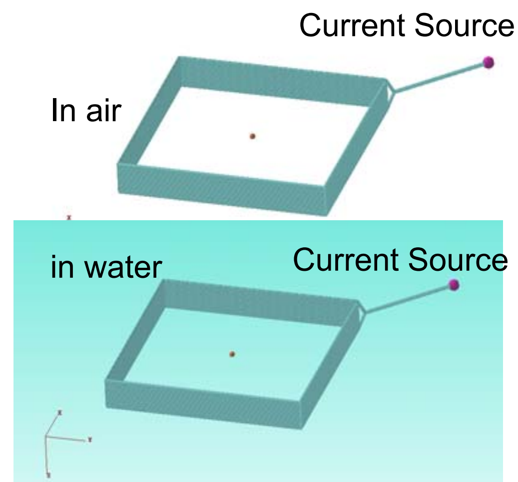
Land based EMI data DO NOT depend on phase changes/time delays.

EMI sensors in UW environment

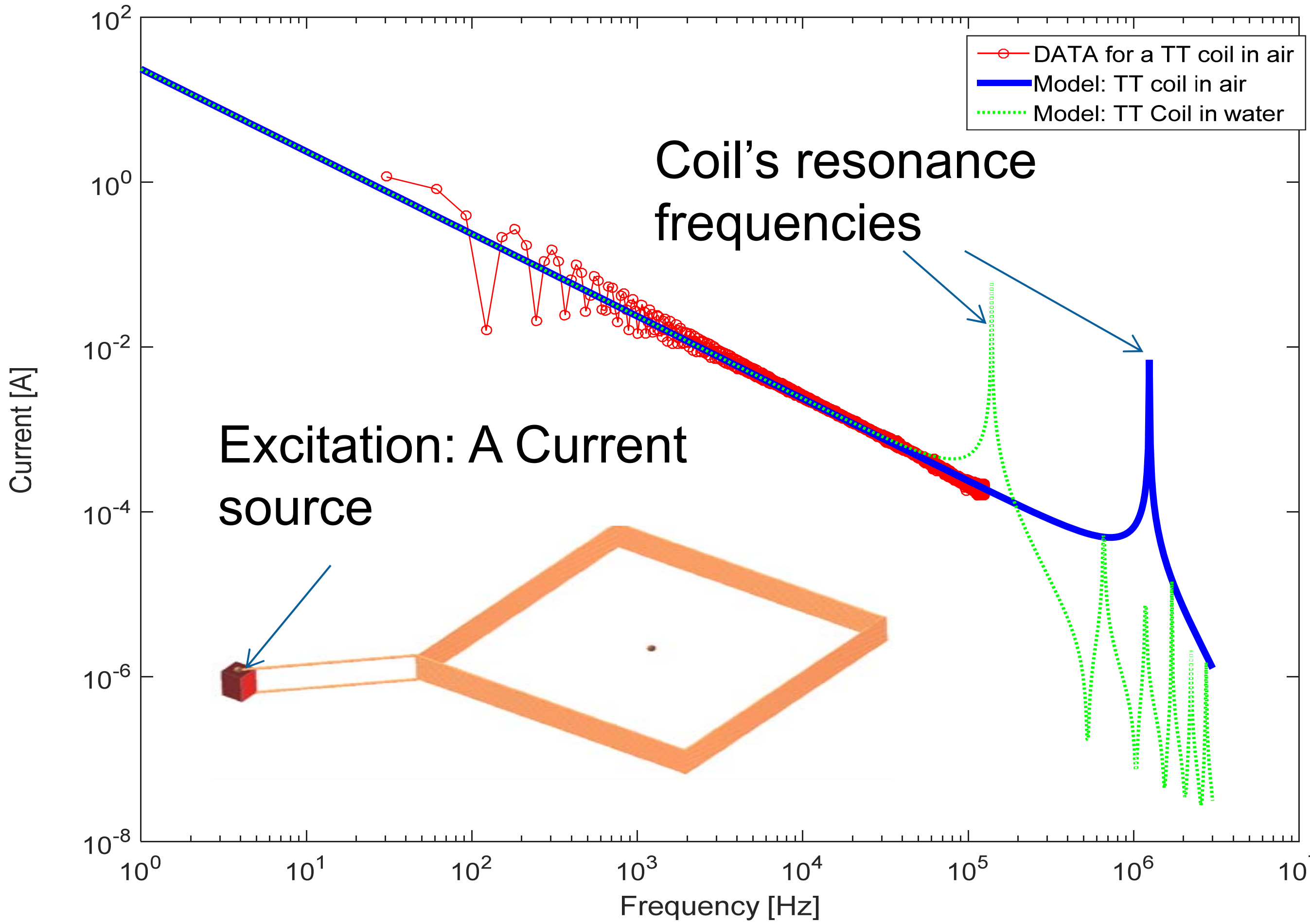
Use 3d EMI solvers for detailed characterization of EMI systems



A 68 cm x 68cm square coil with 16 turns placed:



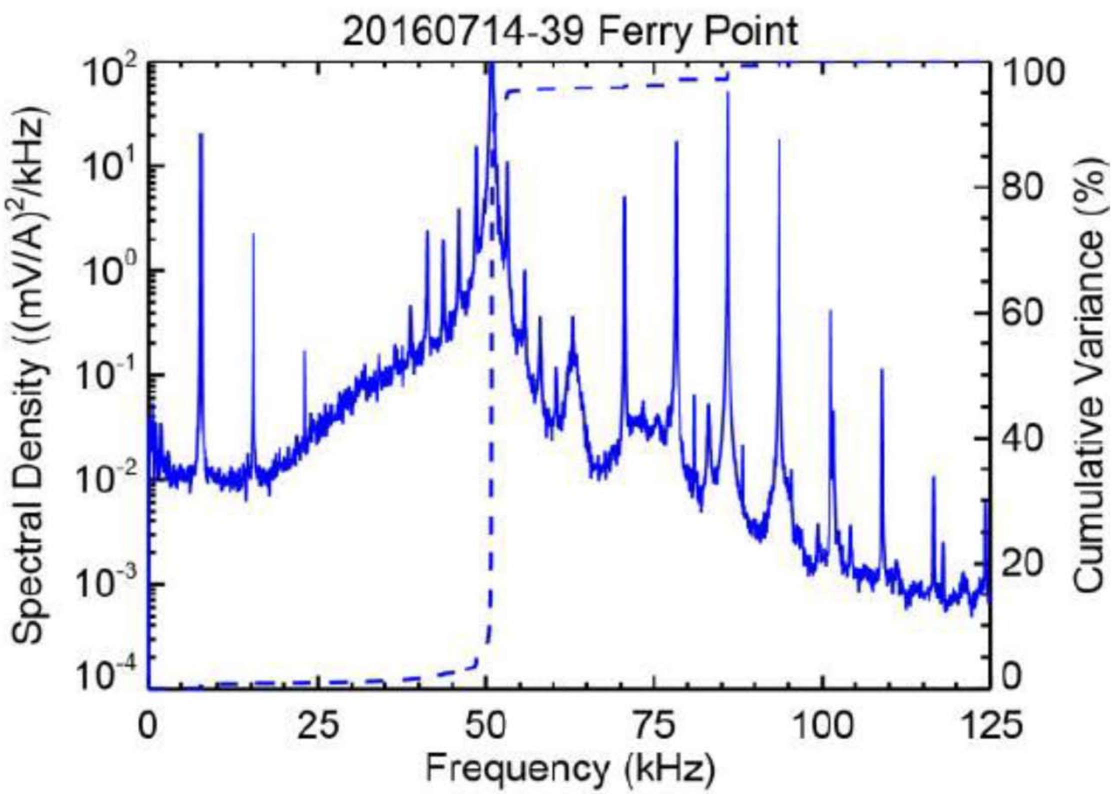
EMI sensors in UW environment



Rect: TEMTADS (TT) Tx coil: 16 Turns; total wire length 42.5 m; Excitation: A Current source

Model: The TT coil placed in: a) air and in water; The Tx coil's resonance frequency moves below 100 kHz.

EMI sensors in UW environment …



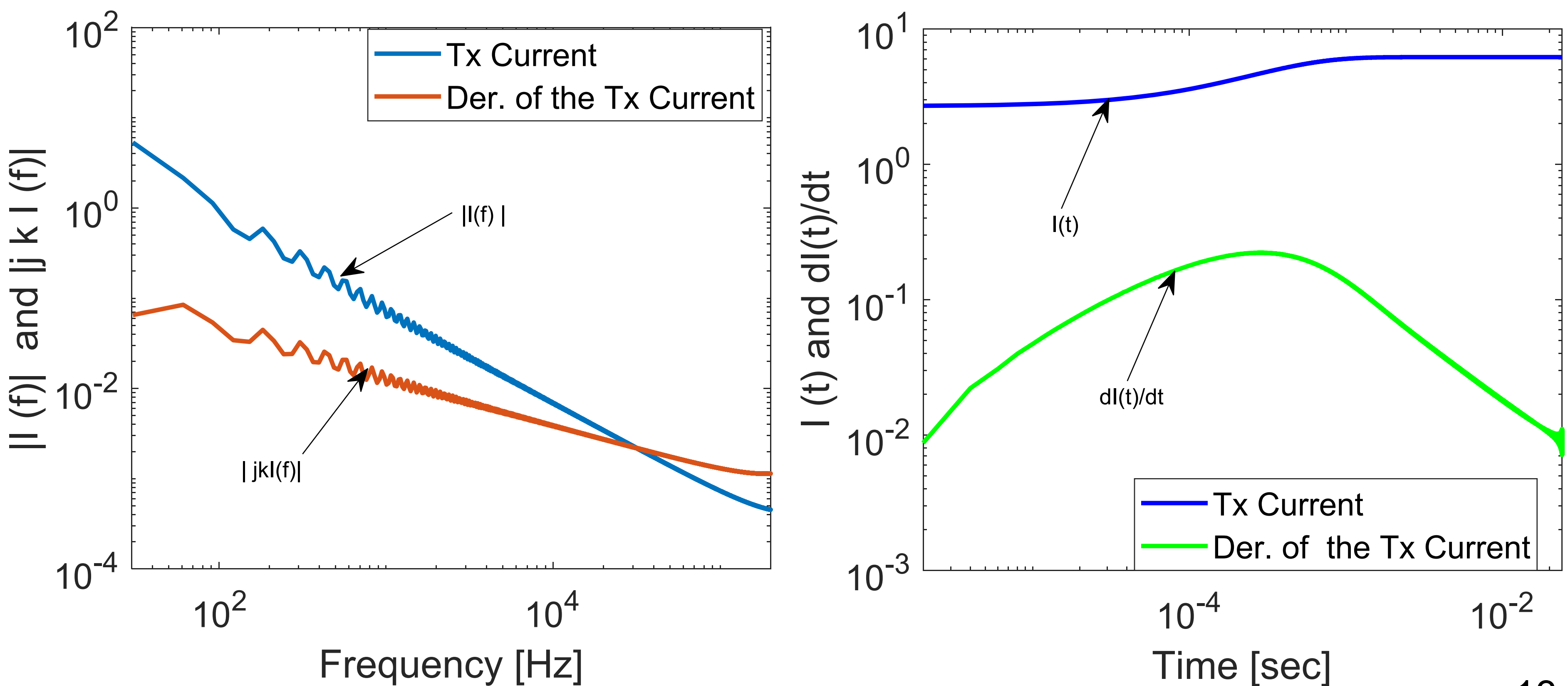
Our model predicts/ explains noise spectra observed in actual data.

Recent experimental data: Courtesy of SERDP MR-2409 interim report

Total Primary Magnetic field

The total magnetic field at **r** point produced by a current element placed at $\mathbf{r}_o$ is

$$\mathbf{H}^{pr}(\mathbf{r},\mathbf{r}_o)=\frac{1}{4\pi}\left(\frac{I}{R}+\frac{1}{v}\frac{\partial I}{\partial t}\right)\frac{d\mathbf{L}\times\mathbf{R}}{R^2}\quad \mathbf{R}=\mathbf{r}-\mathbf{r}_o;\ \mathrm{R}=|\mathbf{R}|,\ \hat{\mathbf{R}}=\frac{\mathbf{R}}{R};\ v=\frac{c}{\sqrt{\varepsilon}}$$



Comparisons between Total and Partial Primary Magnetic fields

Total field

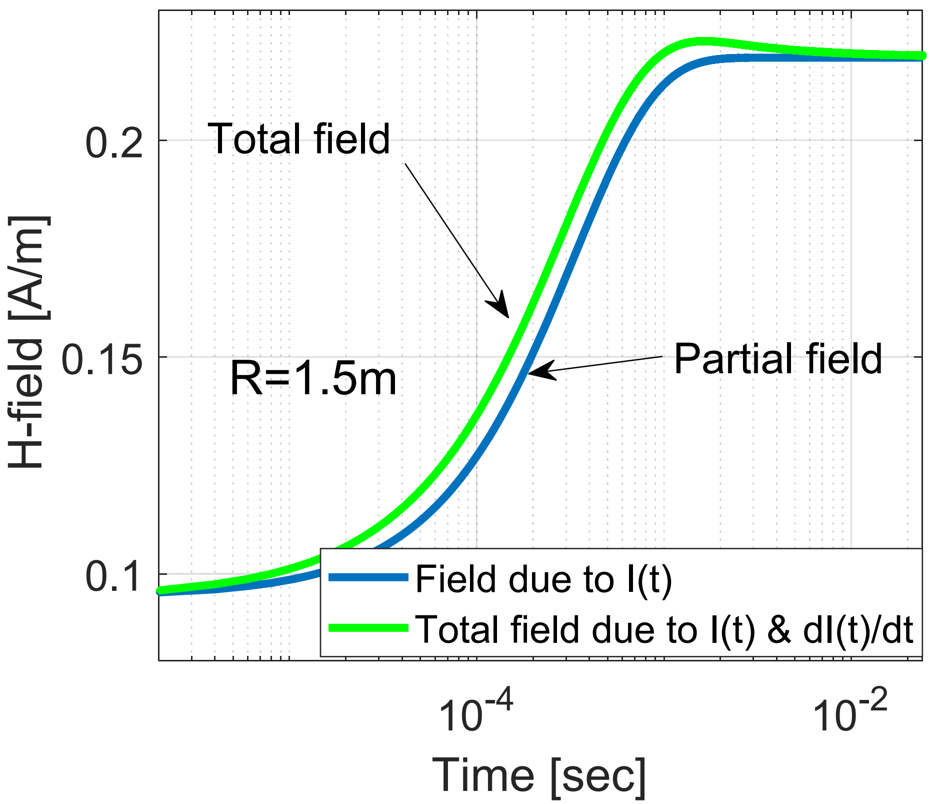
$$\mathbf{H}_{total}(\mathbf{r},\mathbf{r}_o)=\frac{1}{4\pi}\left(\frac{I}{R}+\frac{1}{c}\frac{\partial I}{\partial t}\right)\frac{d\mathbf{L}\times\mathbf{R}}{R^2}$$

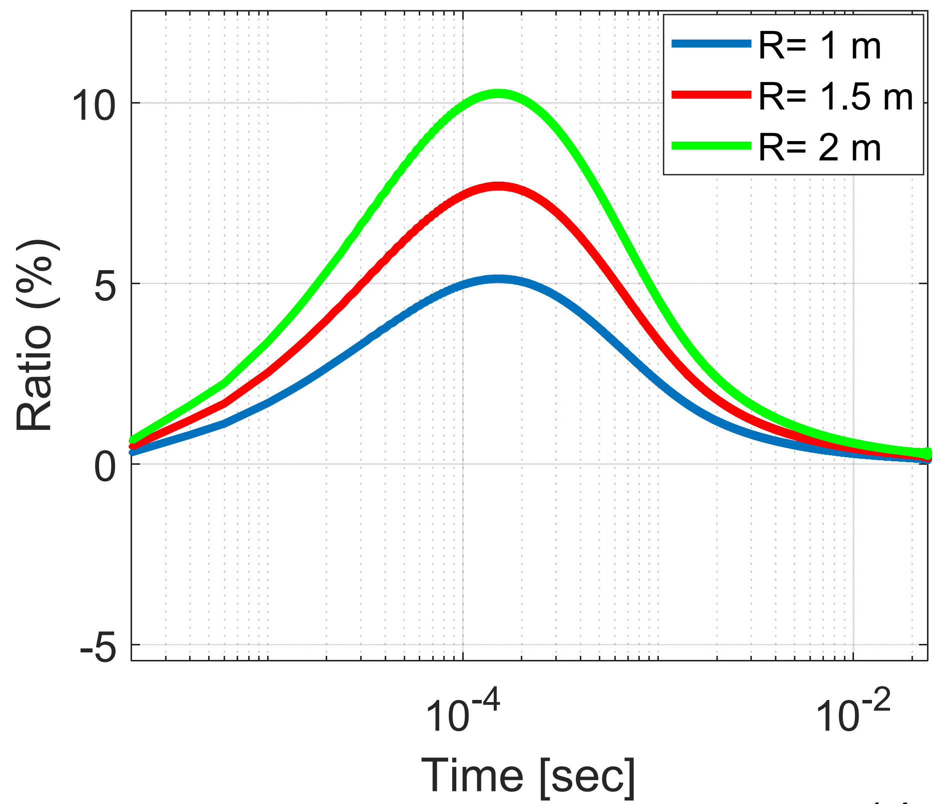
Partial field

$$\mathbf{H}_{partial}(\mathbf{r},\mathbf{r}_o)=\frac{1}{4\pi}\left(\frac{I}{R}\right)\frac{d\mathbf{L}\times\mathbf{R}}{R^2}$$

Ratio

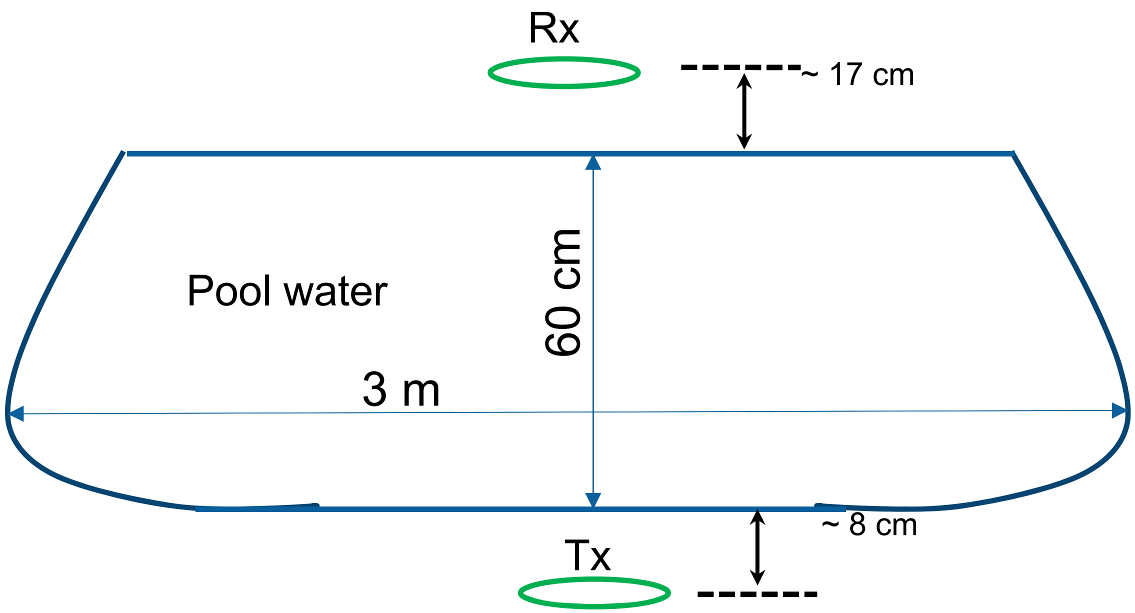
$$Ration=100\frac{\left|\mathbf{H}_{total}-\mathbf{H}_{patial}\right|}{\left|\mathbf{H}_{patial}\right|}$$





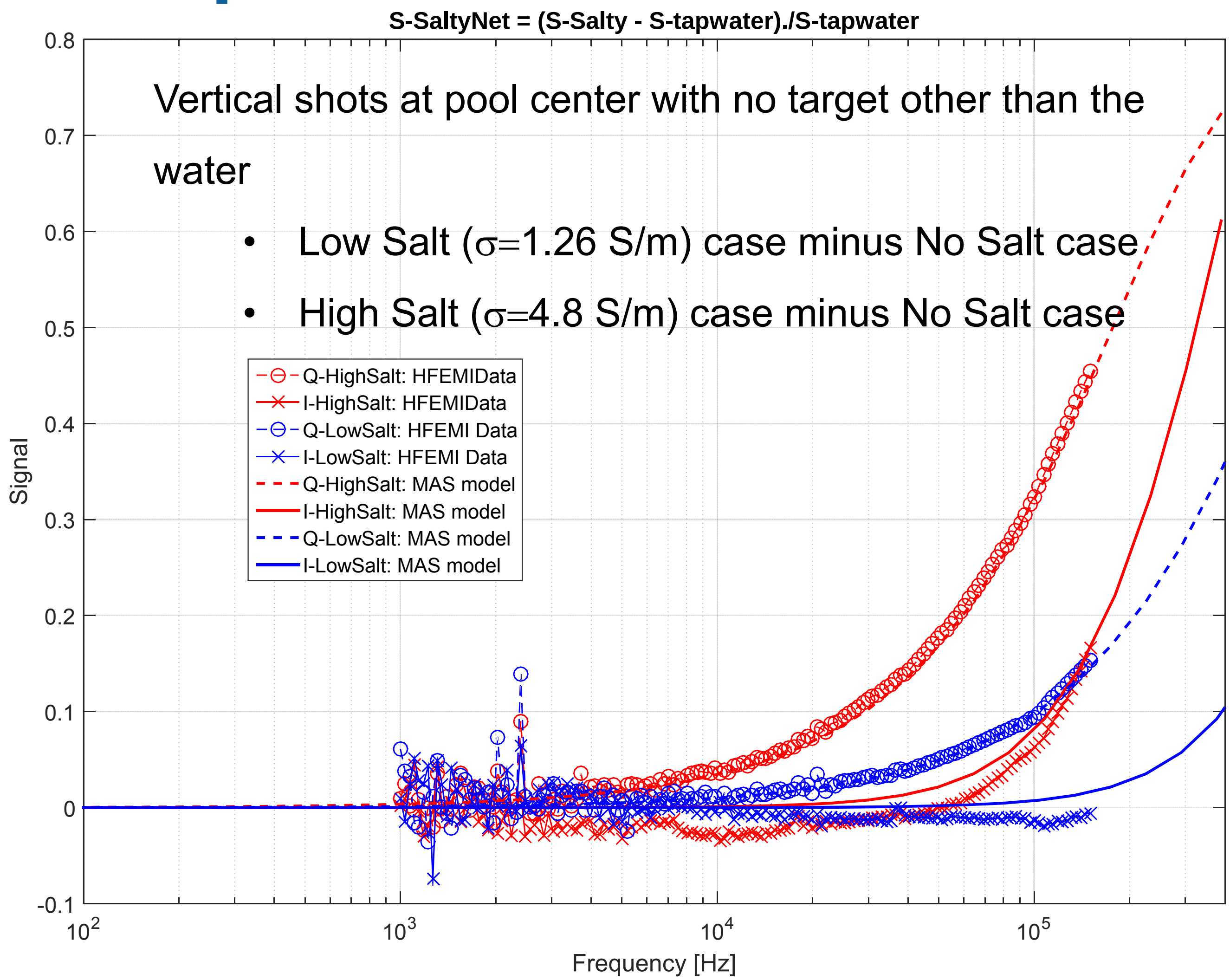
Experimental Setup

A schematic diagram of the experimental data collection



HFEMI Tx & Rx coils are about 27 cm in diameter, 12 turns. Approx distances from the coil centers to the upper and lower water surfaces are indicated.

Comparisons between data and model



In salt water we see a distinct phase shift that one must account for in both cases.

Recovering target's true signal: experimental validation

Rx

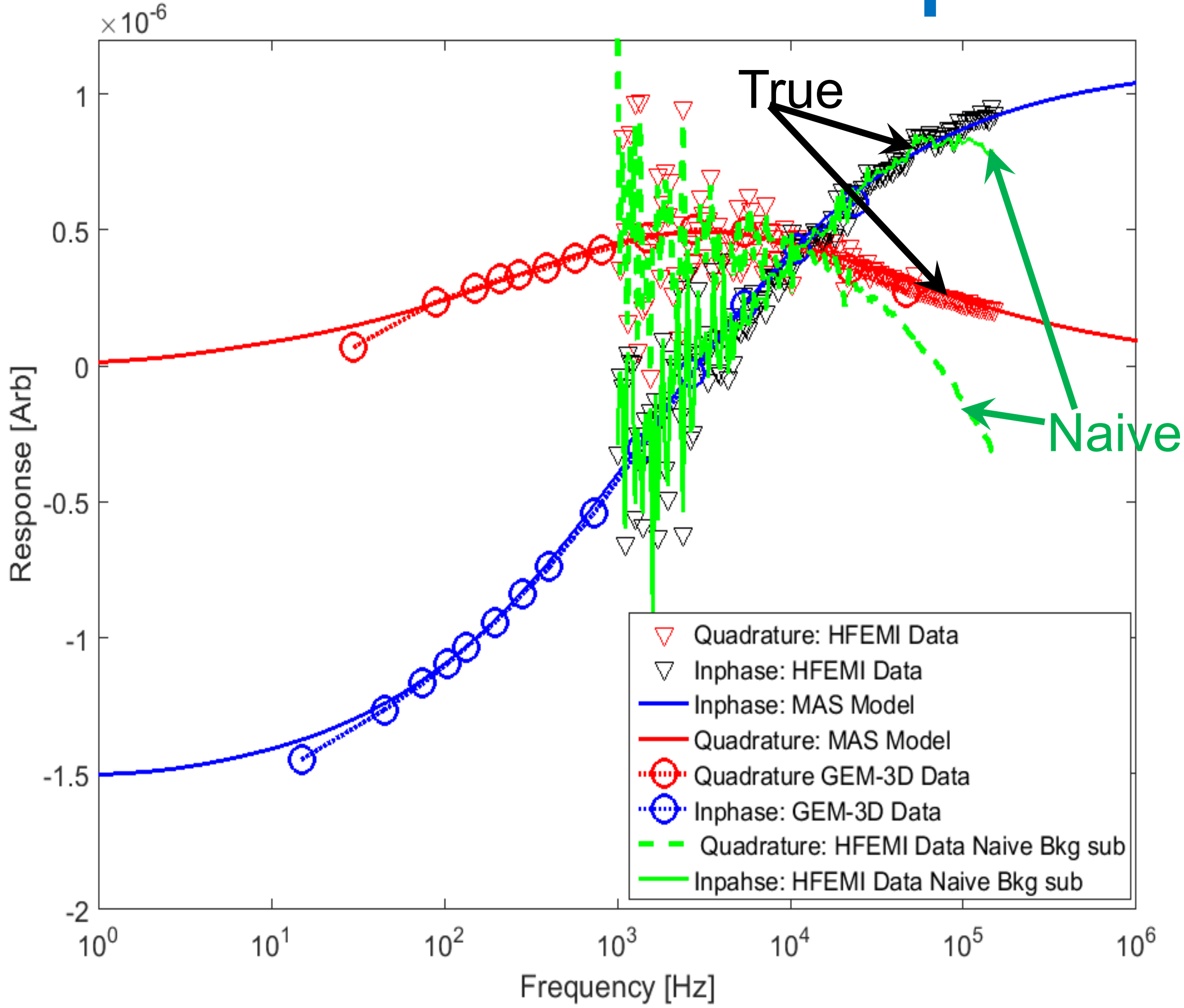
When we took data, rocket and coil were floating directly below the Rx

Tx is under the pool

Rocket floats essentially in touch with surface water but not significantly submerged

Vertical shot of floating rocket minus background water at 4.58 S/m

A New Scheme for Extracting Targets True EMI Responses



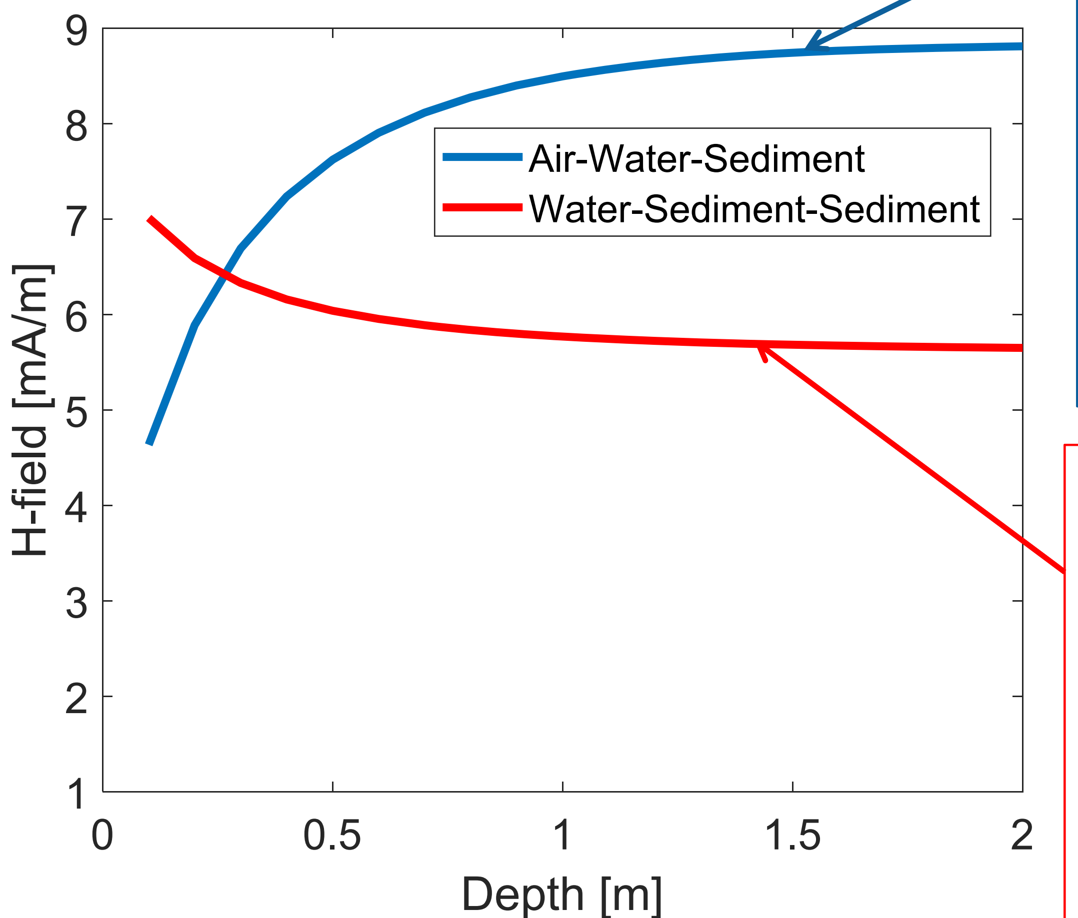
Here, a "naïve" calculation of a rocket's response simply subtracts the salt water background signal from the data, as .

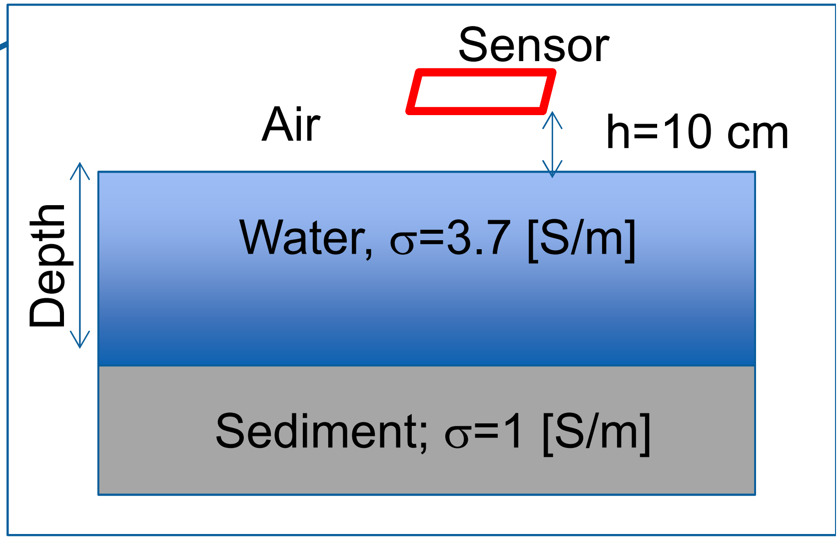
$$naive\ F_{rocket} = S_{rocket+sw} - S_{sw}$$

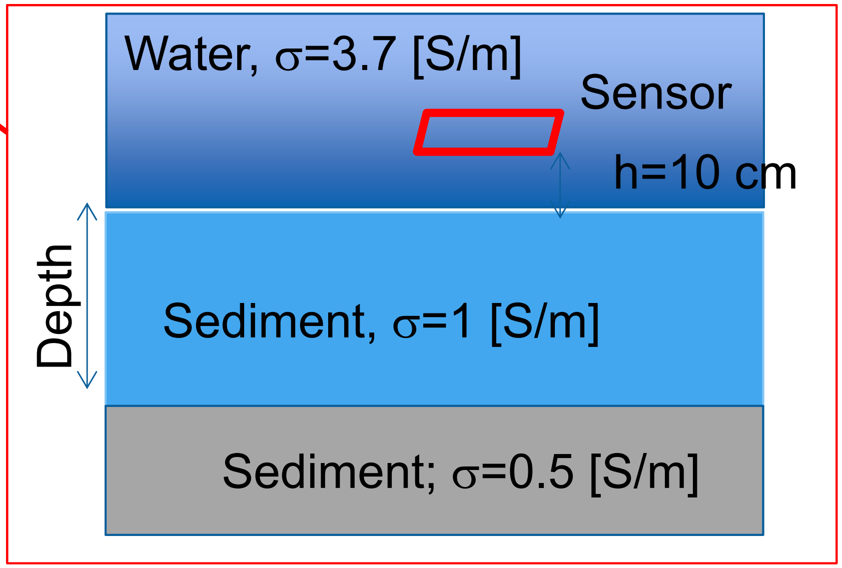
For the true, intrinsic rocket response, one must also scale the result to account for the SW alteration of the primary field.

$$true\ F_{rocket} = \left(S_{rocket+sw} - S_{sw}\right)./\,S_{sw}$$

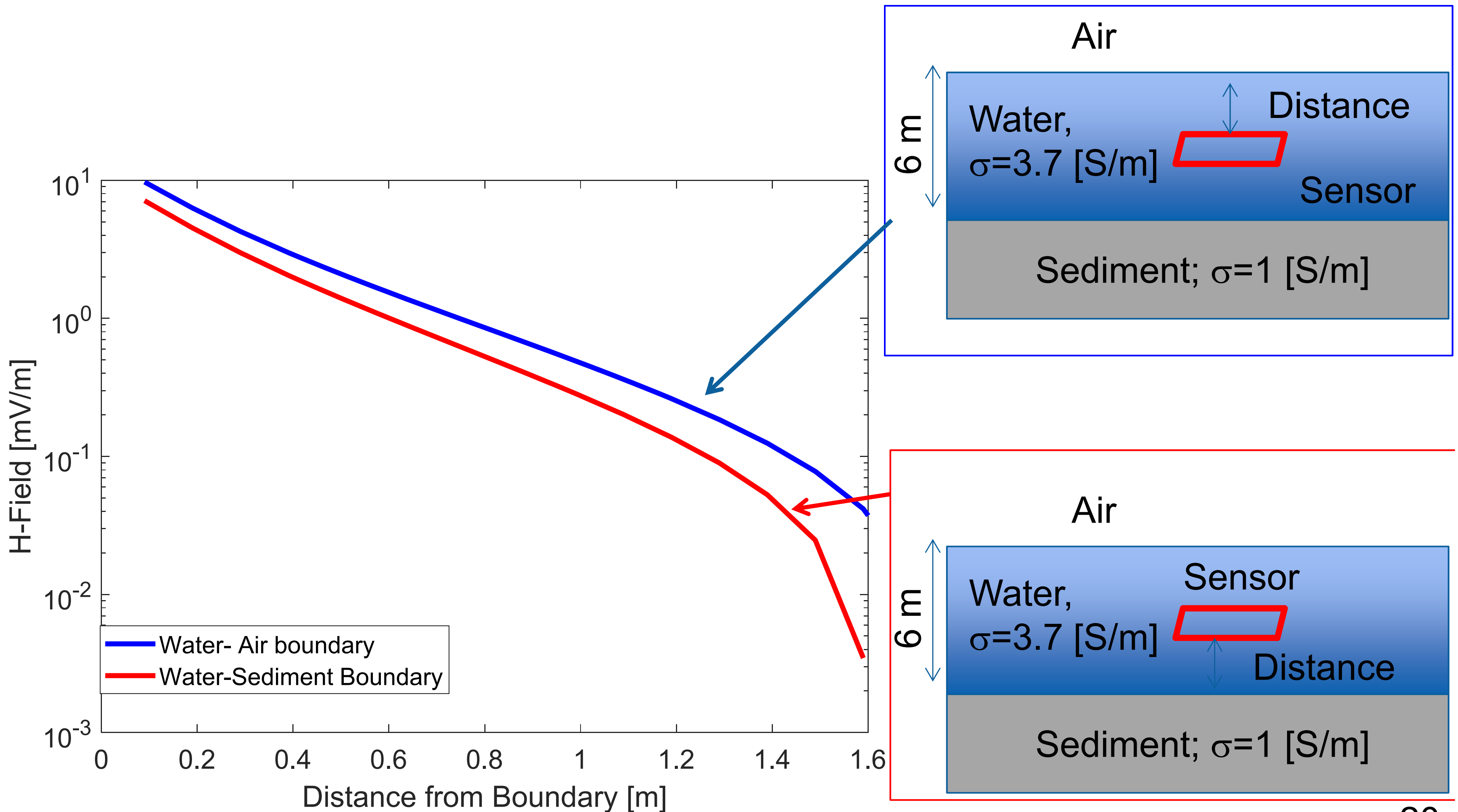
Boundary Effects



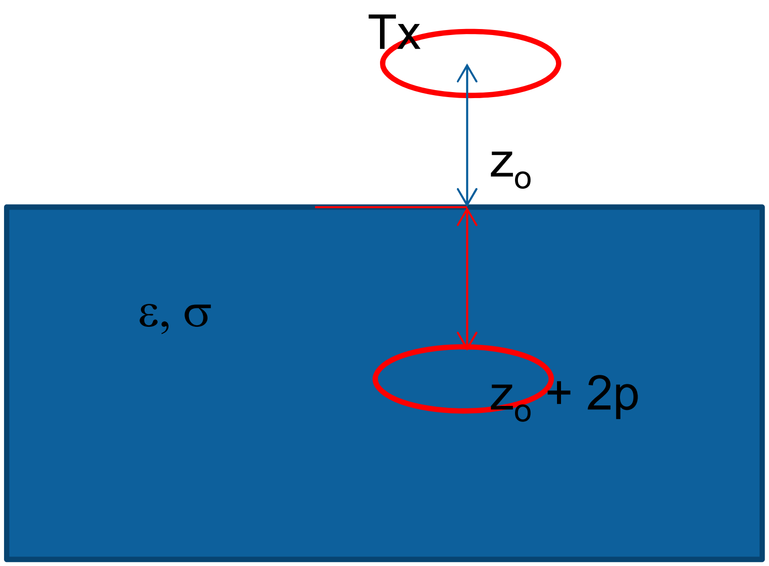




Sensor standoff effects



Complex Image method to account UW effects



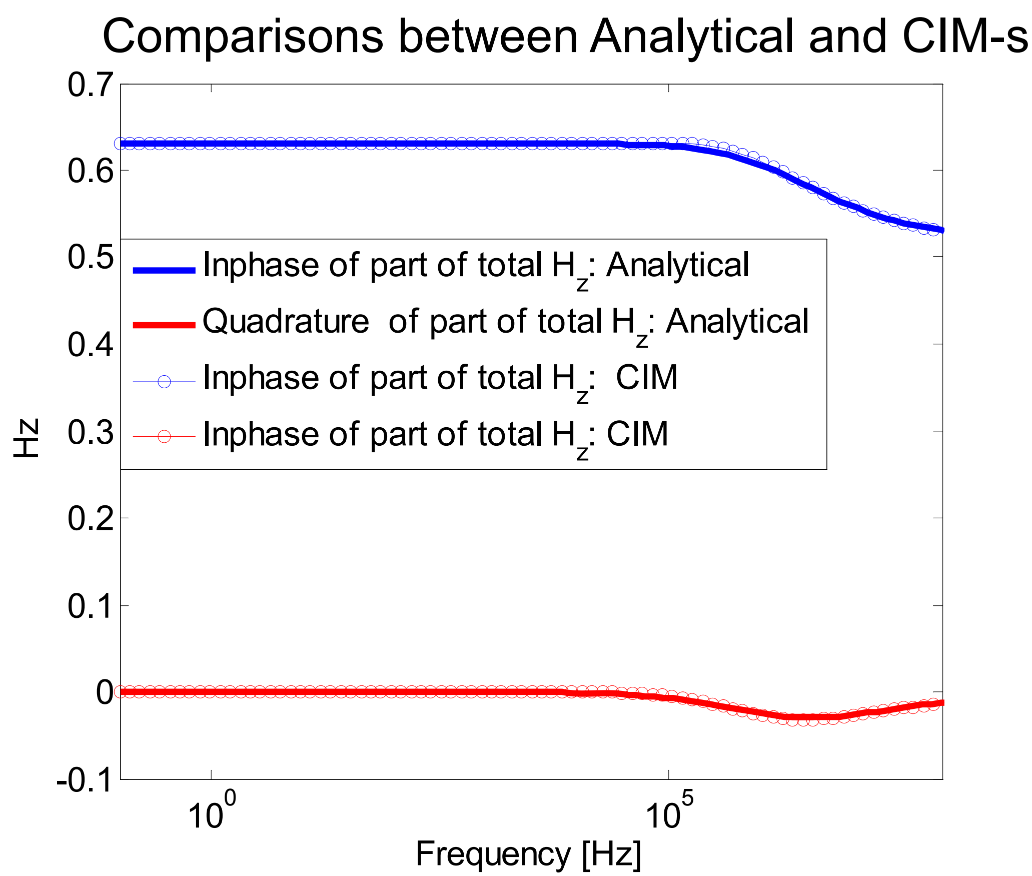
Total field outside conductor is:

$$\mathbf{H}^{total}(\mathbf{r}) = \mathbf{H}^{primary}(\mathbf{r}, x_o, y_o, z_o) + \mathbf{H}^{'}(\mathbf{r}, x_o, y_o, -(z_o + p))$$

Where p is given as:

$$p = \frac{Z}{i\omega\mu_o}; \quad Z = \frac{i\omega\mu_o}{\sqrt{\omega^2 \mu_o \varepsilon_o \varepsilon + i\sigma\omega\mu_o}}$$

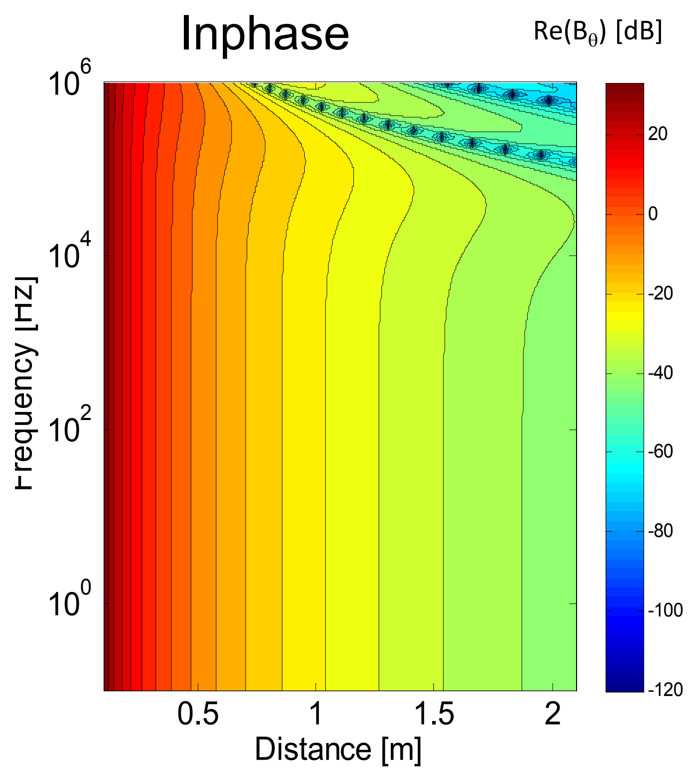
Z is surface wave impedance

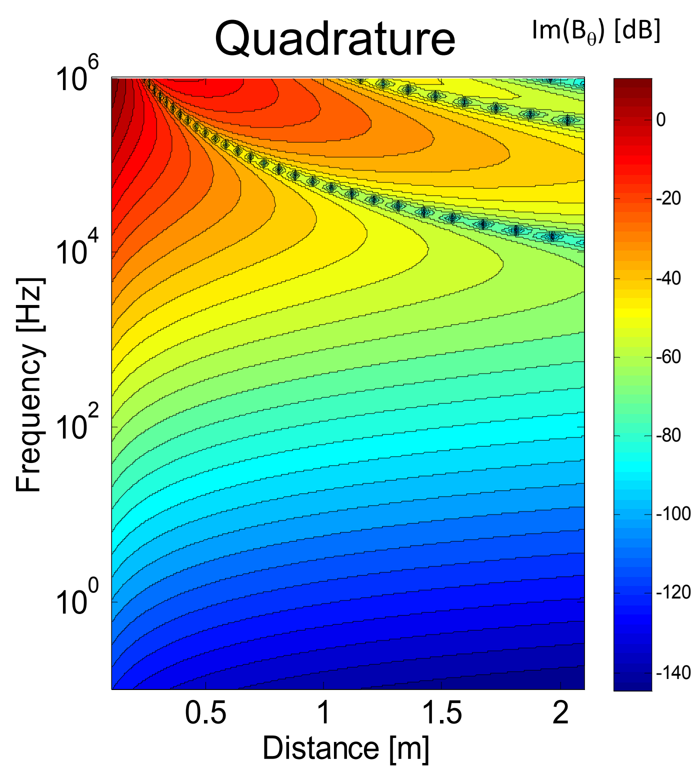


The CIM can be extended for a multi layered structure

Magnetic field due to a magnetic dipole in a conducting space

$$\mathbf{H}(\mathbf{r}) = \mathbf{G}(\mathbf{r}, \mathbf{r}_o \,|\, \hat{\mathbf{m}})\, m; \text{ where } \bar{\bar{\mathbf{G}}}(\boldsymbol{r}, \boldsymbol{r}_0 \,|\, \hat{\mathbf{m}}) = \left[\frac{3\boldsymbol{R}(\boldsymbol{R}\cdot\hat{\mathbf{m}}) - \hat{\mathbf{m}}R^2}{R^5}(1 - jkR) - \frac{k^2 \boldsymbol{R}\times(\boldsymbol{R}\times\hat{\mathbf{m}})}{R^3} \right] \frac{e^{jkR}}{4\pi}; \text{ and } k = \sqrt{\omega^2 \mu_o \varepsilon_o \varepsilon + i\sigma\omega\mu_o}$$

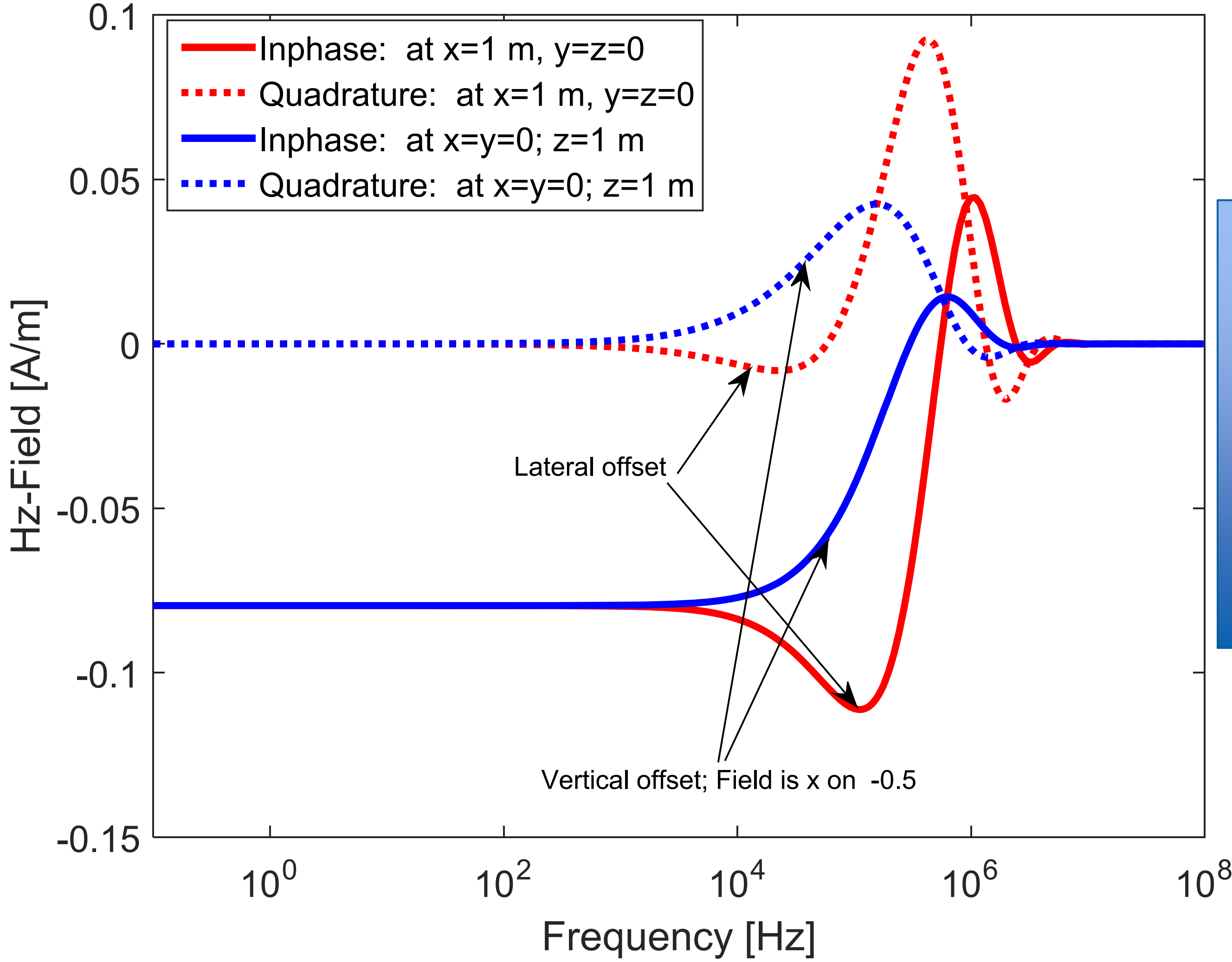


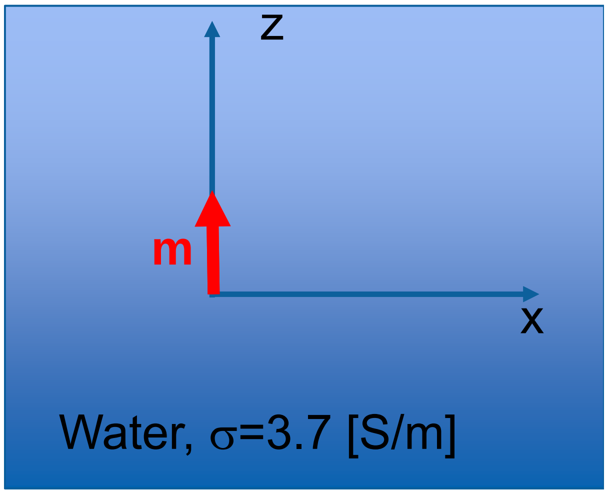


A magnetic m_z dipole placed in (σ = 4 S/m) as a function of frequency (y-axis) and distance (x-axis).

UW EMI data DO depend on phase changes/time delays.

Magnetic dipole in UW environment: offset effects

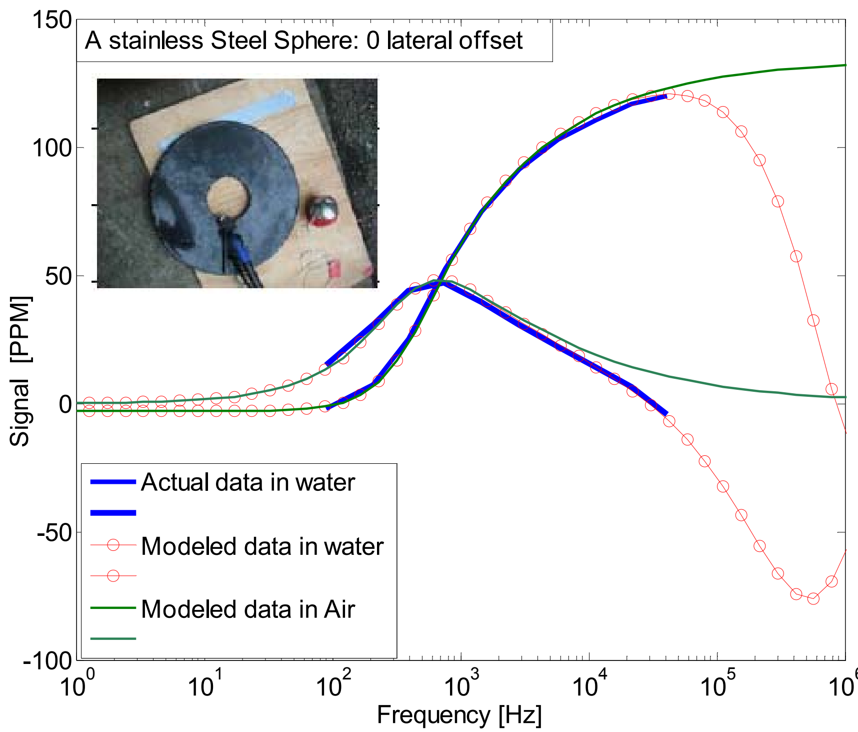


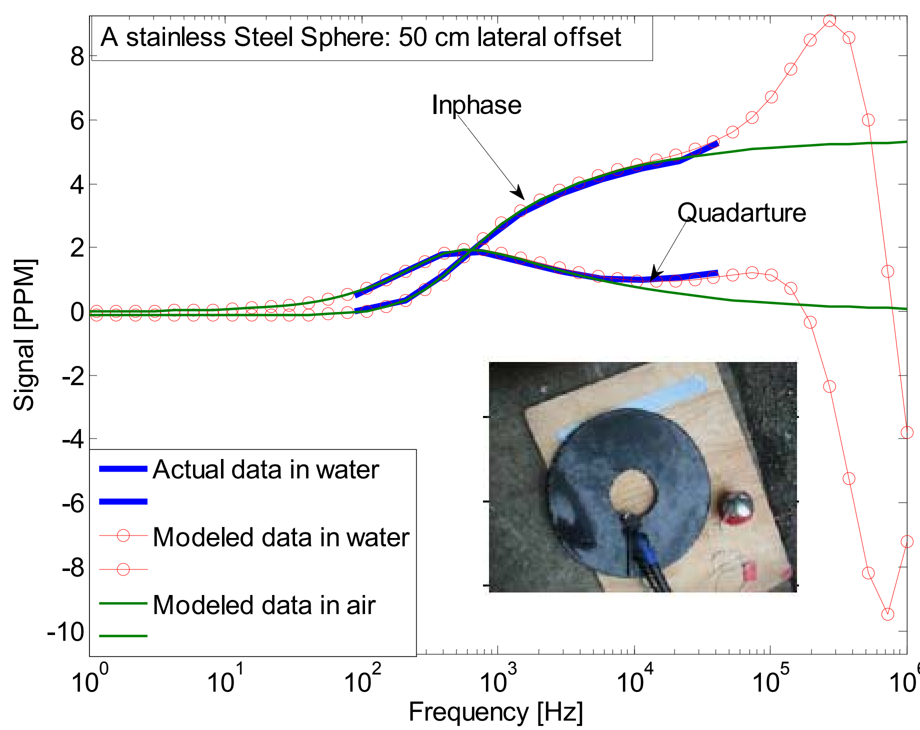


Targets EMI response

Comparisons between numerical (the MAS) and experimental data
Frequency Domain

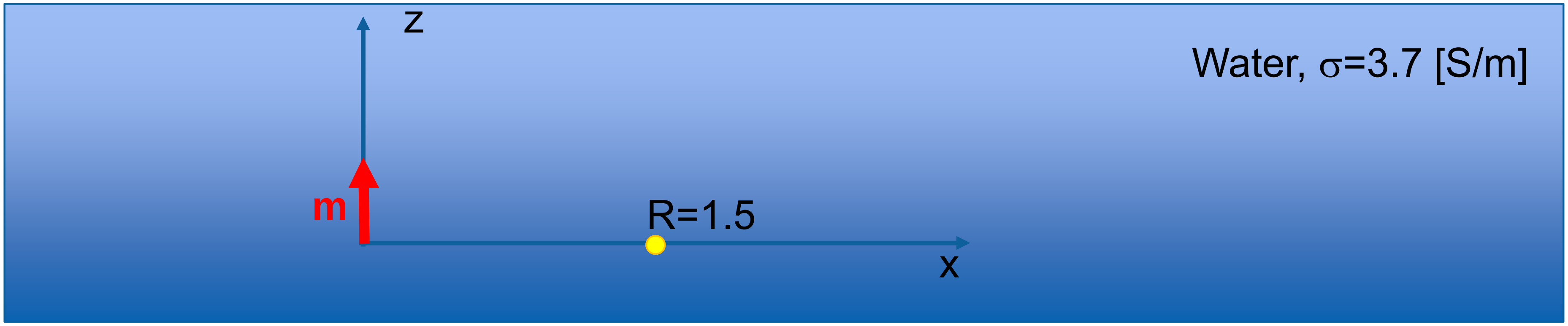
GEM-3D data obtained from SERDP-1321 final report

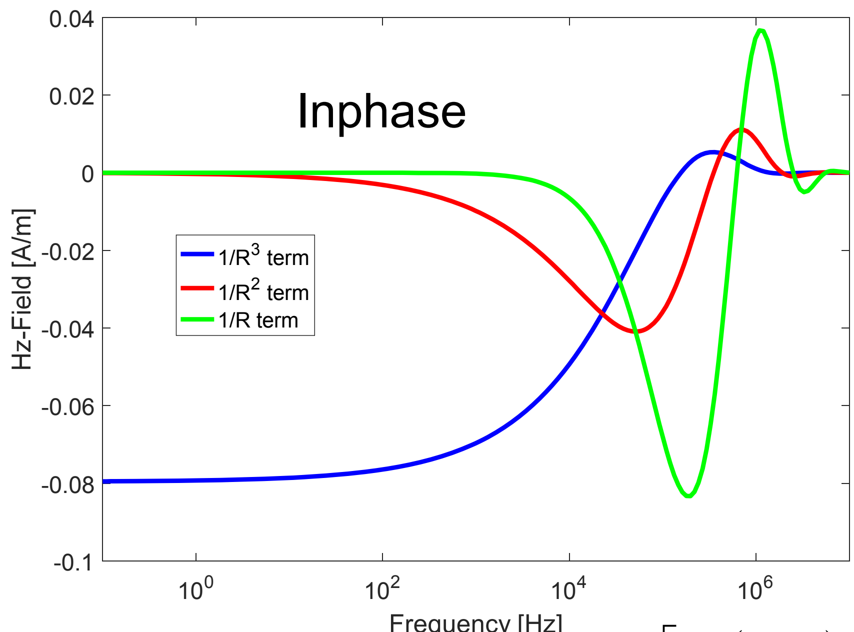


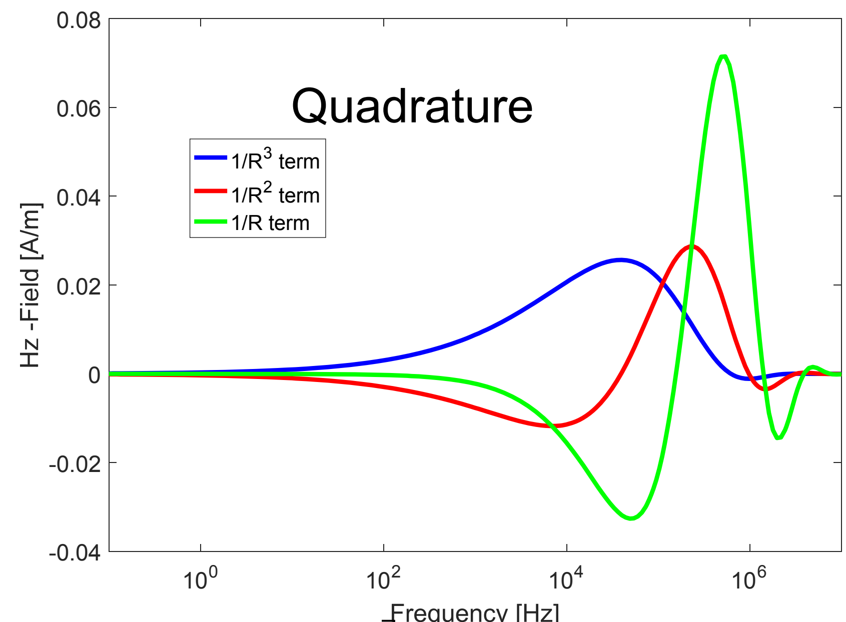


UW environment modifies signals at high frequencies (early time).

Magnetic dipole in UW environment: Contributions from different terms

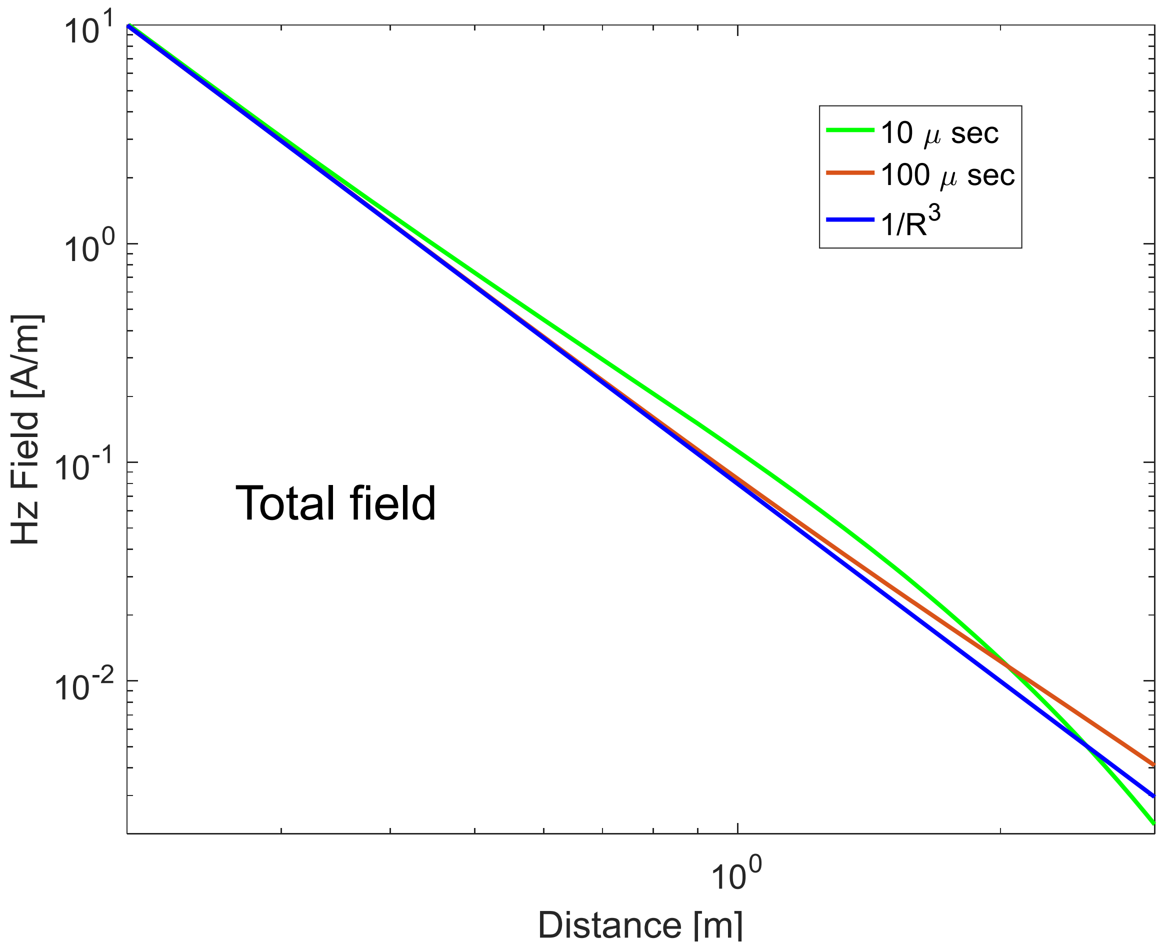


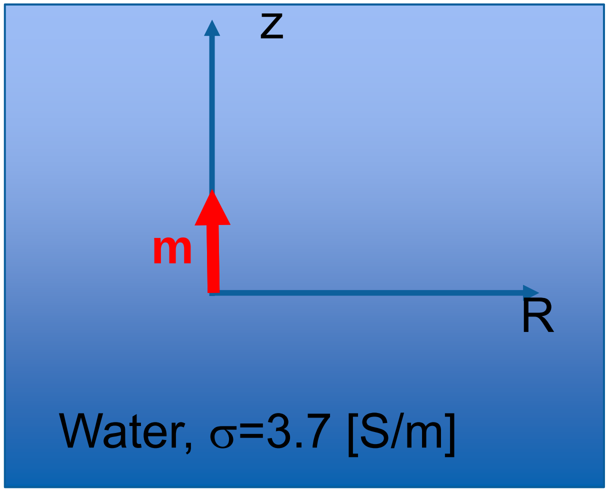




Magnetic field of a dipole $\mathbf{H}(\mathbf{r}) = \left[\frac{3\boldsymbol{R}\left(\boldsymbol{R}\cdot\hat{\mathbf{m}}\right) - \hat{\mathbf{m}}R^2}{R^5}\left(1 - jkR\right) - \frac{k^2\boldsymbol{R}\times\left(\boldsymbol{R}\times\hat{\mathbf{m}}\right)}{R^3} \right] \frac{e^{jkR}}{4\pi}$

Magnetic dipole in UW environment: Field vs distance





Summary

- Conducting environment distorts the both primary and secondary magnetic fields at early times/high frequencies
- Air/Water/Sediment boundaries affect on the EMI signals
- Signal distortion is a function of separation distances between the target and the Tx coil, and between the target and observation points
- Larger separation distance ➔ Target's EMI signals distortions extend at later times
- A new scheme was developed for extracting targets true EMI responses

Publications 2018

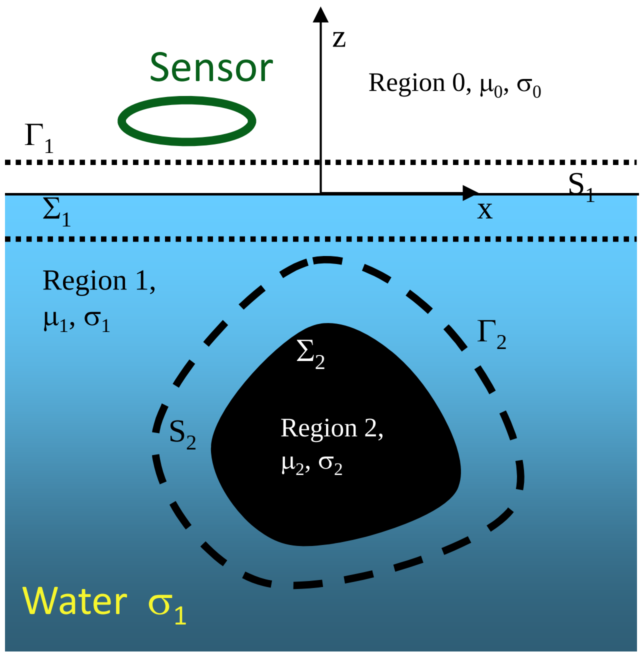
1.Fridon Shubitidze, Kevin O'Neill, Benjamin E. Barrowes, Dartmouth College (USA); John B. Sigman, "Accounting for the influence of salt water in the physics required for processing underwater UXO EMI signals", *Proceedings of SPIE 2018*

2.F. Shubitidze, *and et al. "*Modeling Targets EMI Responses in an Underwater Environment*", SAGEEP-2018.*

BACKUP MATERIAL

Solving under water boundary value EMI problem

The Method of Auxiliary Sources (MAS) for the UW EMI problem



Electric and magnetic field inside and outside the object:

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi\mu_\alpha}\sum_{i=1}\left(\bar{\bar{\mathbf{I}}} + \frac{\nabla\nabla}{k_\alpha^2}\right)\frac{e^{-jk_\alpha R}}{R}\,\mathbf{p}_i$$

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\mu_\alpha}\sum_{i=1}\nabla\times\left(\frac{e^{-jk_\alpha R}}{R}\,\mathbf{p}_i\right)$$

Boundary conditions:

The tangential components of the electric and magnetic fields must be continuous

$$[\hat{\mathbf{n}} \times \mathbf{E}_{\beta-1}^{total}] = [\hat{\mathbf{n}} \times \mathbf{E}_{\beta}^{total}], \quad \beta=1,2$$

$$[\hat{\mathbf{n}} \times \mathbf{H}_{\beta-1}^{total}] = [\hat{\mathbf{n}} \times \mathbf{H}_{\beta}^{total}], \quad \beta=1,2$$

BC's reduce to a linear system of equations!

High Frequency approximations EMI problem

For the land-based problem at high frequencies (or early times) we have developed a Thin-Skin Approximation (TSA) for the MAS

$$\nabla \cdot \mathbf{H} = 0 \quad ? \quad \oint_A \mathbf{H} \cdot d\mathbf{A} = 0$$

$$\text{TSA}: \quad \frac{\partial H_{2,n}}{\partial n} = ik H_{2,n}(n,u,v), \quad k=\sqrt{-i\omega\mu\mu_o\sigma}$$

The MAS/TSA breaks down for UW EMI problems; this forced us to employ the MAS/SIBC (SIBC: Surface Impedance Boundary Condition)

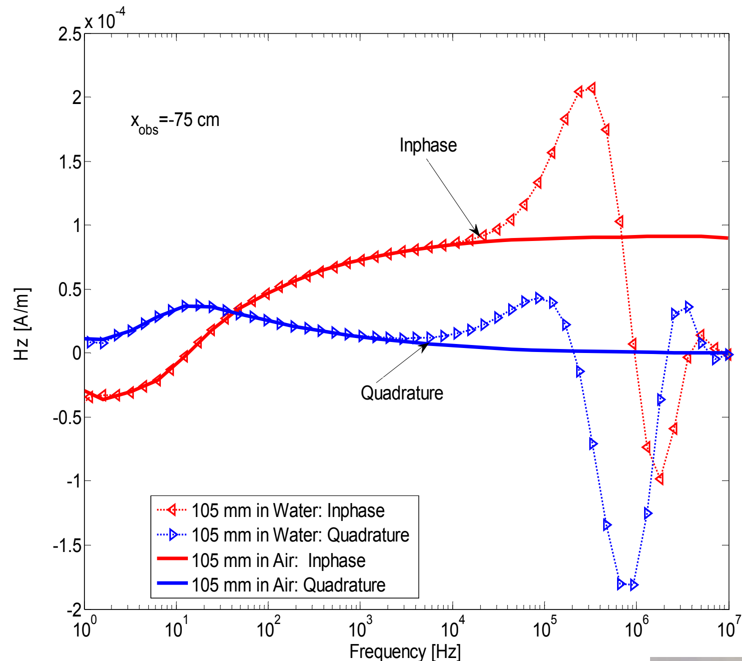
SIBC at high frequencies: $\hat{\mathbf{n}} \times [\hat{\mathbf{n}} \times \mathbf{H}] = \dfrac{1}{Z_s}[\hat{\mathbf{n}} \times \mathbf{E}]$

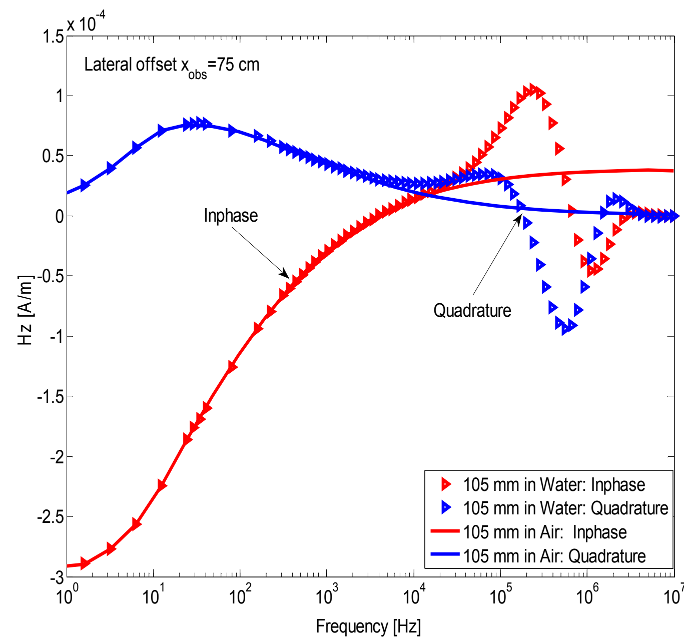
The surface impedance is a function of the skin depth:

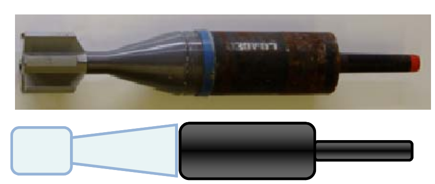
$$Z_s = (1+j)/\sigma\delta = (1+j)\sqrt{\omega\mu/2\sigma}$$

EMI problems studies

Heterogeneous UXO-like object



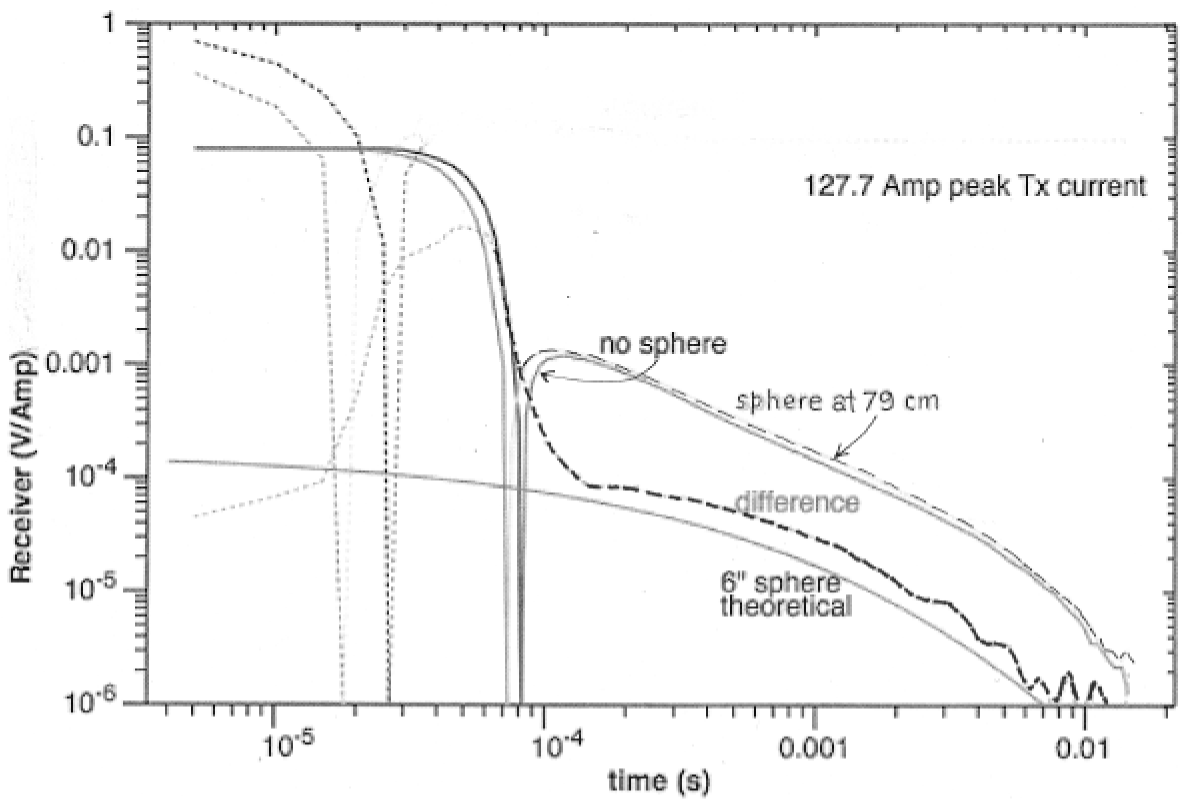




Actual and modeled UXO

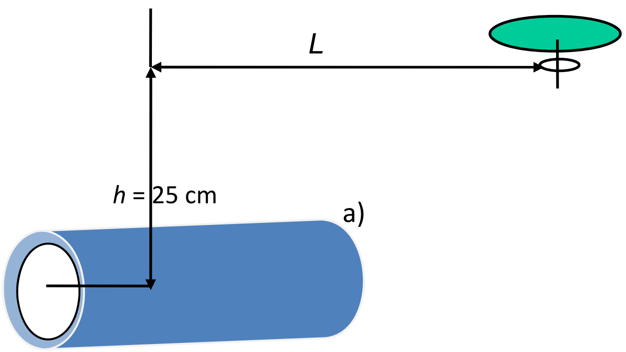
There is significant interaction between the object and the conducting water; this depends on which part is closer to the sensor

A sphere in UW experimental data

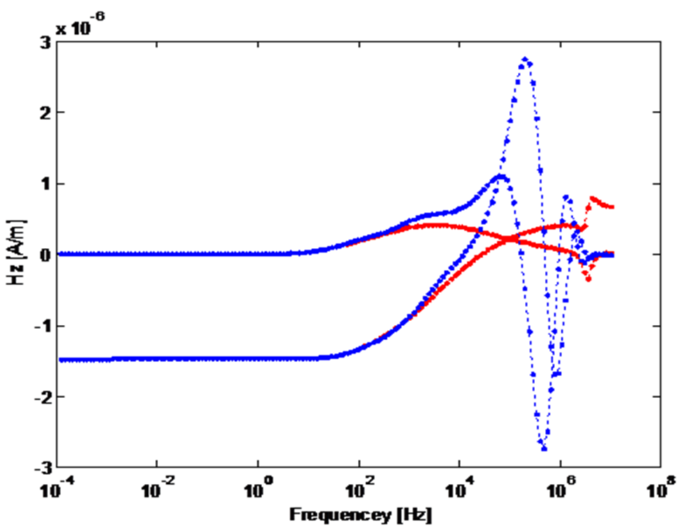


Graph courtesy of SERDP MR 2321 Final Report By H. Frank Morrison, Marine Advanced Research, Inc

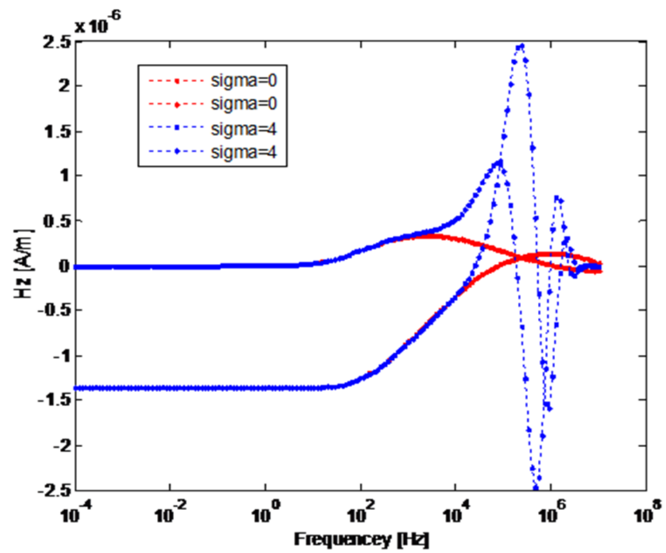
A pipe in a conducting environment



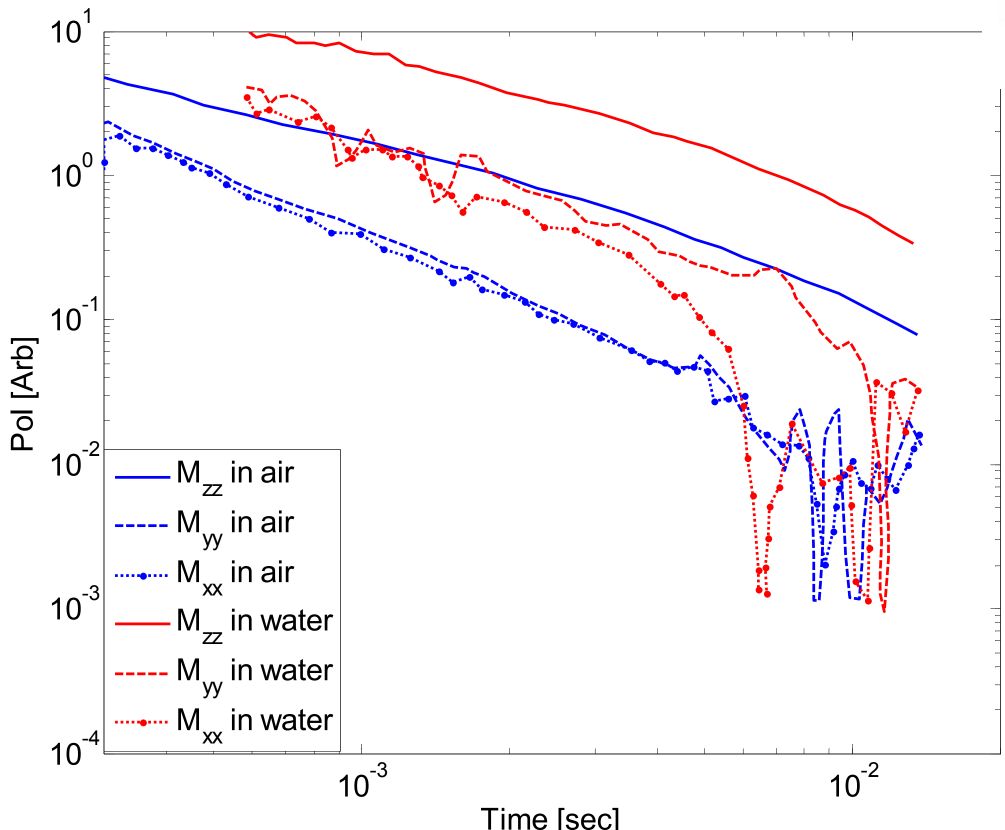
Pipe thicknesses is 10 mm



Pipe thicknesses is 5 mm



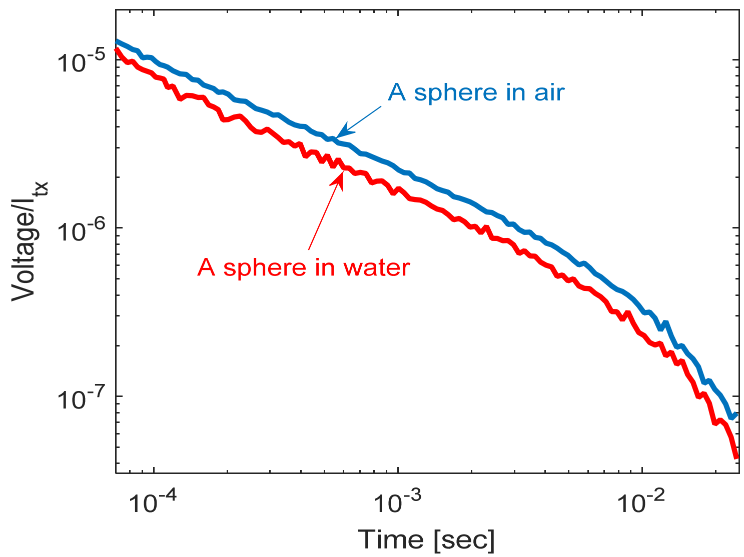
Comparisons between in air and in water data for 105 mm

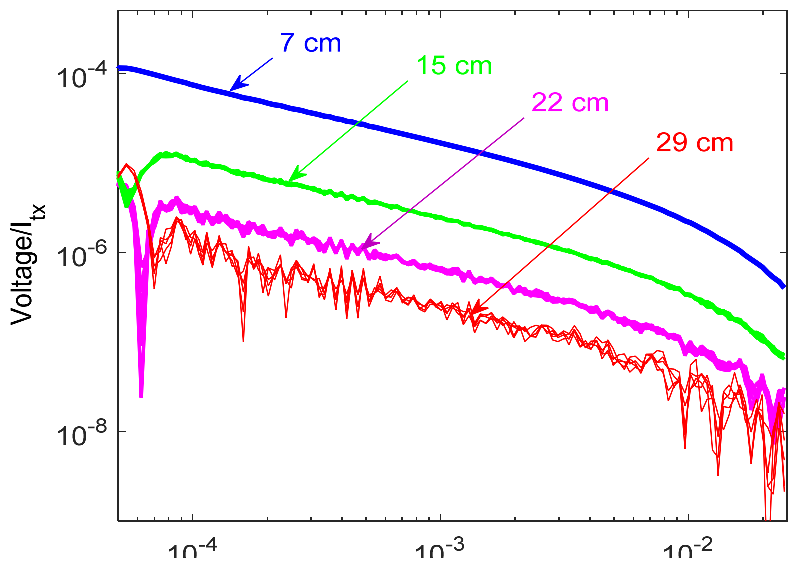


Graph courtesy of SERDP MR 2321 Final Report By H. Frank Morrison, Marine Advanced Research, Inc

UW TEMTADS data

Measured EMI signals for a 4”, submerged aluminum sphere

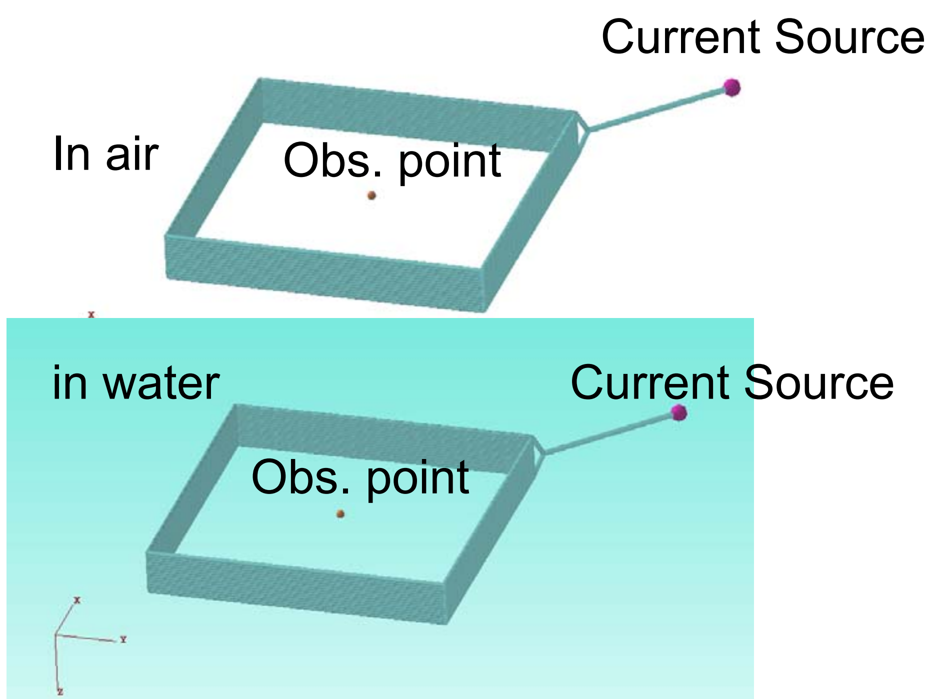


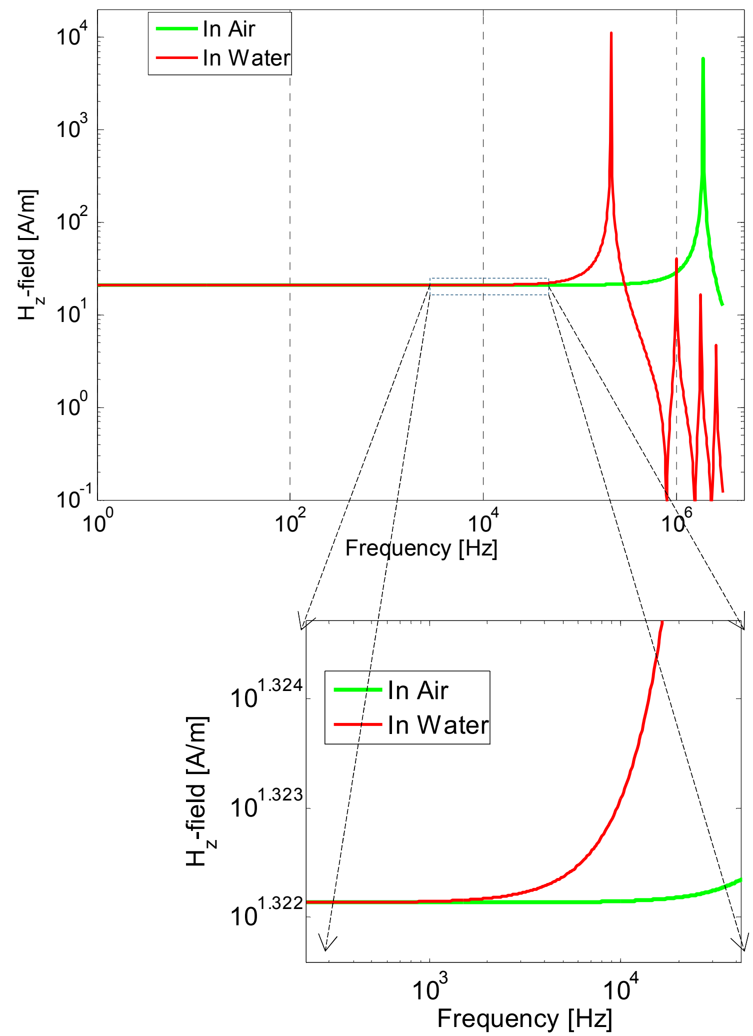


Asses current EMI sensors' capabilities

3d EMI solvers for systems detailed characterization

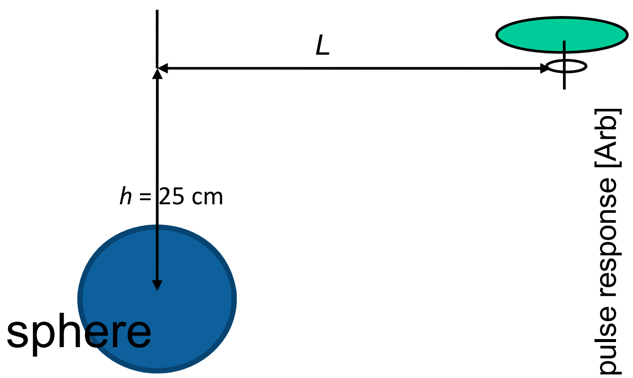
A 68 cm x 68cm square coil with
16 turns placed:

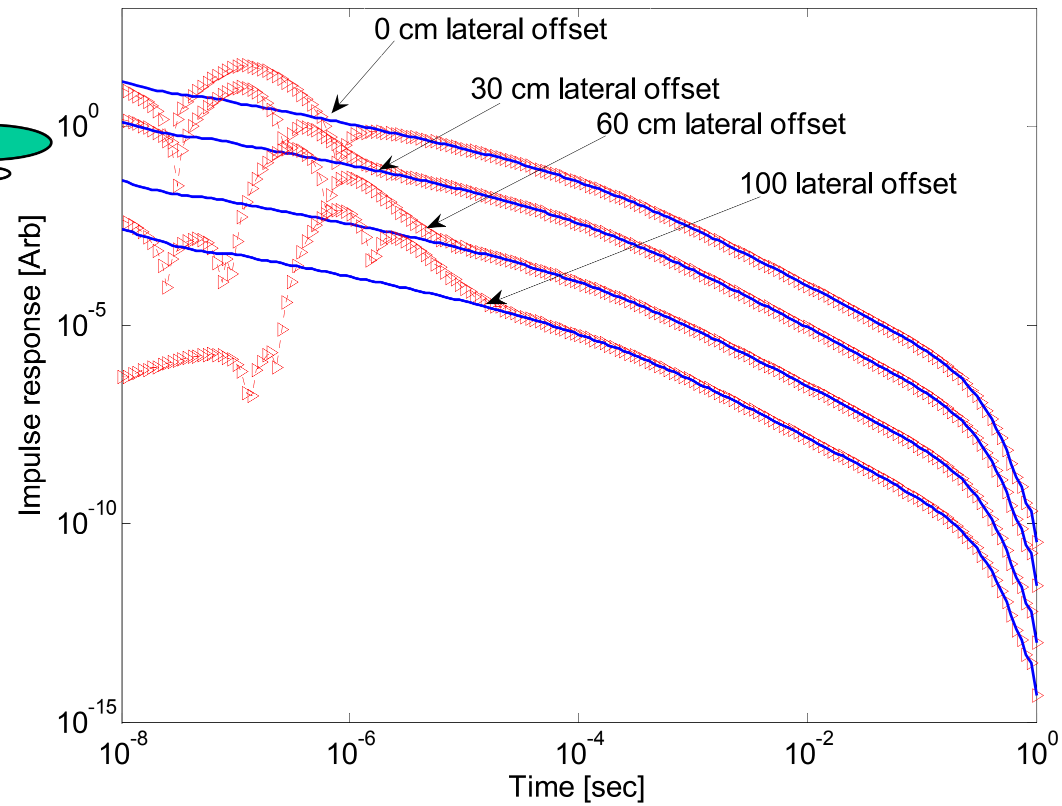




Targets EMI response in TD

Numerical studies: EMI response from a conducting and permeable sphere in TD, which is illuminated with an idealized EM-61 sensor





- In UW, target responses in early time gates differ from those in free space;
- These differences move to later time channels when distances between transmitter and targets increase