Modeling Targets' EMI Responses in an Underwater Environment

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Outline

- UW UXO problem
- EMI sensors in UW environment
- Complete models for the primary and secondary magnetic fields in UW
- Results
  - Experimental
  - Numerical studies
  - A New Scheme for Extracting Targets True EMI Responses
- Conclusions

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

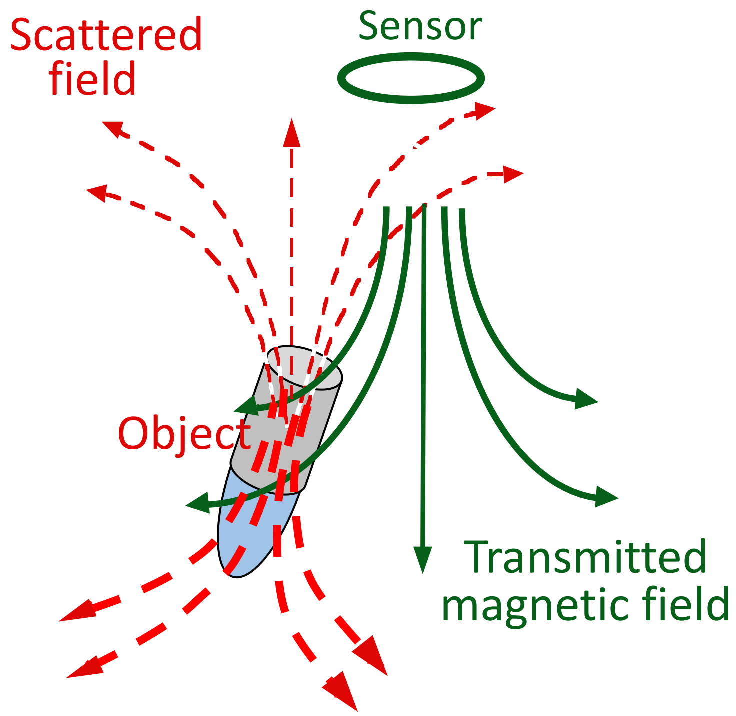
However, direct application of land-based methods to UW scenarios can lead to incorrect interpretations of UW EMI data

- **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

Mathematical formulations: for land based and UW EMI problems

EMI Problem for free space

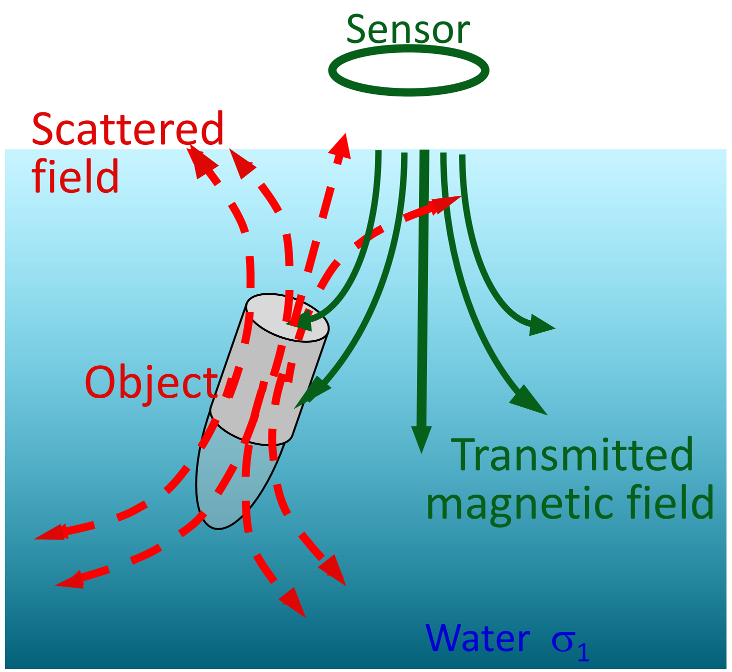


Governing equation: $\begin{cases} \nabla^2 \psi = 0, & \text{outside the object} \\ \nabla^2 \vec{\Pi} + k^2 \vec{\Pi} = 0, & \text{inside the object} \end{cases}$

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

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

EMI Problem for UW environment



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

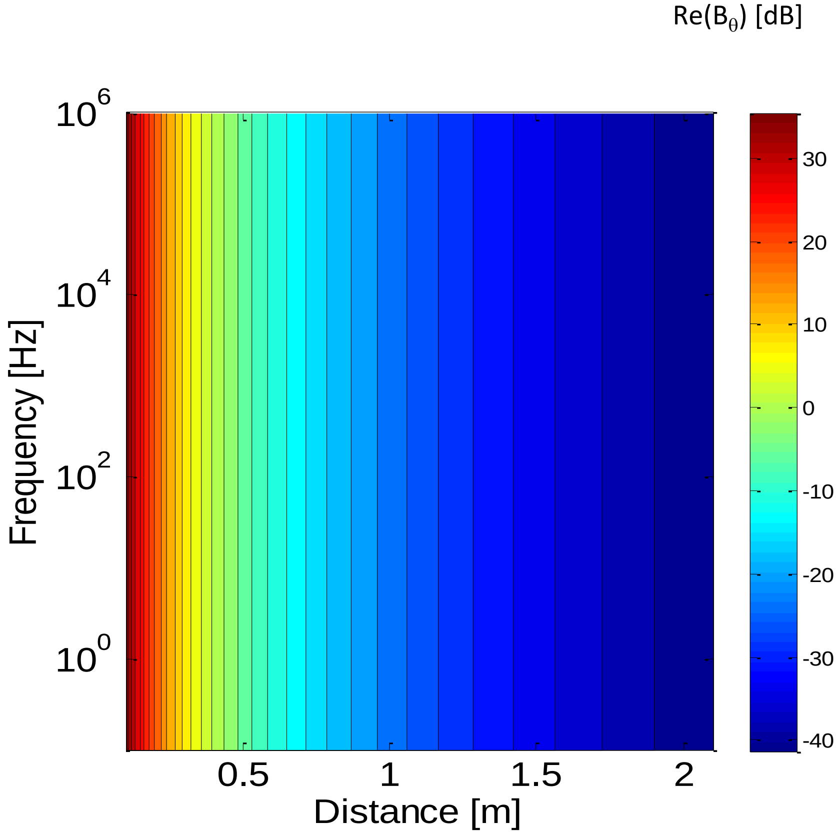
The scattered magnetic field is

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

Both the phase and the amplitude change

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,

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

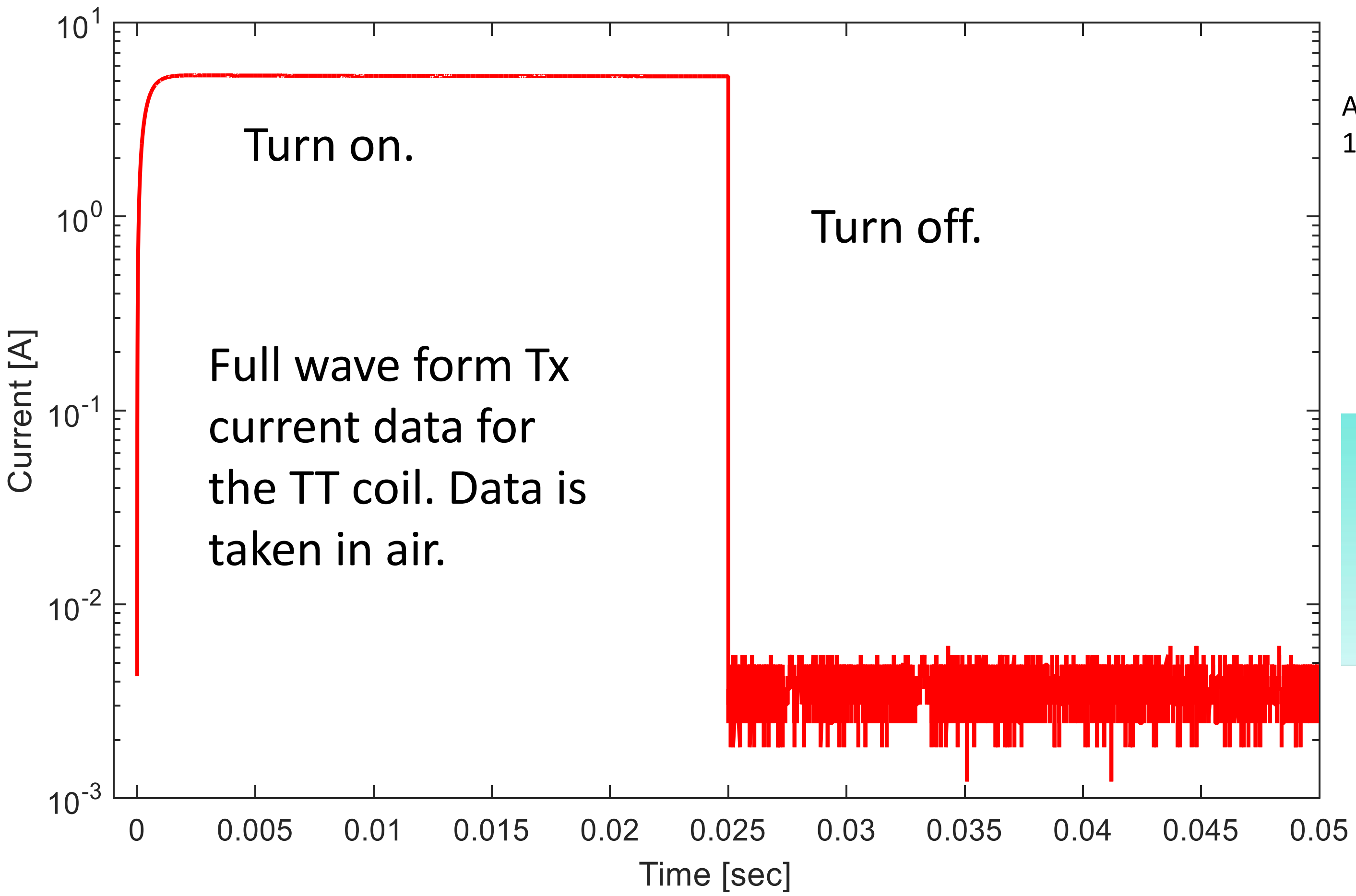
is magnetic field produces by a Tx at $\mathbf{r}_o$ point

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

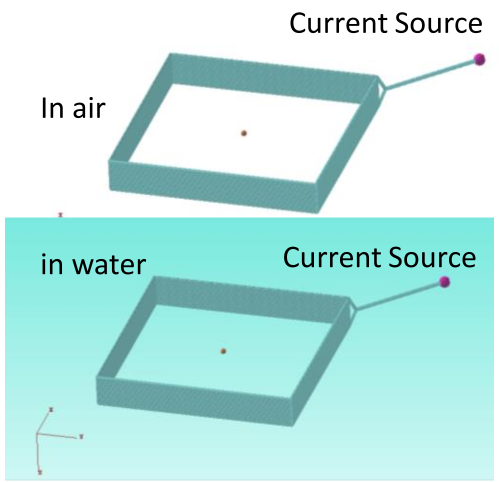
Land based EMI data DO NOT depend on phase changes/time delays.

EMI sensors in UW environment

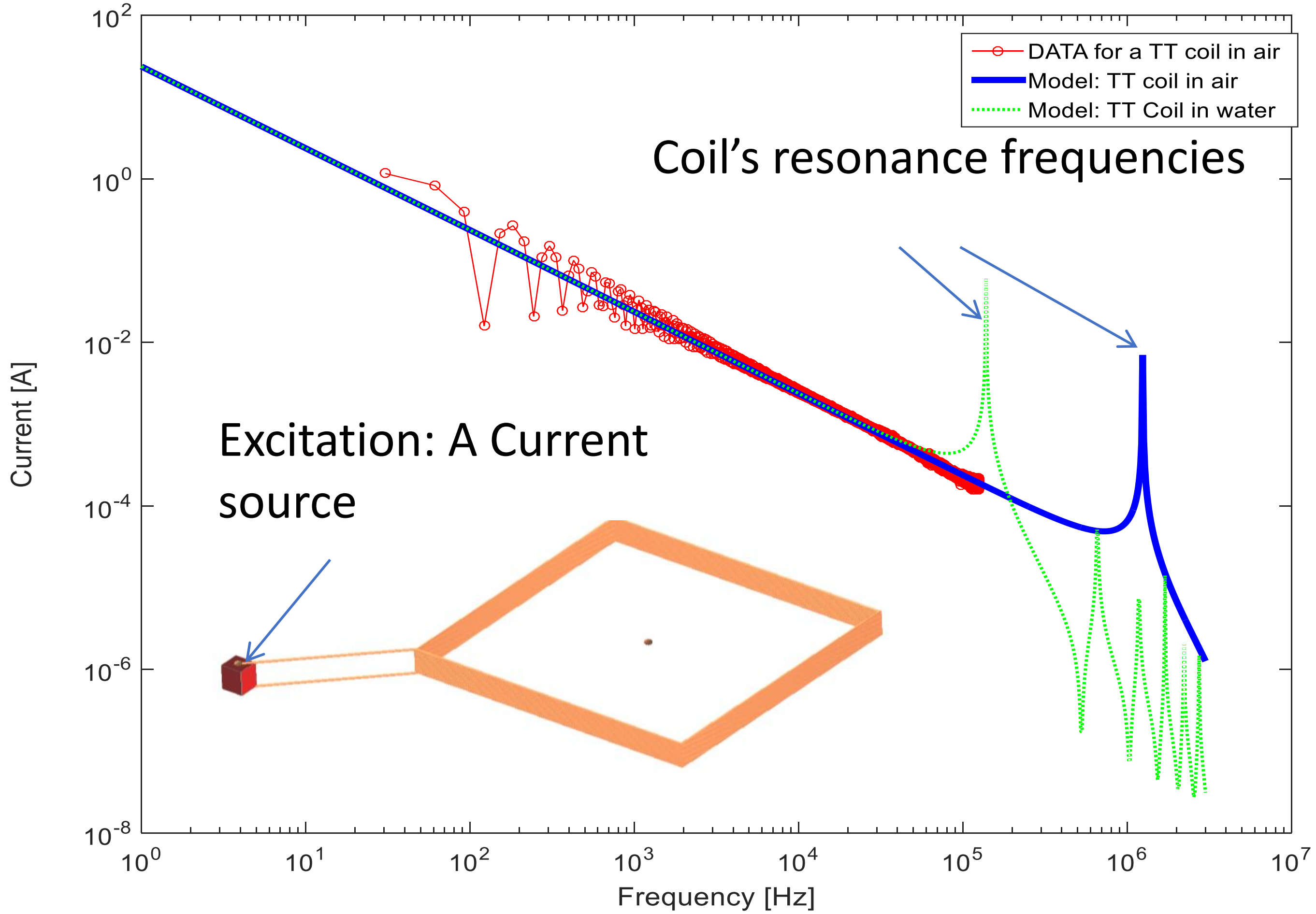
Use 3d EMI solvers for detailed characterization of EMI systems



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



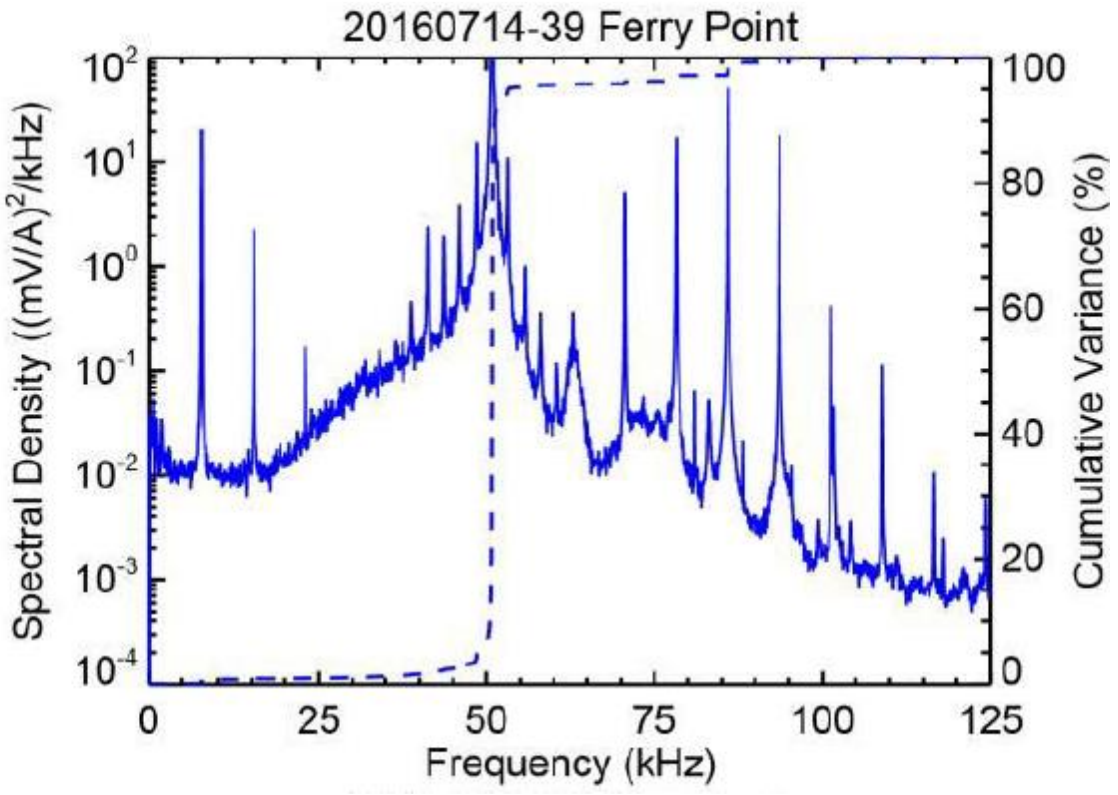
EMI sensors in UW environment



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.

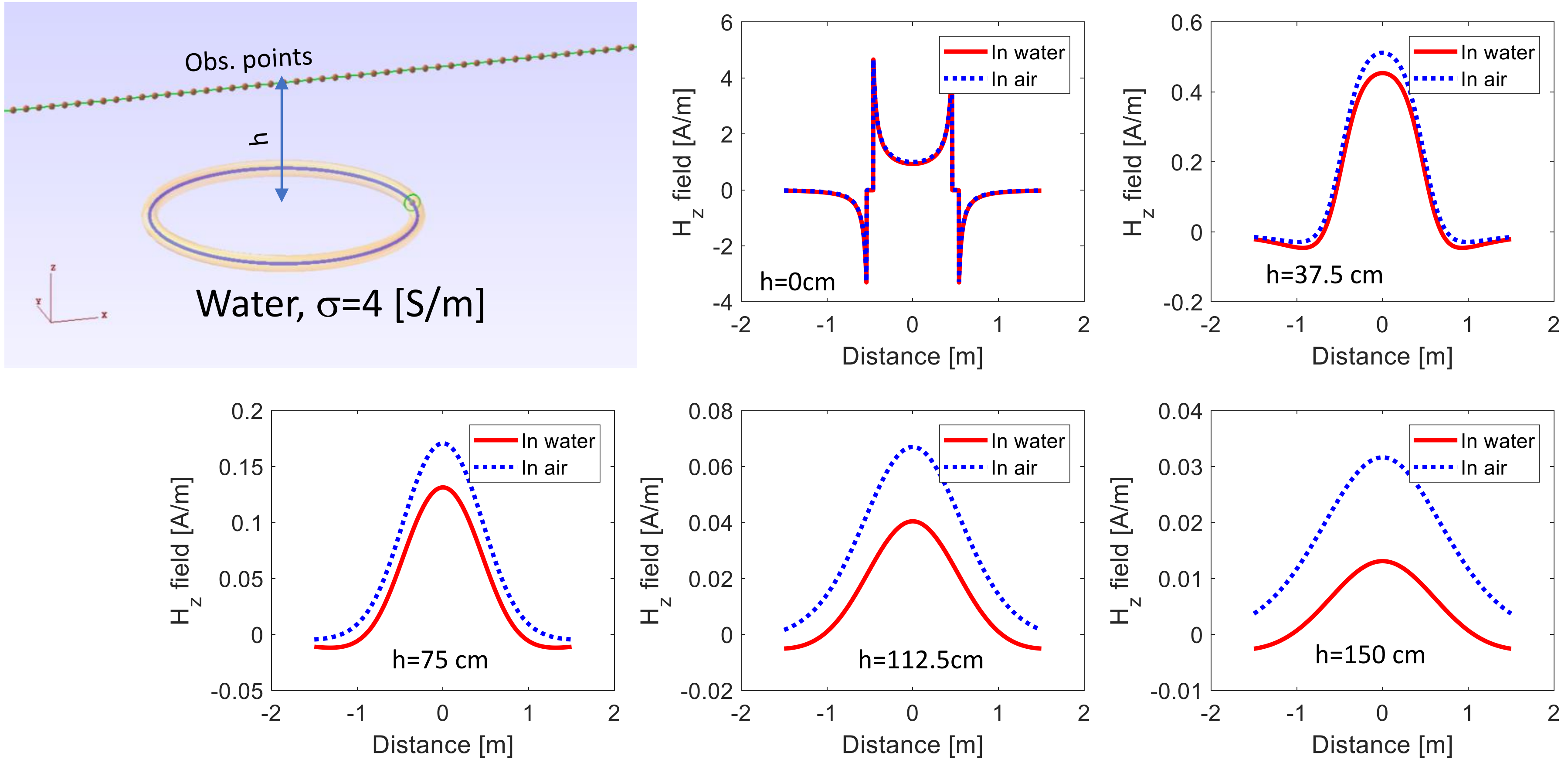
EMI sensors in UW environment …



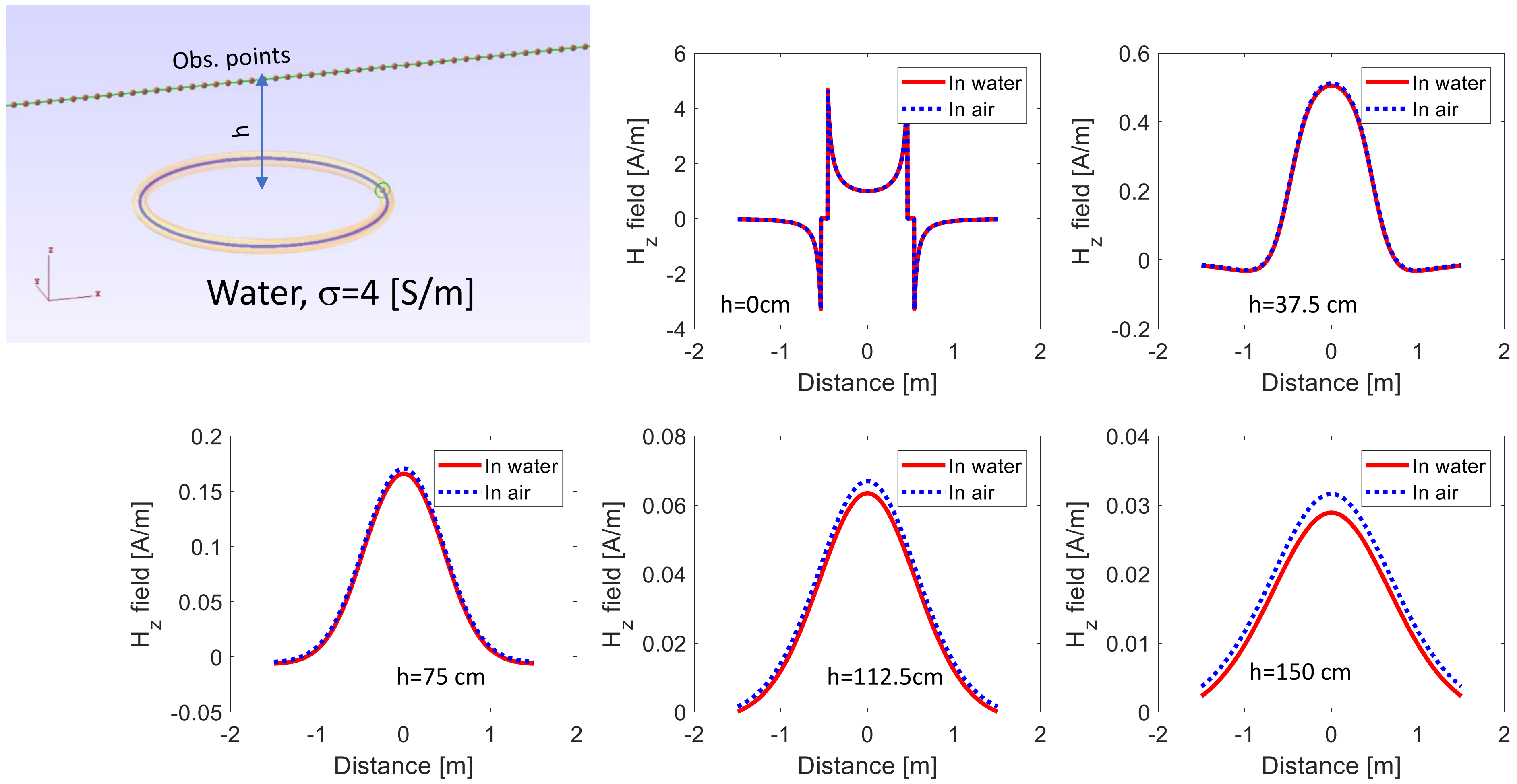
Our model predicts/ explains noise spectra observed in actual data.

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

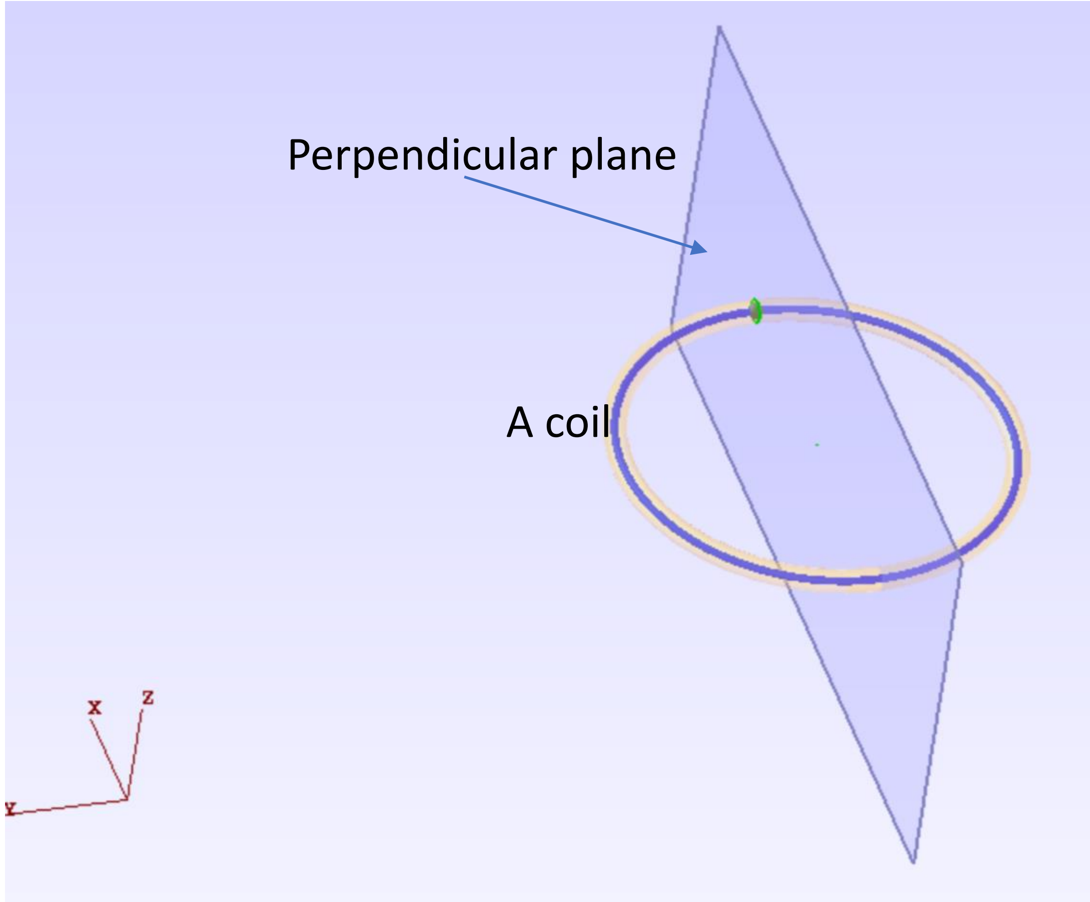
EMI sensors in UW environment …
100 μsec

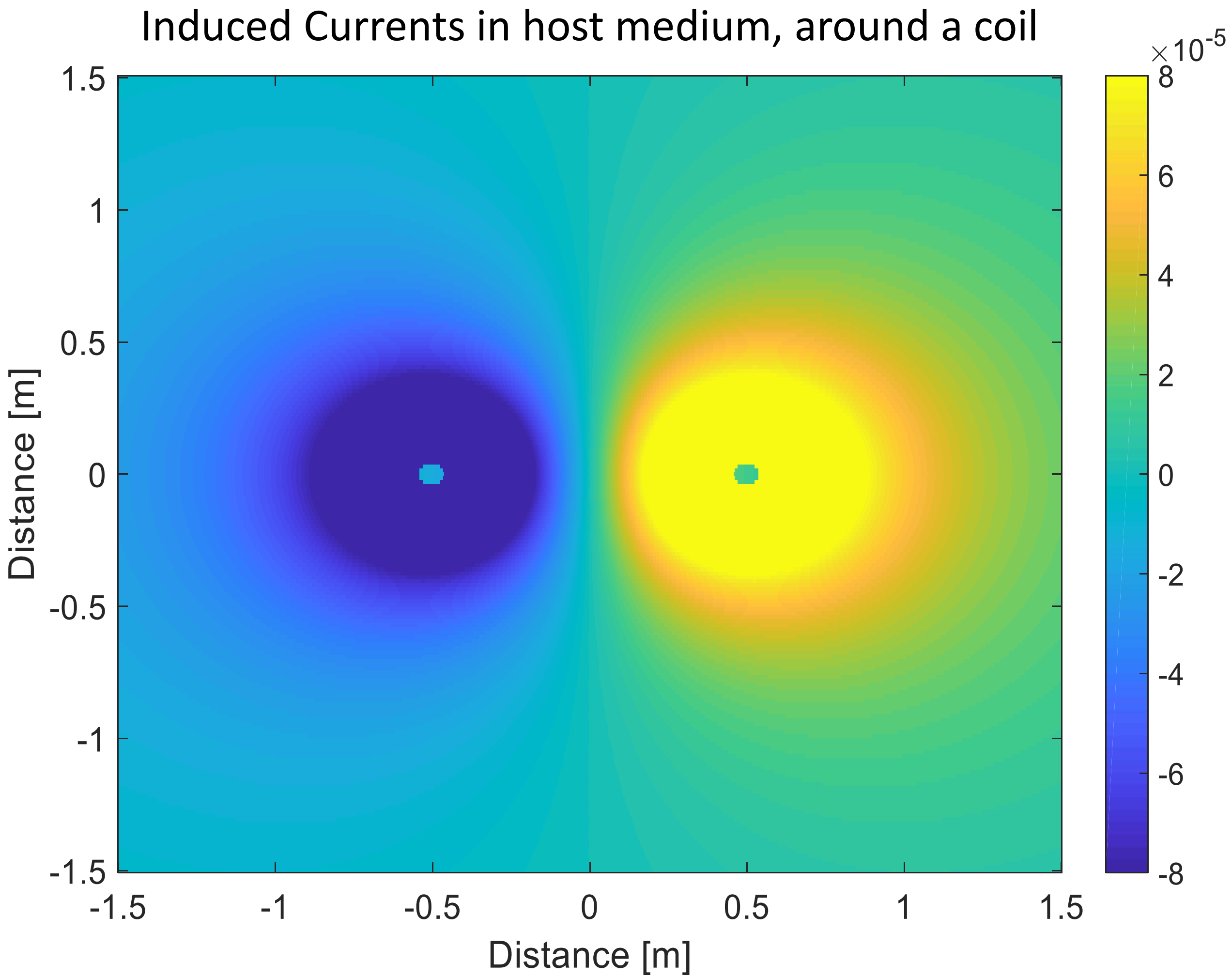


EMI sensors in UW environment …
1 msec



Induced Currents

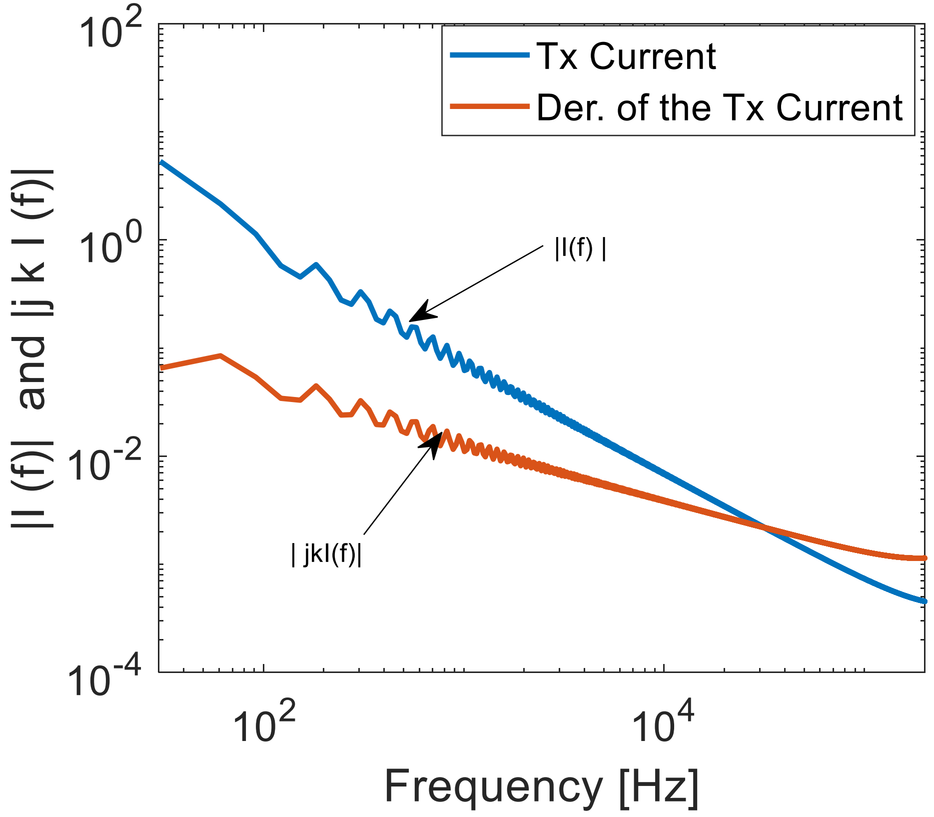


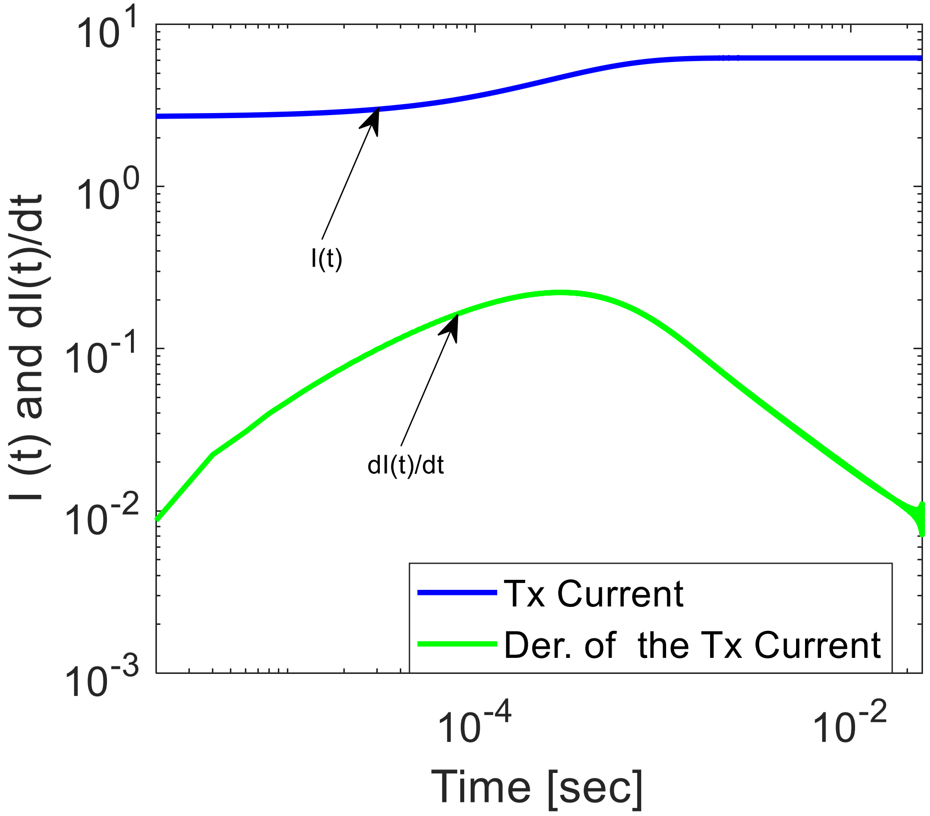


Total Primary Magnetic field

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

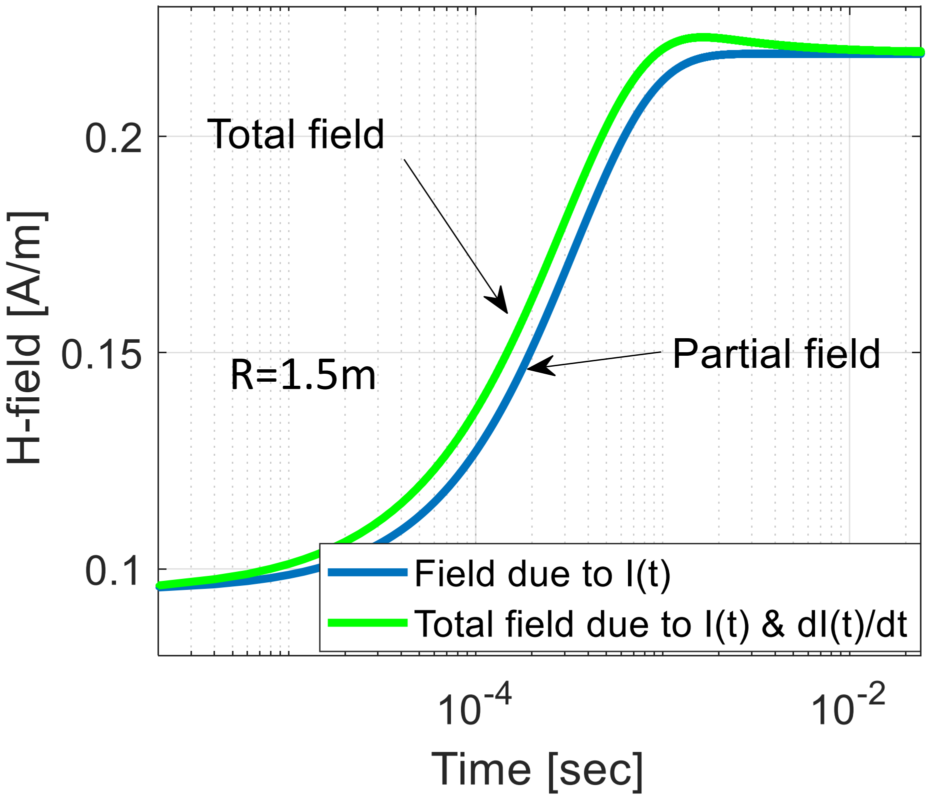
$$\mathbf{H}_{total}(\mathbf{r},\mathbf{r}_o) = \frac{1}{4\pi}\left(\frac{I}{R} + \frac{1}{c}\frac{\partial I}{\partial t}\right)\frac{d\mathbf{L}\times\mathbf{R}}{R^2}$$

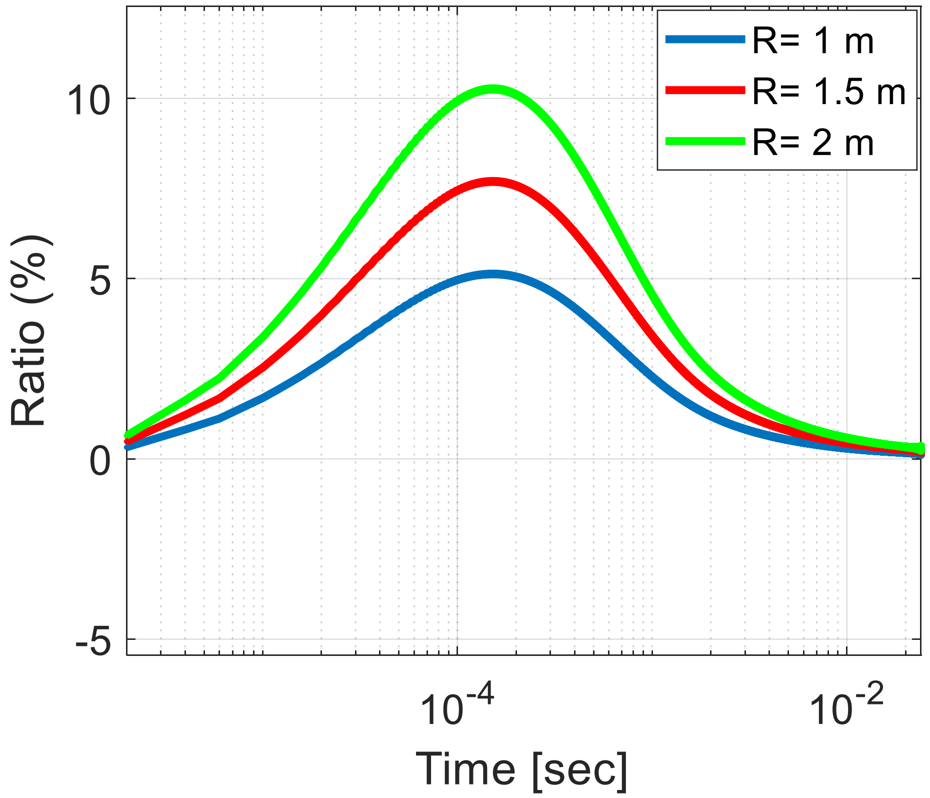
Partial field

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

Ratio

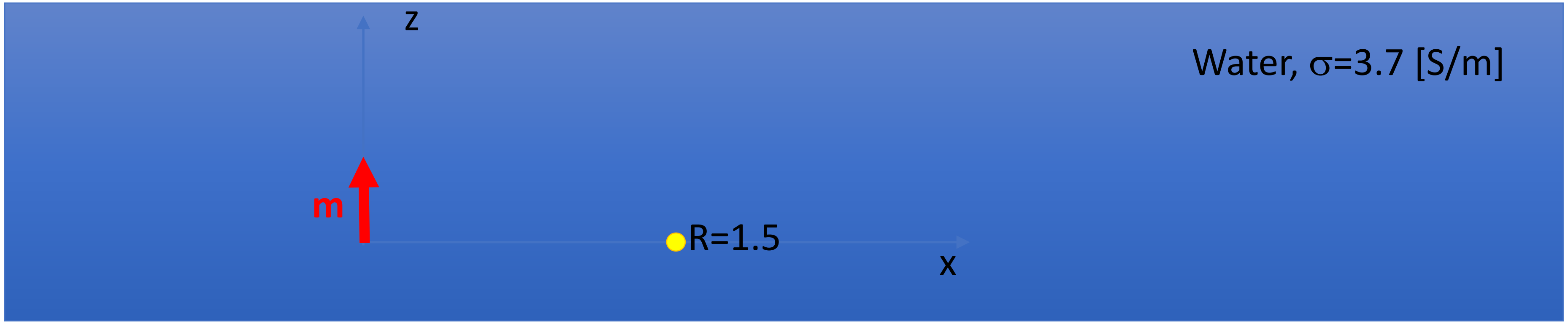
$$Ration = 100\frac{\left|\mathbf{H}_{total} - \mathbf{H}_{patial}\right|}{\left|\mathbf{H}_{patial}\right|}$$

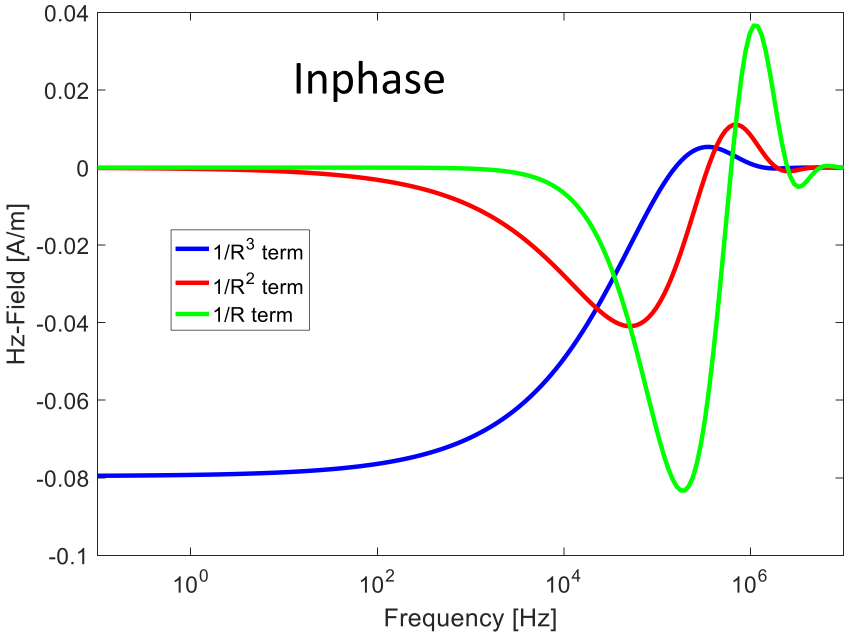


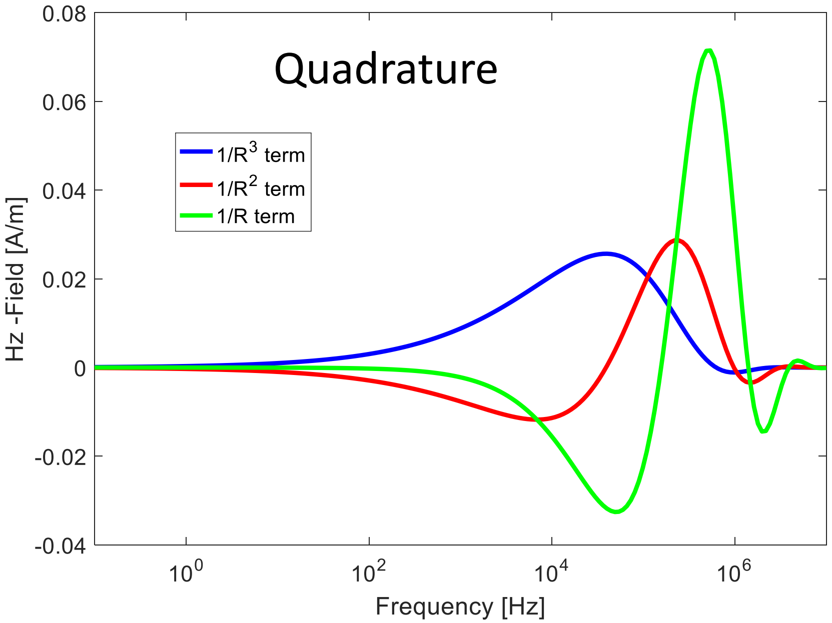


Magnetic dipole in UW environment: Contributions from different terms

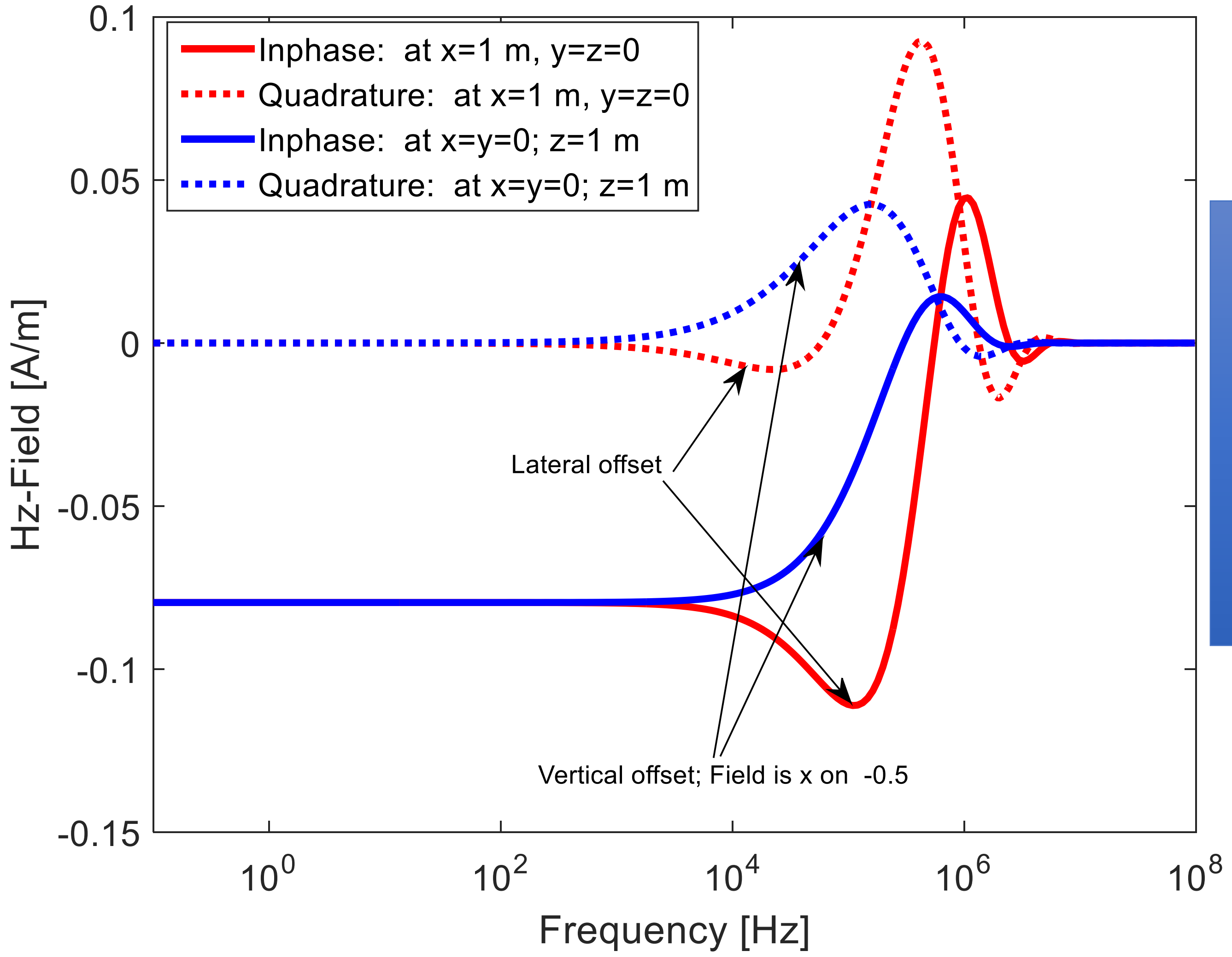
Complete H field $\mathbf{H}(\mathbf{r}) = \mathbf{G}(\mathbf{r},\mathbf{r}_o\,|\,\hat{\mathbf{m}})\ m;$ where $\bar{\bar{\mathbf{G}}}(\boldsymbol{r},\boldsymbol{r}_0\,|\,\hat{\mathbf{m}}) = \left[\frac{3\boldsymbol{R}(\boldsymbol{R}\cdot\hat{\mathbf{m}}) - \hat{\mathbf{m}}R^2}{R^5}(1-jkR) - \frac{k^2\boldsymbol{R}\times(\boldsymbol{R}\times\hat{\mathbf{m}})}{R^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

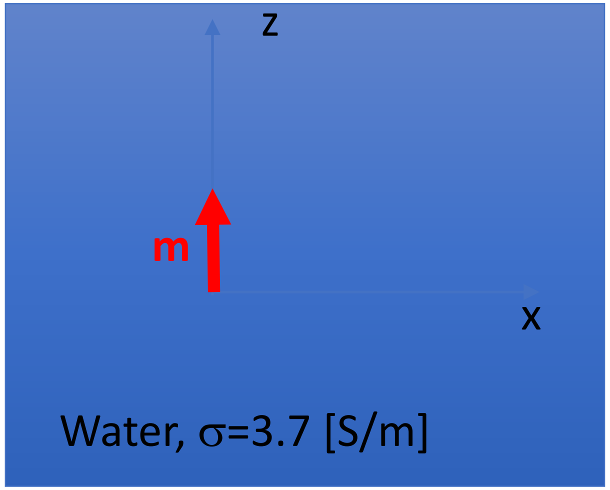






Magnetic dipole in UW environment: offset effects

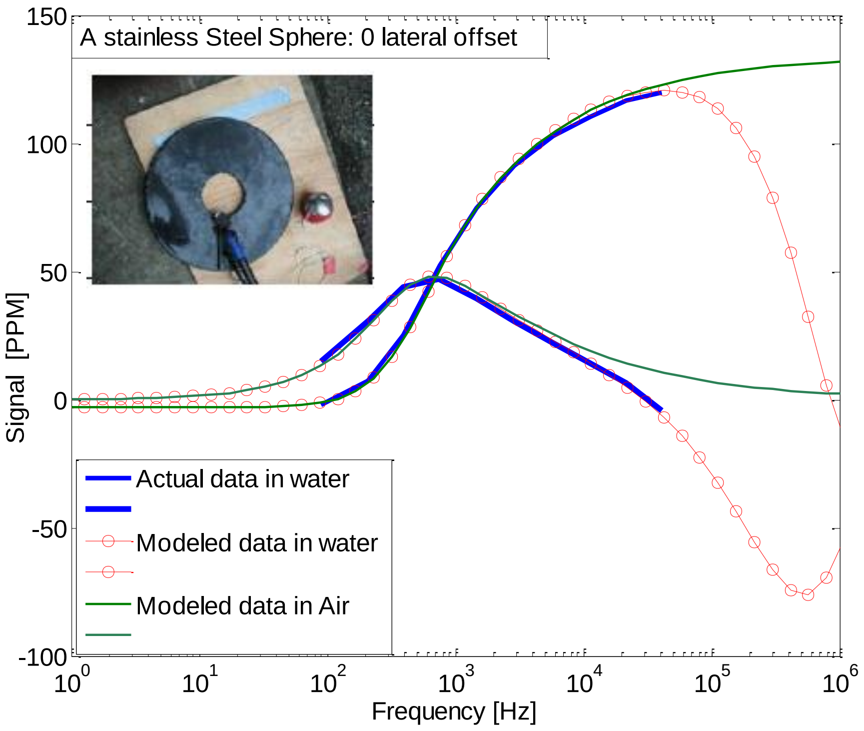


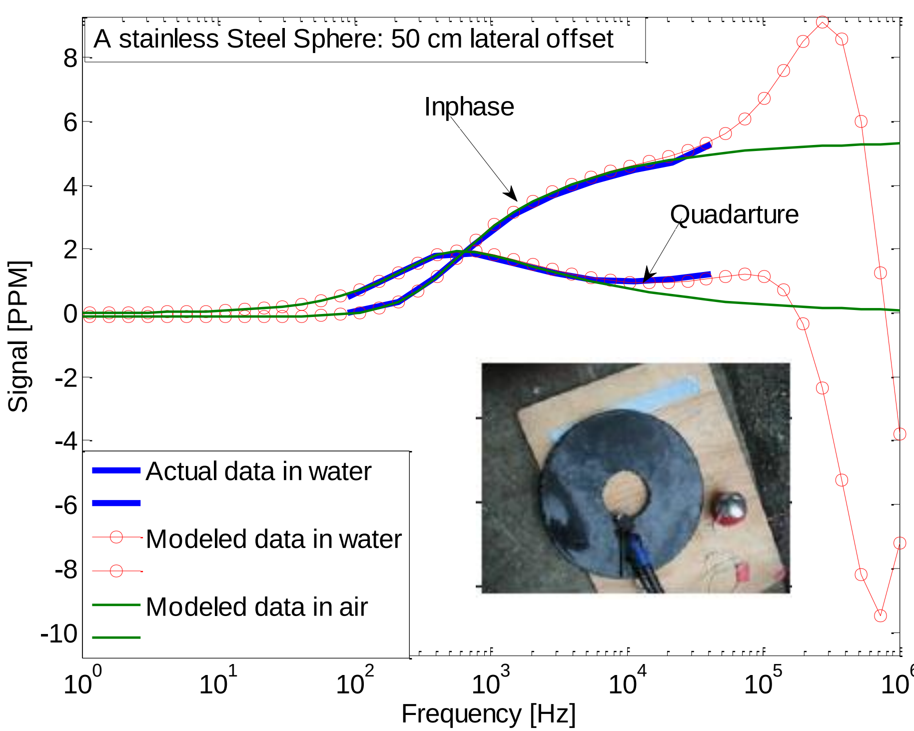


Targets EMI response

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

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

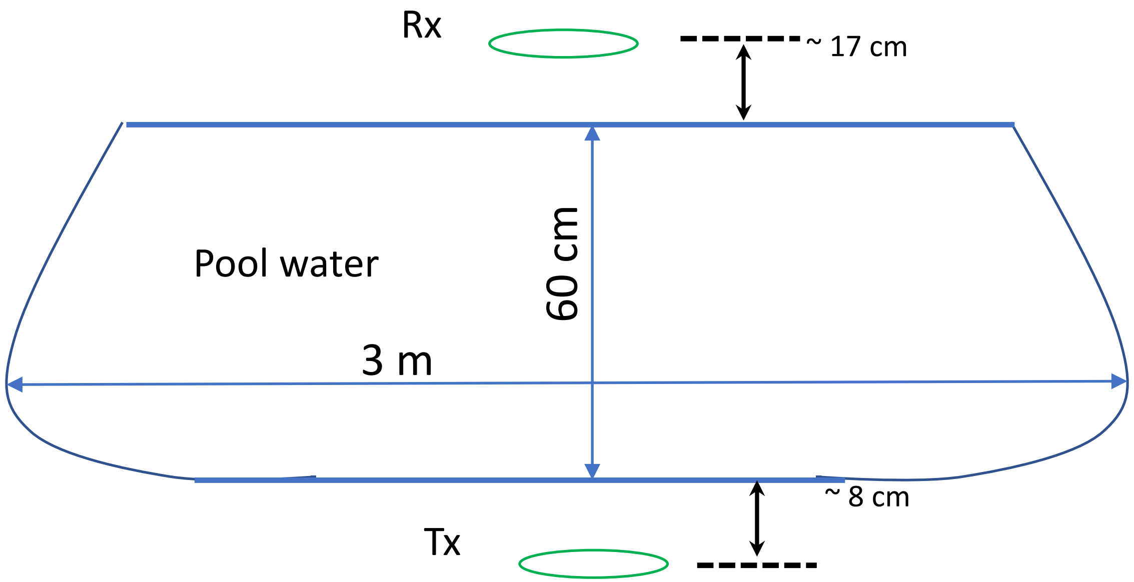




UW environment modifies signals at high frequencies (early time).

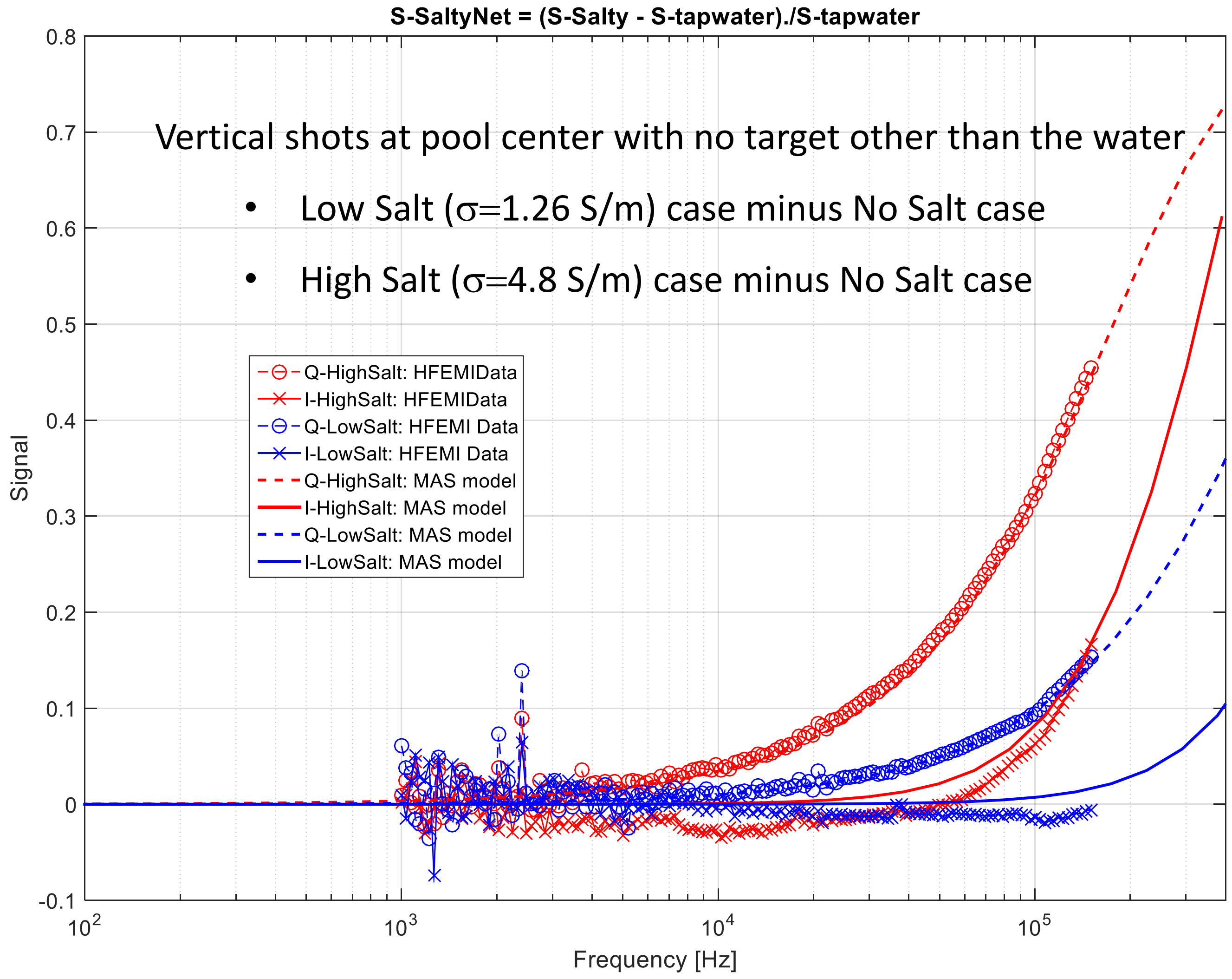
Experimental Setup

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



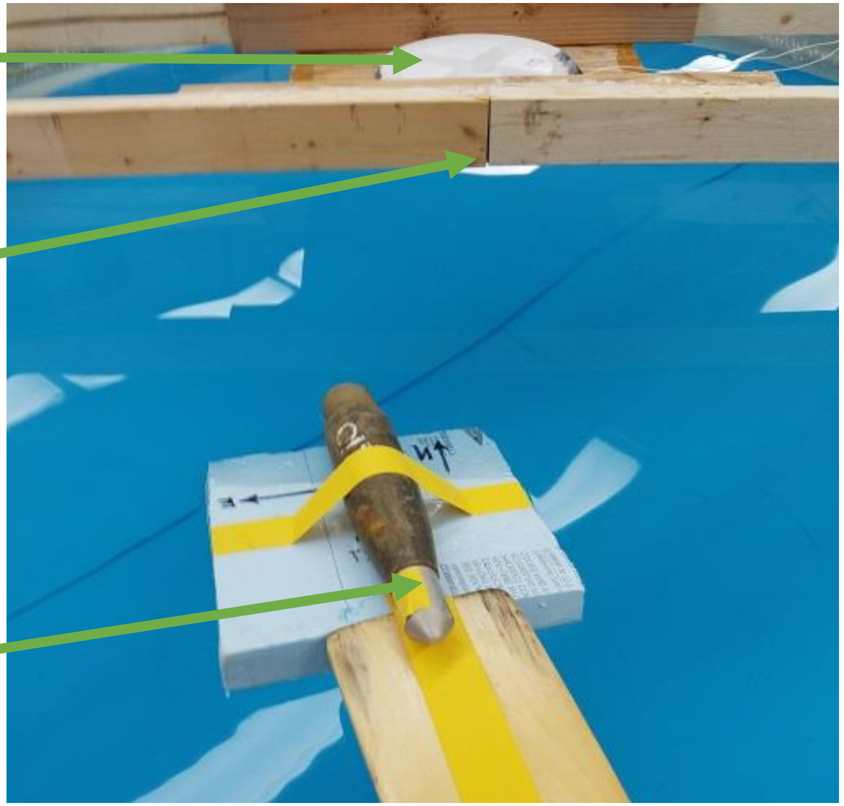
In salt water we see a distinct phase shift that one must account for in both cases.

Recovering target's true signal: experimental validation

Rx

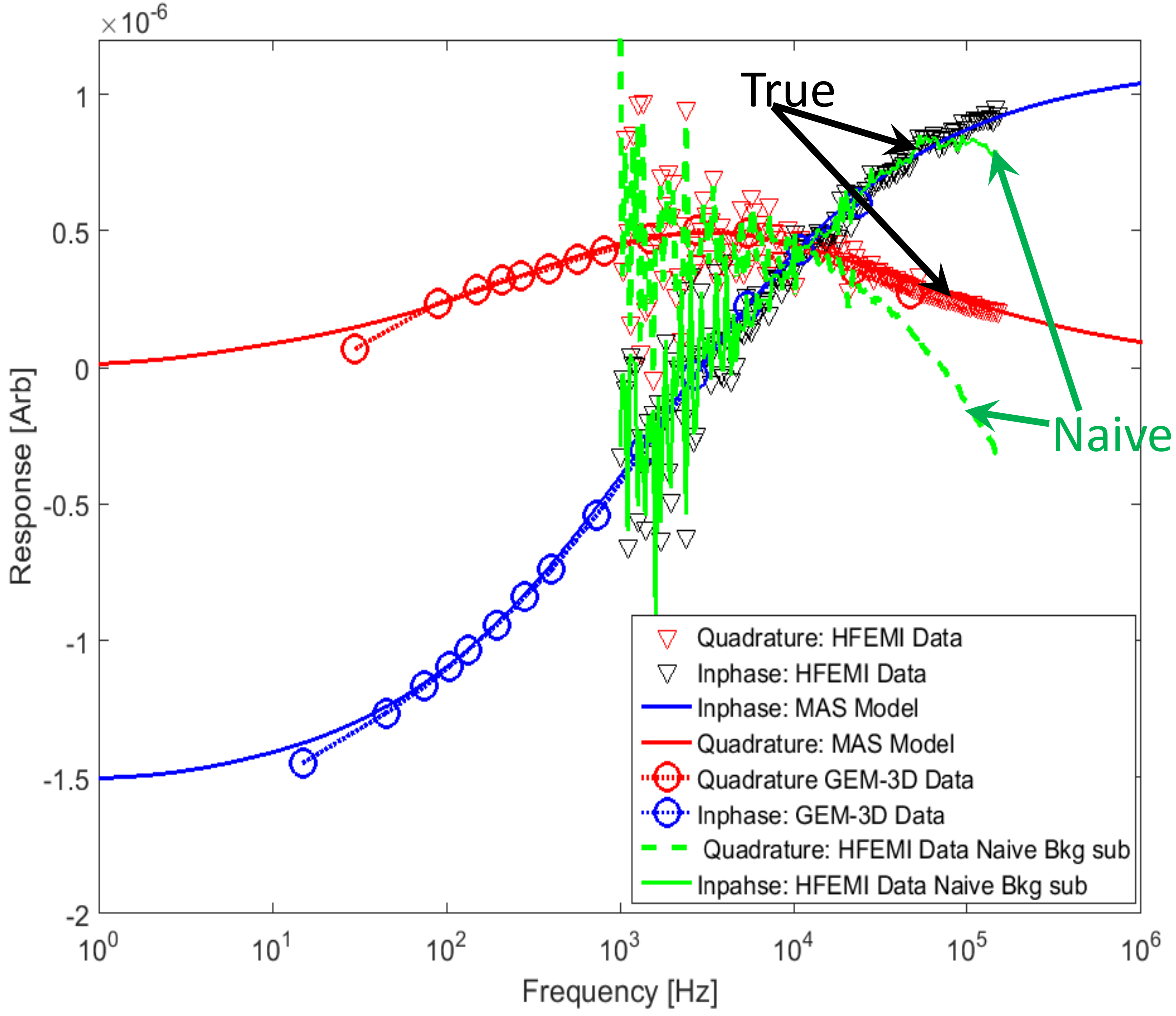
When we took data, rocket and coil were floating directly below the Rx

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 <u>also</u> scale the result to account for the SW alteration of the primary field.

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

Summary

- Conducting environment distorts the both primary and secondary magnetic fields at early times/high frequencies
- 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

Acknowledgments:

This work was supported by the SERDP Project # MR-2728.