

Simulation Analysis of Combined Electric and Acoustic Sources to Predict Fish Deterrence Drivers

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Abstract

Traditional physical barriers for aquatic invasive species (AIS) control, such as screens and nets, can be problematic due to fish mortality rates and their disruption to navigational procedures. Electric deterrent systems (EDSs) are the most mature technology for deterring AIS, with more than 15 years of operational use by USACE in the Chicago Sanitary and Ship Canal (CSSC). However, they pose human safety risks, incur high operational costs, and exhibit reduced efficacy against smaller fish. Consequently, current research focuses on optimally combining multiple types of deterrents to maximize fish deterrence. This work investigates the incorporation of electric and acoustic sources within a single domain using COMSOL Multiphysics® simulations and laboratory experiments. The simulations utilize the Electric Currents and Pressure Acoustics interfaces to predict the primary drivers that deter fish (voltage gradient and acoustic pressure) in a 3D domain that represents a physical fish flume located at the Engineering Research and Development Center–Environmental Laboratory (ERDC-EL). Laboratory experiments with in-water mapping methods are developed to validate and calibrate the models. Preliminary electric-field measurements were used for model comparison, while final electric and acoustic field mapping remain ongoing. These models predict the spatial distribution of deterrence drivers, providing a capability that extrapolates to full-scale installations, reducing the need for resource-intensive in situ mapping. Furthermore, accurately predicted distributions will establish a critical link between deterrence drivers and fish behavior, facilitating optimal placement and parameterization of multiple types of nonstructural deterrents to maximize fish avoidance.

Keywords: Asian Carp, Electric Dispersal Barrier, Underwater Acoustic Deterrent System, Nonindigenous Species, Invasive Species, Nonstructural Deterrents, Population Dynamics, Technology/Engineering, Watershed Management

Introduction

The rapid spread of aquatic invasive species (AIS) can cause substantial ecological and economic damage. AIS put stress on native species by competing for resources, restructuring food webs, and seeking native species as prey. Some future scenarios project losses in the Great Lakes of \$100 million U.S. annually due to AIS [1]. To address the spread of AIS while still allowing for navigation, nonstructural deterrents (NSDs) are employed. Two are of particular interest to this research: electric deterrent systems (EDSs) and underwater acoustic deterrent systems (uADSs).

EDS is a mature technology, having been actively deployed for more than 15 years [2]. It deters fish by introducing an electric field within the waterway. uADS, an alternative NSD, is being actively developed by the Army Corps of Engineers (USACE). Submerged loudspeakers play sounds to induce movement away from the speakers. Laboratory testing has shown specific sound patterns and tone sequences are particularly ef-

fective [3]. While uADS has undergone less field validation, it offers substantial potential for deterring AIS while addressing several important limitations associated with electric barrier systems.

First, while EDS induces a physiological response in fish [4], uADS induces a behavioral response [3]. Asian Carp, a critical AIS for USACE, are otophysians with Weberian ossicles [5], associated with enhanced hearing sensitivity. Acoustic sources may therefore target certain invasive species while causing minimal disruption to native fish species. Second, since no NSD is 100% effective, redundancy through multiple types is expected to increase efficacy. Laboratory experiments have shown that EDS has a 95% probability of inducing immobility in small fish; however, the threshold required to achieve a given level of efficacy varies with fish size [6]. Because smaller fish experience a lower voltage differential across their bodies, achieving comparable deterrence may require higher applied voltages and, consequently, greater power demand. Al-

Fish Flume with Electric and Acoustic Deterrents

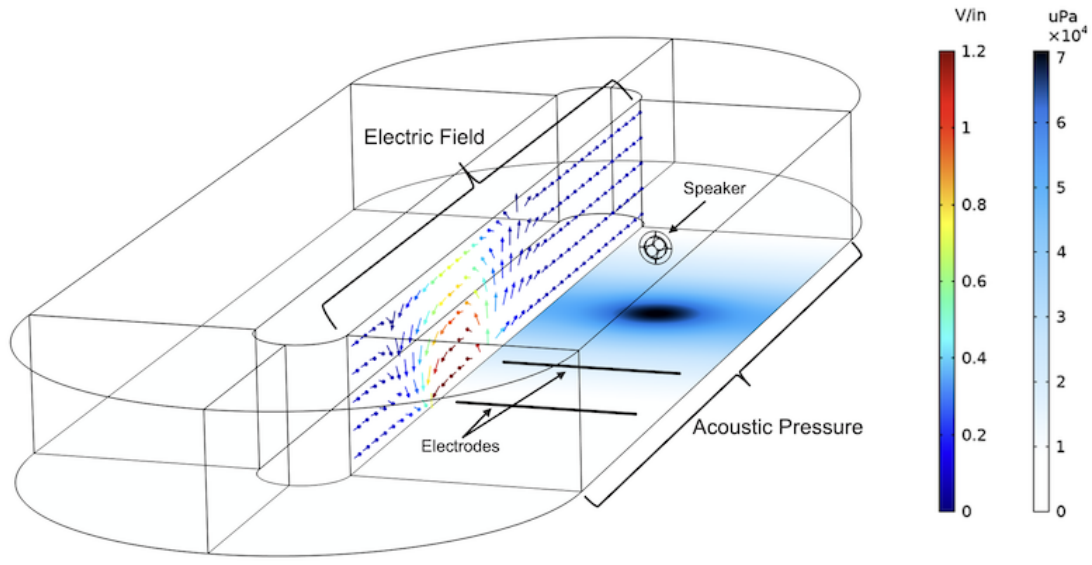


Figure 1. The fish flume, with both the electric and acoustic deterrents. Source magnitude is illustrative and does not represent the source magnitudes described in the experimental results.

ternatively, uADS is not dependent on fish size, though fish age may impact its effectiveness. Third, large EDS installations can require substation electrical power to establish an effective field, with power demand influenced by factors such as water depth, water conductivity, site geometry, and the size of targeted fish. uADS may help to reduce these power requirements and associated costs.

These considerations are reflected in ongoing USACE efforts, including, among others, the Brandon Road Interbasin Project, where uADS and EDS are planned for deployment in close proximity as complementary deterrent technologies [7]. An Electrical–Underwater Acoustic Deterrent System (EuADS) has no known prior deployment, and is therefore an undertaking without precedent. Our research is seeking to answer: How can electric and acoustic deterrents be used in tandem to capitalize on the strengths of each? Because this is the first-of-its-kind system, a fundamental understanding is needed of their combined effect on fish and how the two technologies can be operated together effectively. To develop this understanding, we are constructing a scaled fish flume with both deterrent systems.

The experiments in the physical fish flume have greatly benefited and will continue to benefit from a numerical model. First, it allowed us to size equipment before installation in the physical domain. Second, it will accelerate experiments with live fish. Although the fields could be mapped with physical sensors every time a parameter is changed, it would be impractically slow. Third, once the model is built and validated, the same physics can be applied to real-world installations.

The following sections detail our numerical simulations, laboratory setup and data collection methodology, and preliminary comparison of field data to simulation data. Our comparison is limited to the electric field, while the simulation results include both acoustic and electric fields.

COMSOL Model

We used COMSOL to predict the drivers of fish deterrence (the electric and acoustic fields) within a single domain. The multiphysics nature of our problem made COMSOL an ideal software choice.

Geometry

In order to make subsequent comparisons between the COMSOL model and our experimental data, we sought to replicate the physical fish flume located at ERDC-EL as closely as necessary to make a useful comparison of the data. The fish flume has a racetrack configuration and uses propellers to control hydraulic flow conditions.

Previous work [8] has shown that COMSOL can be readily used to model electric barriers. However, the level of geometric detail required to accurately represent the acoustic response of the flume was less certain. Several approaches could be used to describe the boundary conditions on the walls and floor, and some would include modeling a wall of finite thickness to represent the walls. The flume includes thick glass viewing sections and multiple fiberglass panels, chosen for their electrically insulating properties. To avoid unnecessary complexity, the initial geometry was kept as simple as practical, with additional details to be in-

corporated only if experimental results indicate greater fidelity is necessary for AIS deterrence predictions.

The geometries contained in our model are therefore: the water, the electrode rods, and the loudspeaker (see Figure 1). It will be helpful to note that the y-direction is parallel to the length of the racetrack's straightaway, the x-direction is parallel to the shorter dimension, and the z-direction is the water column.

Physics Interface: Electric Currents

The Electric Currents physics interface was chosen to model the EDS. Although the applied electric signal is pulsed DC, its pulse parameters are sufficiently slow relative to the electrical relaxation time of the water. The electric field rapidly approaches a quasi-static (steady current) nature during each energized portion of the waveform. The relevant deterrence quantity is the voltage gradient, a predictor of the voltage that would be experienced across the fish, which can therefore be evaluated from the steady-state voltage distribution while the pulse is applied. Consequently, transient electromagnetic effects associated with pulse initiation can be neglected, and the time-invariant Electric Currents interface provides an appropriate representation of the field for the intended analysis.

The boundaries of the water domain were all insulated. The electric source was applied to $\frac{1}{4}$ -in.-diameter cylindrical electrodes. To model the electric source, the domains representing the volume of metal for each of the electrodes were removed. Though they could remain in the simulation, no data on the fields within the electrodes were needed. "Terminal" or "Electric Potential" boundary conditions were applied, both yielding identical results, but "Terminal" added convenience variables for computing power and current.

For several plots presented in later sections, the default mesh resolution was insufficient. The mesh was therefore initialized using the "Extremely Fine" setting, then further refined by manually changing the maximum element size to ≈ 4 in.

Figure 2 shows an example streamline plot. The water height was 22.5 inches, and 12.6 V peak-to-peak was applied to the two electrodes. These parameters correspond to the experimental data comparison.

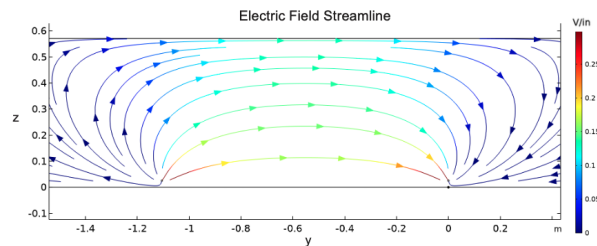


Figure 2. Electric field streamline plot. The y-z plane shown is centered on the middle of the flume width.

As expected, the electric-field magnitude is greatest near the electrodes and decreases with distance from the source. The field distribution is also approximately symmetric about the electrode centerline in the y-direction, consistent with the geometry and placement of the electrodes.

Physics Interface: Acoustic Pressure

The Pressure Acoustics, Frequency Domain physics interface was chosen to model the uADS. Though pure tones are not the only sounds found to be effective against AIS [3], the complexity of the domain and the desire to get simulation results that match sensor data make a frequency-domain simulation a natural first choice.

Previous work by USACE [9] compared several models of increasing complexity, including a cylindrical spreading model, a parabolic equation model, a parabolic equation with range-based bathymetry, and a 3D parabolic model with out-of-plane solutions. The COMSOL model is most similar to the latter.

The lowest-order approximation within COMSOL is to model the surface of the water with the "Sound Soft Boundary" condition in the physics interface, and the walls/floor as "Sound Hard." More complex approximations are discussed in the Acoustic Field Mapping section.

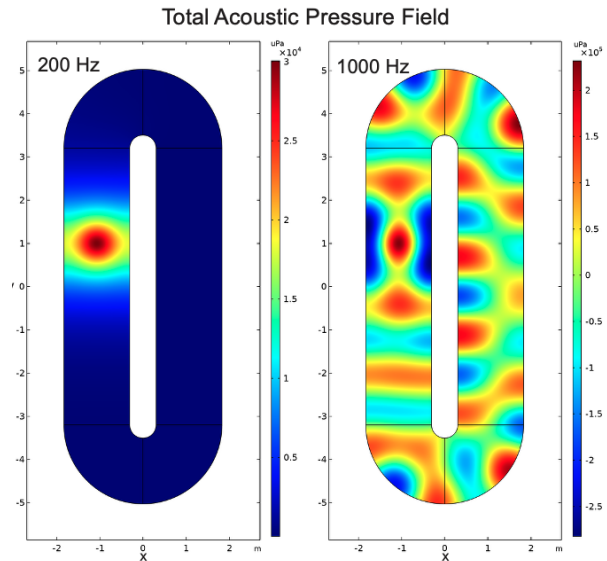


Figure 3. Acoustic pressure x-y cuts on the floor of the flume, one at low frequency (200 Hz) and one at mid-range frequency (1000 Hz).

The loudspeaker used in the laboratory experiments was a piston piezoelectric underwater acoustic transducer. The speaker's shell is split into two halves. They move along a piston when the signal is applied to the piezoelectric material, causing the two shells to move along the piston in opposite directions. Therefore, in

our simulation, we applied two separate “Normal Velocity” boundary conditions to the two halves of the shell, one in the positive y -direction and one in the negative y -direction.

Using COMSOL’s guidance [10], the maximum element size was set to be $\frac{\lambda_{min}}{5} = \frac{c}{5f_{max}}$, where f_{max} is the highest frequency in the simulation, λ_{min} is the smallest wavelength, and c is the speed of sound in the medium (water).

Lower-frequency solutions showed symmetric responses. Higher-frequency solutions showed more complicated responses. This is to be expected, but the complex nature of the domain makes it difficult to verify the high-frequency solutions before laboratory field mapping.

Laboratory Setup and Data Collection

Our laboratory setup consists of an electric source, an electric-field measurement system, an acoustic source, and a hydrophone. A custom cart was built by Electro Mechanical Solutions Inc., which allowed us to move a downrod in the x - y plane (Figure 4). The hydrophone and electric-field probes were mounted to this downrod. The discussion below provides a theoretical framework to directly compare laboratory measurements to COMSOL predictions.

Electric Field Mapping

For the preliminary testing described here, a B&K Precision 4040B signal generator was used as a low-current source to evaluate the data-acquisition hardware and software, verify the measurement workflow, and support initial comparisons between experimental measurements and the COMSOL model. The voltage achieved at the surface (0.15 V/in.) in this preliminary testing is an order of magnitude less than that used by USACE (2.3 V/in.) at the CSSC. For future work, a 1.5 POW system manufactured by Smith-Root Incorporated is planned.

We targeted the settings currently in use by USACE at the Chicago Sanitary and Ship Canal (CSSC). They use a 34 Hz square wave with a 2.3 ms (approximately 8% duty cycle) pulse width [8]. Because the B&K Precision 4040B is limited to a minimum duty cycle of 20%, that setting was used for the preliminary validation testing [11]. The signal generator output was connected to 1/4-in. steel rods.

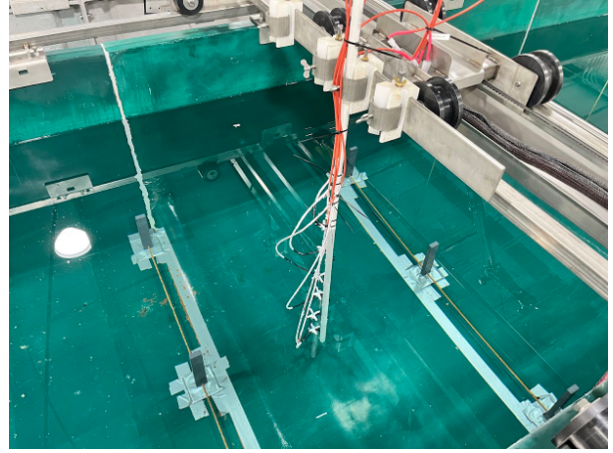


Figure 4. Electric probes in the water, between the two electrodes.

The Electric Currents interface solves the steady-current forms of Maxwell’s equations. Under this formulation, the electric field is related to the electric potential by $\vec{E} = -\nabla V$, where V is the electric potential. Considering a single component of the electric field,

$$E_y = -\frac{\partial V}{\partial y} \approx -\frac{V(y + \Delta y) - V(y - \Delta y)}{2\Delta y}.$$

This central difference approximation provides a direct relationship between the modeled electric field and the experimental measurement. By measuring the voltage difference between two points separated by a small, known distance ($2\Delta y$), the average electric-field component over that separation can be estimated and compared directly with the COMSOL predictions.

To implement this approach experimentally, triaxial probes were constructed with a 2-in. electrode spacing along each of the three orthogonal axes. Each axis provides a differential voltage measurement across the corresponding electrode pair, allowing the three components of the local electric field to be estimated simultaneously. Previous work [12] used an electrode spacing of approximately 24 in. to characterize the electric field at the full-scale electric barrier in the CSSC. Applying the same spacing within the present flume would substantially increase spatial averaging because the electric field varies more rapidly with position over the smaller experimental domain. The 2-in. probe spacing was selected to balance two competing considerations. A shorter spacing provides a more localized estimate of the electric field at the probe center. A longer spacing, however, decreases error from geometric uncertainty and produces a larger differential voltage, improving the signal-to-noise ratio (SNR). The selected probe size therefore represents the minimum spacing that provided adequate SNR and sufficiently low geometric error.

First, a wider distance helps to minimize errors caused by unknowns in the geometry of the probe. For exam-

ple, if screws with a head length of 0.1 in. are used on either end of a 2-in. probe, there may be uncertainty about whether you are measuring the voltage across 2 in. (if the base of the head is in contact with the water) or 2.2 in. Assuming a uniform field within the probe, geometric error becomes error in the measurement as

$$\hat{E}_y = -\frac{V(y + \Delta y + \epsilon_{\text{geom}}) - V(y - \Delta y - \epsilon_{\text{geom}})}{2\Delta y}.$$

Substituting $V(y) = -E_y y + b$ gives $\hat{E}_y$ as

$$-\frac{-E_y(y + \Delta y + \epsilon_{\text{geom}}) + b - (-E_y(y - \Delta y - \epsilon_{\text{geom}}) + b)}{2\Delta y}.$$

Therefore, the measured field is

$$\hat{E}_y = E_y + E_y \frac{\epsilon_{\text{geom}}}{\Delta y}.$$

Thus, under the assumption of a uniform electric field, error caused by uncertainty in the spacing is inversely proportional to the nominal distance Δy . Geometric error can be decreased by increasing the probe length.

Second, a wider spacing improves SNR by increasing the differential voltage developed across the probe. The differential measurement system has a measured noise floor of approximately 0.7 mV [13]. An SNR of approximately 20 dB is generally considered sufficient for reliable measurement [14], corresponding to a signal amplitude approximately 10 times greater than the noise level. Accounting for the attenuation of the differential probe, this corresponds to approximately 140 mV across the measurement electrodes in the water. For a 2-in. electrode spacing, the resulting 20-dB SNR threshold corresponds to an electric-field magnitude of approximately 70 mV/in.

After the probe size was determined, building and waterproofing were necessary. The probes were 3D printed, with connectors built to fit into existing housings on the downrod. We used a six-conductor shielded cable to go from the receivers to the differential probes. The first prototype used casting epoxy painted on the receivers to waterproof all but the screws exposed at the ends of the probe. This proved to be very time-consuming because the epoxy was too fluid to paint until it had hardened for some amount of time, but then it would harden very quickly. The second prototype was waterproofed using JB MarineWeld. This was found to have a perfect consistency for painting the probes, and it was the prototype used in the presented results. However, it was found that this weld would flake off under small amounts of mechanical stress. We plan to refine our waterproofing procedure in the future.

A custom relay multiplexing system was developed for multiple reasons. First, it allowed us to take 36 differential measurements with only eight PicoScope TA057 [13] differential probes. The relay system multiplexed

4 triaxial receivers to 2 probes, and the remaining 2 triaxial receivers were wired directly to the other 6 probes. The differential probes each had attenuation settings of 1/20 or 1/200. For this stage of validation, we used the 1/20 attenuation. A USB strip was used to power each of the differential probes using a DC input. The output of each of the differential probes was connected to an input on a PicoScope 4824A [15]. The PicoScope was used as an oscilloscope to capture the waveform in time. Custom software controlled the measurement sequence and saved the individual waveforms corresponding to each receiver location and each of the three orthogonal field components.

Acoustic Field Mapping

Though we have not yet performed the field mapping for the acoustic speaker, we installed the speaker within the test domain and composed a plan for the field mapping. We used the Lubell 916C [16] loudspeaker. Our plan for validating the model is as follows.

First, we are comparing far-field measurements contained in the Lubell datasheet to our source in COMSOL. We placed the source in a spherical domain surrounded by perfectly matched layers (PMLs), trying to replicate the near-free-space polar plot provided in its datasheet. This calibration is an ongoing effort.

Second, within the physical domain, we plan to start by playing a sequence of pure tones. We will search for the frequency such that approximately one wavelength is measured across the flume and use that to start evaluating the model.

Finally, we will use a hydrophone to map the sound pressure level across the domain and compare it to the COMSOL model. The Lubell 916C loudspeaker reports 180 dB relative to 1 μPa at 1 kHz at 1 m from the speaker [16]. We plan to adjust the “Normal Velocity” magnitude such that the amplitude of the acoustic pressure matches the measurement we take with the hydrophone.

To convert the total acoustic pressure p_t to the sound pressure level L_p , we will use the equation

$$L_p = 10 \log_{10} \left(\frac{\text{RMS}(p_t(t))^2}{p_{\text{ref}}^2} \right).$$

Since the Pressure Acoustics, Frequency Domain interface contains the steady-state solution, $p_t(t)$ is merely a sinusoid with amplitude $|p_t|$. Using dB relative to 1 μPa as the units for sound pressure level, and $p_{\text{ref}} = 1 \mu\text{Pa}$, yields

$$L_p = 10 \log_{10} \left(\frac{(|p_t|/\sqrt{2})^2}{(1 \cdot 10^{-6})^2} \right)$$

as the correct equation for conversion.

Through these three steps, we will iteratively adjust the

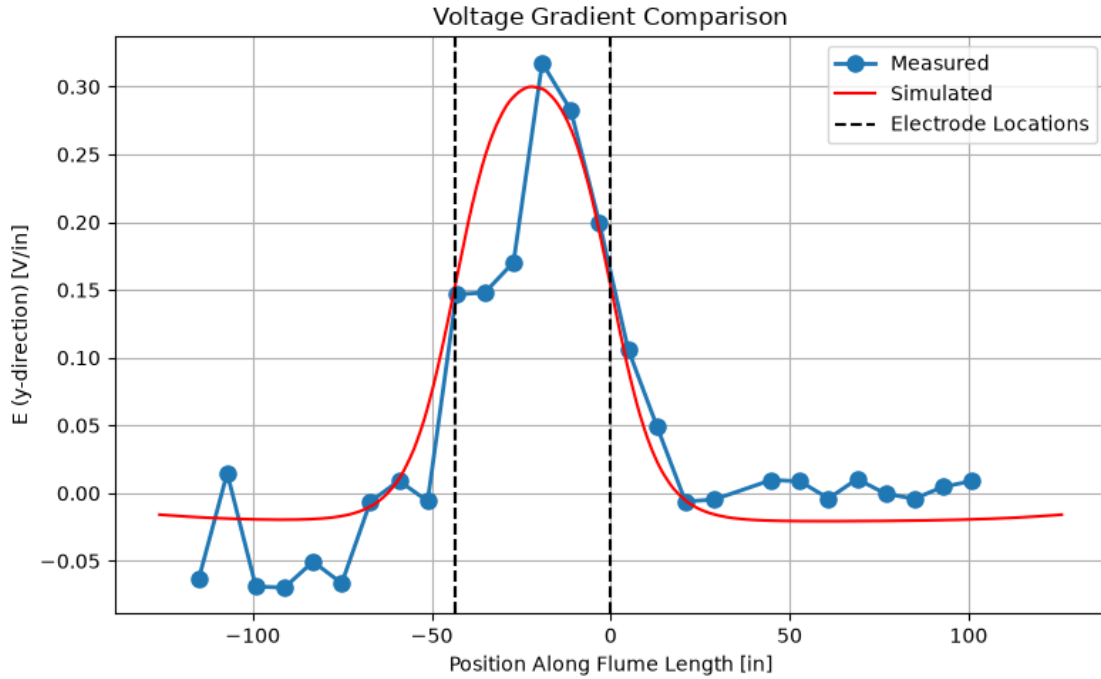


Figure 5. Comparison of the simulated data to the data collected in the physical fish flume. The voltage gradient is computed across ≈ 2 in., corresponding to the probe size.

model as necessary. We are currently using “Sound Hard” boundary conditions for the floor and walls of the domain. This simplification may be too inaccurate. Other options include, in order of increasing complexity:

1. Apply an “Impedance” boundary condition uniformly across the walls.
2. Apply an “Impedance” boundary condition with varying impedance across the walls.
3. Add the fiberglass walls to the geometry and create a multiphysics coupling between the “Pressure Acoustics” interface and a “Structural Mechanics” interface.

This is one example of how we may adjust the model as the physical data are collected in order to ensure it sufficiently captures the acoustic deterrence driver.

Model Validation

In order to validate the model, the triaxial receiver rod was wheeled using the cart along the y-direction, several inches from the outer wall of the flume.

After postprocessing our measured data, we used the COMSOL API, wrapped by the MPh Python library, to evaluate the results dataset. We mapped the physical locations to the COMSOL domain, then evaluated the voltage at approximately +1 in. and -1 in. from those locations, corresponding to the voltage difference physically measured with the receivers. The resulting comparison is shown in Figure 5.

There is an asymmetry of the measured data around

the center point of the electrode. We believe this may have been caused by the aforementioned issues in waterproofing, with the cable mechanically stressed in such a way as to allow water to seep in when it was below the center of the electrodes. This asymmetry will be investigated in future work. Figure 6 shows the better data reflected over the midpoint.

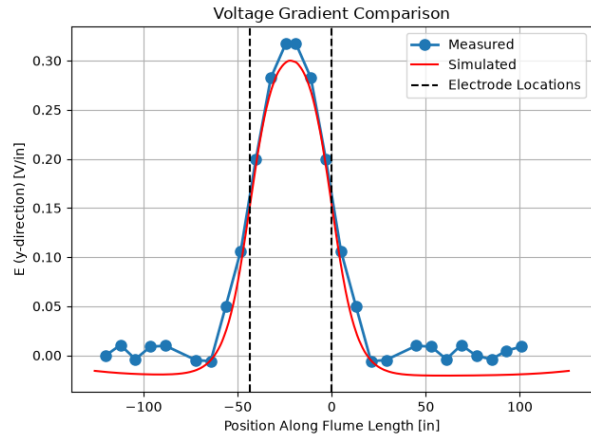


Figure 6. Same data as Figure 5, but measured data points were taken from the center of the electrodes and onward in the positive y-direction and reflected across the center.

The electric-field mapping shows an agreement in peak location, peak magnitude, and electric-field shape with the COMSOL model. The simulated field is lower near the extremities, but that may be explained by the geometric error of the probe distances. The lack of negative voltage in the measured data is surprising, but may

be due to the SNR, as those values fall below the 70 mV/in. range discussed previously. The model was calibrated to account for probe spacing uncertainty, using a probe spacing of 2.2 in. Figure 6 shows the measured and simulated data are in agreement.

Conclusion

In conclusion, COMSOL enabled the development of an integrated electric-acoustic model within a single computational domain. We developed a methodology to compare simulated electric and acoustic fields to laboratory measurements.

The model informed equipment sizing, source and sensor placement, and laboratory configuration. The measured voltage gradient, a predictor of the voltage across a fish, showed agreement by the COMSOL model. A higher-voltage source may further improve agreement between measured and simulated fields by increasing the signal relative to the probe noise floor, thereby improving SNR.

The preliminary agreement between measured and simulated electric-field gradients provides confidence in the representation of the flume geometry and establishes a basis for the acoustic model validation. Future work will refine and validate the comparison methodology, calibrate the acoustic source model using hydrophone measurements, and evaluate acoustic model performance.

This research improved understanding of EuADS through simulation in a single domain. By supporting the design and evaluation of combined deterrent systems, this work contributes to AIS-management efforts in the Great Lakes region and other waterways where similar passage-control challenges exist.

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Acknowledgements

The authors thank Fred Martin for collecting the validation data and logging the procedure, Chris Donnelly for machining the acrylic electrode holders and printing the triaxial receivers, David Lozano for creating the many iterations of the triaxial receiver CAD drawings, and Xander Moore for his input on the manuscript and corresponding poster.