Bear (1884) "Telegraphing Without Wires"

— Simulator & Dataset (v1.1)

1. Overview

This dataset provides a computational reconstruction of S. J. M. Bear's 1884 experiment on conduction-based signal transmission through water, presented before the American Institute of Electrical Engineers at Philadelphia. The dataset contains field simulations, receiver modeling, and time-domain keying behavior generated via a finite-difference solution of the variable-conductivity Laplace equation.

The goal is to reproduce and analyze early "wireless" communication through conductive media using modern computational methods, enabling quantitative exploration of a design space that Bear and his contemporaries could only probe qualitatively.

1.1 Changes from v1.0

- **Eliminated duplicate PDE solve:** The Thévenin receiver extraction now reuses the TX-driven potential solution from the tub resistance calculation, cutting the most expensive computation in half.
- **Improved boundary current estimation:** Replaced np.gradient-based flux computation with direct conductance-weighted summation across electrode boundary faces. More robust near sharp electrode-water interfaces.
- **Physically calibrated parameters:** Wider electrode spacing (30 vs 10 grid cells), realistic 10-cell voltaic battery model (5 Ω internal, 3 Ω contact), and calibrated relay thresholds (~3 µA pull-in). The dataset now exhibits meaningful variation across experiments.
- **Improved visualization:** Time-trace plots use 4-panel subplots (key, V_{tub}, I_{relay} in µA, relay state) for proper signal visibility at disparate scales.
- **Polarization convergence:** Fixed-point iteration now checks convergence (10^{-6} tolerance, up to 20 iterations) instead of running a fixed 12 steps.
- **Code quality:** Experiment variant construction uses a clean _variant() helper. Solver boundary conditions documented. Version strings updated throughout.

2. Dataset Structure

Each experiment configuration generates three primary file types:

A. Field Data (NPZ)

```
Files: *__fields.npz
```

Contains:

- **sigma** — spatial conductivity map (float32)
- **V_tub_1V** — normalized potential distribution (1 V across TX electrodes)
- **V_delivered_no_pol** — delivered potential without polarization

- **V_delivered_pol** — delivered potential with electrode polarization
- **Ex_1V, Ey_1V** — electric field components
- **Jx_1V, Jy_1V** — current density components
- **Emag_1V, Jmag_1V** — field magnitudes
- **V_port_1V** — potential from Thévenin port excitation
- **tx_plus, tx_minus, rx1, rx2** — electrode masks (uint8)

B. Time Series Data (CSV)

`Files: *__timeseries.csv`

Column	Description	Units
t	Time	seconds
key	Transmitter key state	0/1
Vpol	Electrode polarization voltage	V
Vtub	Delivered tub voltage	V
Isource	Source current from battery	A
Vth	Thévenin receiver voltage	V
Irelay	Relay current	A
relay_state	Relay actuation state	0/1

C. Experiment Summary (JSON)

`Files: *__summary.json`

- Configuration parameters (grid size, battery, electrodes, relay)
- Thévenin equivalent parameters (V_{th} per 1V, R_{th})
- Tub resistance estimate
- Relay activation thresholds and click indicators
- Delivered voltages and currents (with and without polarization)

D. Sweep Data

A conductivity sweep (18 points, σ = 0.05 to 3.0) is saved as sweep_sigma_v1p1.csv and sweep_sigma_v1p1.json, with an accompanying I_{relay} vs σ plot.

3. Experiment Variations

The dataset includes 9 experiment configurations exploring different conductivity scenarios and receiver parameters:

Experiment	Key Variation	Relay Click (with pol.)
baseline_bear1884	Uniform saltwater (σ=1.0)	No
var_freshwater_uniform	Low conductivity (σ=0.15)	Yes

var_brine_uniform	High conductivity (σ=2.5)	No
var_half_fresh_half_brine	Split domain (0.15 / 2.5)	No
var_insulating_obstacle	Insulating sheet in path	No
var_brine_plume_receiver	Gaussian plume near RX	No
var_wire_in_water	High-σ wire connecting TX→RX	Yes
var_sensitive_relay	Lower pull-in threshold (1 μA)	Yes
var_receiver_farther	RX moved to x=205	No

Note: In the current model, lower conductivity yields stronger relay signals because more of the battery voltage drops across the tub (rather than across internal resistance). Bear's historical observation that salt water *helped* signal transmission relied on an electrochemical polarity mechanism (zinc-zinc repulsion blocking the short-circuit path) that is not yet modeled. This is a candidate for v2.0.

4. Computational Method

4.1 Potential Field

The potential field is computed by solving the variable-conductivity Laplace equation:

```
div(σ ∇V) = 0
```

using a 5-point finite-difference stencil on a 240×130 grid. Inter-cell conductances use harmonic averaging, which is the correct discretization for discontinuous σ fields (e.g., electrode-water interfaces). The domain boundary enforces zero normal flux (∂V/∂n = 0) naturally through the sparse matrix structure, modeling insulating tub walls.

4.2 Receiver Modeling

The receiver is modeled as a Thévenin equivalent circuit. Two PDE solves determine V_{th} (open-circuit voltage at the receiver port due to TX excitation) and R_{th} (output impedance, from a 1V excitation across the RX port). The relay current is then:

$$I_{relay} = V_{th} / (R_{th} + R_{relay})$$

4.3 Boundary Current Estimation

v1.1 uses direct conductance-weighted flux summation across electrode boundary faces. For each electrode cell adjacent to a non-electrode cell, the flux is computed as $\sigma_{harmonic} \cdot (V_{electrode} - V_{neighbor})$. This replaces the v1.0 approach of using np.gradient, which introduced artifacts near electrode boundaries.

4.4 Time-Domain Dynamics

A simple first-order electrode polarization model introduces time-dependent signal degradation during keying. The telegraph key operates at 2 Hz with 50% duty cycle. Polarization voltage builds exponentially during key-down (τ = 0.35 s) and decays during key-up. The relay uses hysteretic pull-in / release thresholds.

4.5 Battery Model

Bear's 10-cell voltaic battery is modeled as a 10 V source with 5 Ω internal resistance and 3 Ω electrode contact resistance. The voltage delivered to the tub is:

$$V_{tub} = (V_{bat} - V_{pol}) \cdot R_{tub} / (R_{series} + R_{tub})$$

5. Generated Figures

Each experiment produces the following visualizations in the output/figs/ directory:

- ***__sigma.png** — Material conductivity map
- ***__potential_delivered_no_pol.png** — Potential field (no polarization)
- ***__potential_delivered_with_pol.png** — Potential field (with polarization)
- ***__streamlines_1V.png** — Current streamlines overlaid on potential
- ***__trace.png** — 4-panel time trace (key, V_{tub}, I_{relay}, relay state)
- ***__thevenin_curve.png** — I_{relay} vs R_{relay} Thévenin load curve
- **sweep_sigma_v1p1__Irelay.png** — Conductivity sweep results

6. Reproducibility

All data were generated using the provided Python script:

```
Bear-1884-v1_1.py
```

Dependencies:

- numpy
- scipy
- matplotlib

Running the script reproduces all experiments, datasets, and figures. The simulation is fully deterministic (no random components). Typical runtime is under 5 minutes on a modern machine.

7. Intended Use

- Study of signal propagation through conductive media
- Historical reconstruction of early wireless experiments
- Quantitative design-space exploration of Bear's apparatus
- Education in electrostatics and applied electromagnetics
- Finite-difference PDE modeling demonstrations
- Benchmarking patent-to-simulator reconstruction workflows

8. Known Limitations & Future Work

- The electrochemical polarity mechanism (zinc-zinc repulsion blocking the short-circuit path) described by Bear is not modeled. The current simulator uses only ohmic conduction physics.
- Grid resolution (240×130) is moderate. A convergence study at higher resolution would strengthen confidence in the numerical results.

- Conductivity values are relative (not calibrated to physical S/m units). Mapping to Bear's actual salt-water conductivity (~5 S/m) is a future step.
- The polarization model is a simple first-order lag, not a full Butler-Volmer electrochemical model.

9. Citation

If using this dataset, please cite the original paper:

S. J. M. Bear, "Telegraphing Without Wires — An Experiment," *Transactions of the American Institute of Electrical Engineers*, vol. I, pp. 1–13, October 1884.