



L'X – MSc&T Environmental Engineering & Sustainability Management

Electromagnetic Induction Sensing for the Identification of Buried Lead Service Lines



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The Problem, the Approach, and the Headline Result

- Roughly 2 million lead service lines are confirmed in the United States, and a further 23.5 million connections remain of unknown material.
- The 2024 Lead and Copper Rule Improvements require full replacement within ten years and count every unknown as lead - a utility carries the full replacement liability for any connection it cannot affirmatively classify as non-lead.
- Replacement is a solved civil-engineering problem; verification is not. No fielded non-invasive technique both locates a buried service line and identifies its material.
- This internship adapted and applied ULEMA - an ultra-light multi-static time-domain electromagnetic induction array developed over two decades for unexploded-ordnance discrimination - to the service-line problem, under ESTCP Project EW25-8806.
- Three strands of work: a regulatory and economic analysis of the verification bottleneck; a physical analysis of whether copper, lead and galvanized steel are separable by EMI; and the design, fabrication and field deployment of ULEMA-P, a non-metallic pipe-survey configuration of the instrument.
- **Result: steel separates decisively from the non-ferrous metals; copper and lead separate narrowly by decay shape; discrimination was demonstrated successfully at both shallow emplacement and at operational burial depth (4–6 ft).**

Introduction and Context

- Lead was a deliberate material choice for service lines — ductile, corrosion-resistant, inexpensive — required by many U.S. plumbing codes into the 1930s.
- Toxicological mechanism: Pb^{2+} substitutes for $\text{Ca}^{2+}/\text{Zn}^{2+}$ (ionic mimicry). Neurological damage in children is irreversible at blood-lead levels below 5 $\mu\text{g}/\text{dL}$; adults face hypertension, renal and reproductive effects.
- Environmental pathway: bioaccumulation and biomagnification through wetland sediment and aquatic food webs. Lead does not degrade, so every gram released remains in the environment indefinitely.
- U.S. regulatory timeline: 1986 SDWA ban on new lead plumbing → 1991 LCR (7%/yr rule, largely inoperative) → 2021 LCRR (mandatory inventory) → 2024 LCRI (10-year full replacement; unknowns treated as lead).
- Europe: no consolidated EU count; ~120 million people potentially exposed. National prevalence spans <5% to 90%. Germany and the Netherlands have effectively retired lead service lines; the UK and France still hold millions.
- Verification bottleneck: excavation is definitive but costs \$320–1,120 per line and does not scale to the ~25 million lines requiring verification nationally.
- Host project: ESTCP EW25-8806 (Dartmouth / Shubitidze group), phase-one testing at an EPA test bed.

Data and Methods — Physics and the ULEMA Instrument

- Electromagnetic induction sensing: Faraday's and Ampère's laws in the quasi-static regime. Skin depth $\delta = \sqrt{1/\pi f \mu \sigma}$; soil is effectively transparent across the working band.
- Material decay time constant $\tau \propto \sigma \mu L^2$. Copper and lead are both non-ferrous — no permeability contrast, only a 12–13× conductivity ratio. Galvanized steel's $\sigma \mu_r$ product is ~17× copper's and ~220× lead's — a decisive, permeability-driven separation.
- ULEMA: multi-static, tri-axial, time-domain array. Four transmit coils fired sequentially; four tri-axial receivers; 10 MSPS FPGA acquisition; RTK GPS + IMU for direct geolocation.

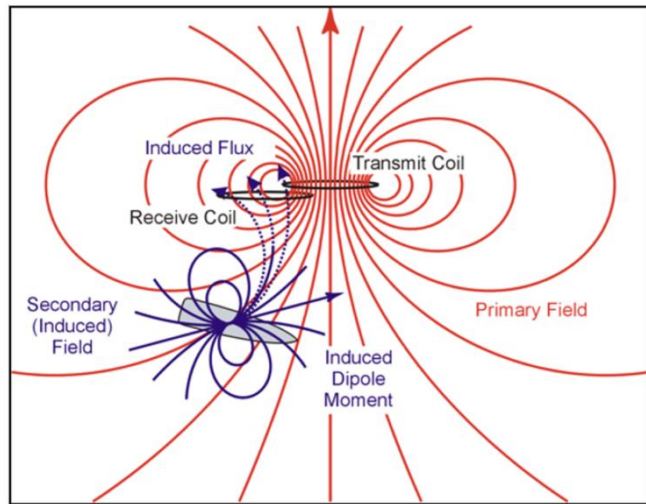


Fig. 1 — Induction geometry

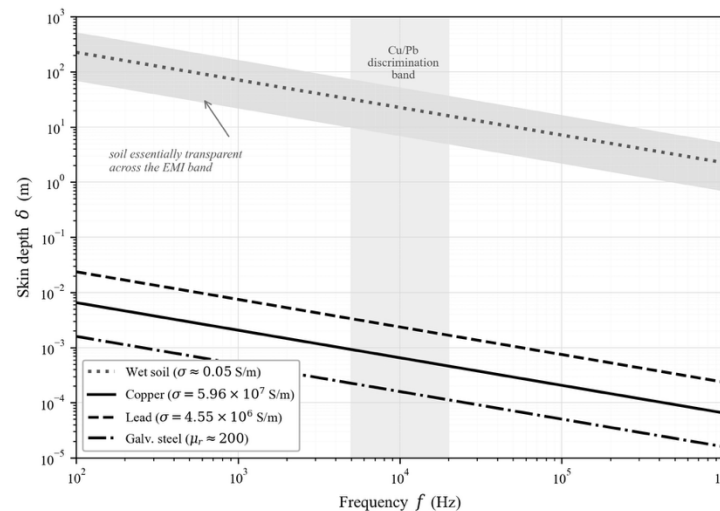


Fig. 2 — Skin depth vs. frequency

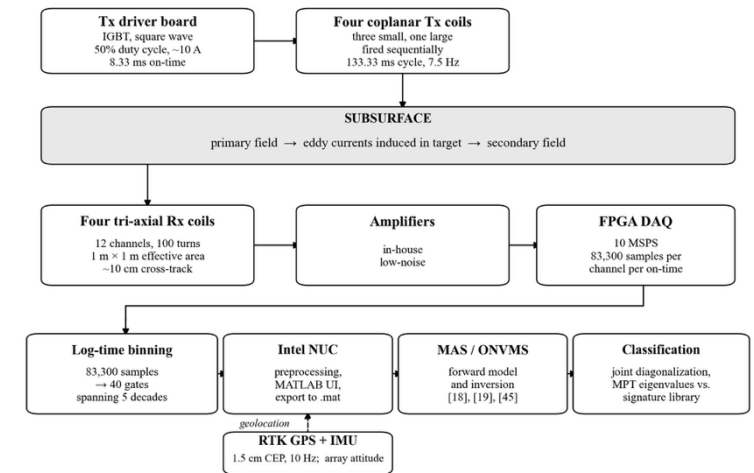


Fig. 3 — ULEMA signal chain

Data and Methods — Fabrication and Field Deployment

- ULEMA-P: pipe-survey configuration. Larger transmit coil to reach 4 - 6 ft depth; every structural element is non-metallic, since it sits inside the array's own primary field.
- **Personal contribution: designed and fabricated the frame, the robot mounting interface, and assembled the sensor head and electronics, iterated through successive versions to ruggedize the assembly for towed field operation. Executed a week of field testing. Managed and educated team of two.**
- Real-time operator display in three modes — static, dynamic, and a coverage heatmap — so survey gaps can be closed during the same visit. Field testing conducted with the group at the EPA test bed.

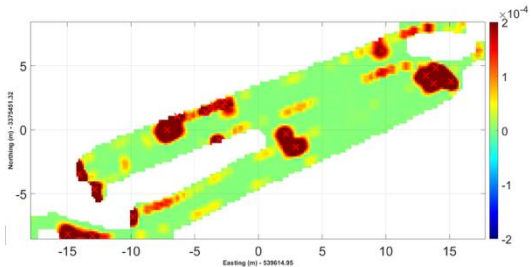


Fig. 4 — Coverage heatmap (example)



Fig. 5 — Sensor mounting plate



Fig. 6 — Electronics under assembly



Fig. 7 — ULEMA-P under tow, field

Results

- Static-mode transients: steel separates decisively from copper and lead; copper and lead separate narrowly, over roughly the middle decade of the recorded decay.
- Joint-diagonalization eigenvalues from the pipe-configured array agree closely with the established handheld instrument — validating the ULEMA-P build.
- Early-time amplitude does not order by conductivity: material is carried by decay shape, not signal strength.
- **Discrimination demonstrated successfully at shallow emplacement and at 4–6 ft — within the depth at which service lines are actually buried. Rate quantification is ongoing.**

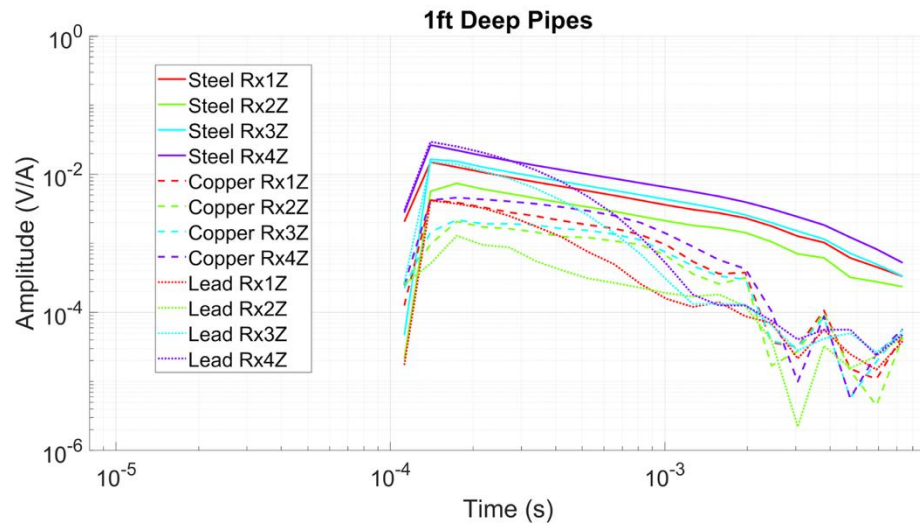


Fig. 8 — Static-mode response, Cu / Pb / steel

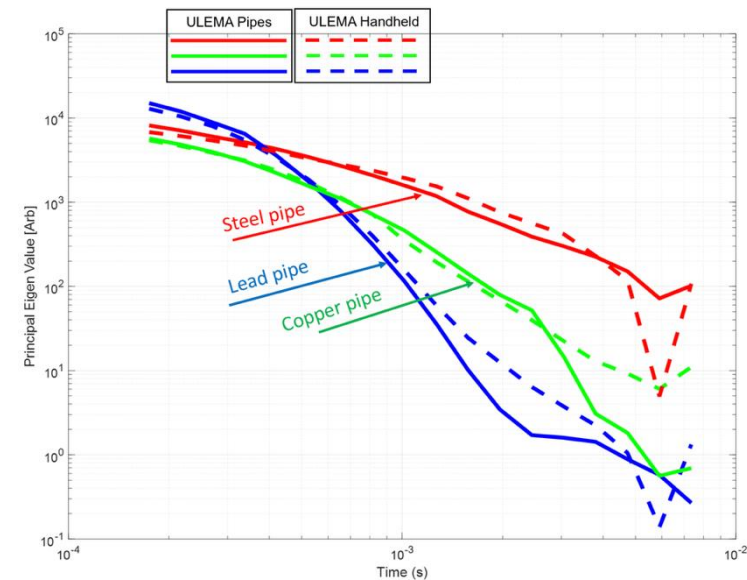


Fig. 9 — Joint-diagonalization eigenvalues

Discussion and Analysis

- Measured decay ordering agrees with the $\sigma\mu_r$ -based prediction, at both shallow and operational burial depth.
- The economic case rests on avoided replacement liability (\$6,930–12,500 per line), not avoided excavation (\$320–1,120 per line) — the two are frequently conflated.
- Throughput is the binding constraint: clearing the national inventory by 2034 requires on the order of 2.5 million determinations per year, a rate no method requiring individual property access can reach.
- Limitations: the point-dipole inversion basis does not strictly apply to a linear target; the shallow-depth margin is not the operational-depth margin; transmitter synchronization faults were open at the close of the reporting period.
- Challenges: the copper/lead discrimination window is narrow and one-dimensional; every structural material is constrained by the non-metallic requirement; hardware, mounting and processing were all under revision simultaneously.

Conclusion and Perspectives

- Ferrous rejection is decisive. Copper–lead discrimination — the harder case the project turns on — was demonstrated in kind, at both shallow and operational depth; quantifying the margin at depth is the outstanding measurement.
- Recommendations: extend the inversion to a linear-target basis; close the transmitter synchronization fault; quantify the classification margin at operational depth; report ferrous rejection and copper–lead accuracy separately.
- Phase two moves to a Department of Defense installation, without the documented ground truth of the test bed.
- The underlying method is transferable beyond lead service lines — to any buried-metal inventory problem, including gas distribution networks and utility-strike prevention.
- **Personal contribution: original research on the regulatory and environmental framework; assembly and fabrication of the electronics and sensor head; design and iteration of the sensor mounting; field testing with the group and the inversion / joint-diagonalization processing of the resulting data.**

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