HIRT: Hybrid Impedance-Resistivity Tomography System

A Low-Cost, High-Resolution Subsurface Imaging System for Archaeological, Forensic, and Humanitarian Demining Applications

HIRT Development Team

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Abstract

Buried beneath the surface of former conflict zones lies a deadly legacy: millions of tons of unexploded ordnance (UXO) that threaten civilians and obstruct historical recovery. Current methods for detecting these deep targets are either dangerously primitive (manual probing) or prohibitively expensive (commercial geophysics). This document introduces the **HIRT (Hybrid Impedance-Resistivity Tomography)** system—a novel, low-cost solution designed to democratize high-resolution subsurface imaging. By combining two sensing technologies—Magneto-Inductive Tomography (MIT) and Electrical Resistivity Tomography (ERT)—into a passive probe array, HIRT creates 3D models of the subsurface similar to a medical CT scan. This system enables archaeological and humanitarian teams to 'see' metallic wreckage, filled craters, and clandestine burials at depths of 3–6 meters without excavation. Developed in response to the ongoing crisis in Poland's Kozle Basin, HIRT aims to provide a safe, scalable, and scientifically rigorous tool for reclaiming hazardous ground.

Keywords: crosshole tomography, electrical resistivity, magneto-inductive, UXO detection, humanitarian demining, conflict archaeology, subsurface imaging

1. Introduction: The Hidden Legacy of War

For millions of people worldwide, the war is not over. Long after peace treaties are signed, land remains contaminated with unexploded ordnance (UXO), transforming fields, forests, and construction sites into potential minefields. More than 60 countries grapple with this legacy, putting over 100 million people at risk. The challenge is not just removing these hazards, but *finding* them—often buried deep in soil that has shifted over decades.

The legacy of World War II is particularly persistent. In Germany alone, approximately 2,000 tons of munitions are discovered annually. But as these devices age, they become more unstable, and their chemical fuses degrade. The window for safe removal is closing, yet the pace of discovery is limited by the tools available to field teams. To accelerate this work, we need technology that can look deeper and clearer than standard metal detectors, without the crushing cost of industrial geophysical services.

1.1 Historical Motivation: The Kozle Basin

The development of the HIRT system was directly inspired by the specific, urgent needs of the Kozle Basin in Poland. Once the site of the Third Reich's massive Blechhammer synthetic fuel plants, this region was the target of relentless Allied bombing campaigns in 1944–1945. Over 39,000 bombs were dropped, turning the landscape into a cratered moonscape [3].

Today, thousands of these craters remain, many filled with sediment and concealing unexploded bombs. Recent research suggests 4,000–6,000 UXBs may still lie dormant in the basin. Standard surface scanners struggle here: the conductive clay soils block ground-penetrating radar (GPR), and the depth of the targets (3–6 meters) renders handheld detectors useless. The HIRT system was conceived to solve this specific problem: to penetrate conductive soil and identify deep anomalies without the risk of physical excavation.

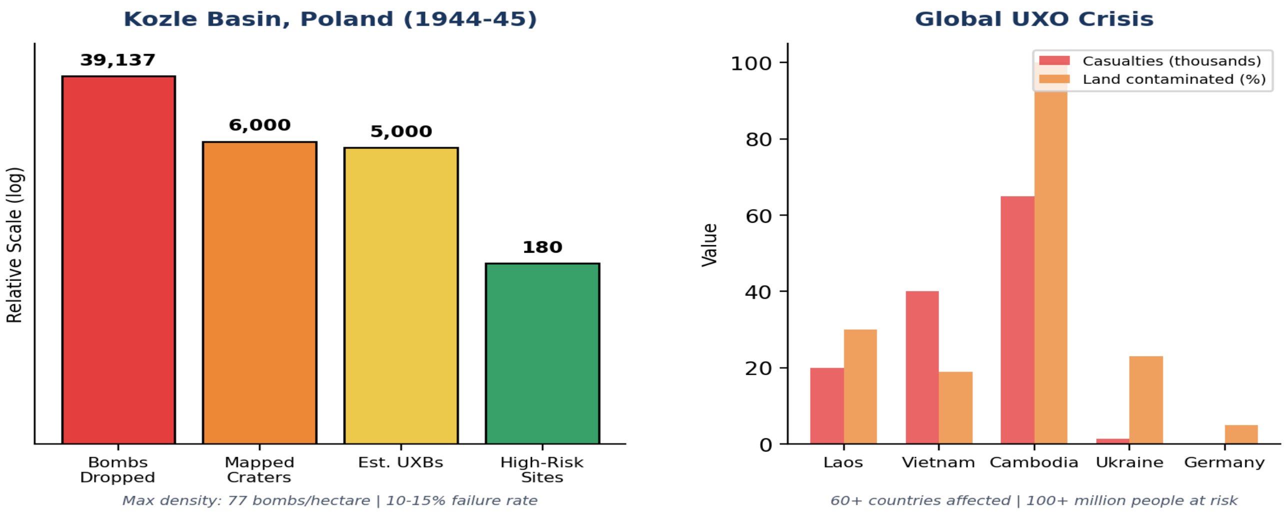

Figure 1. The scale of the challenge. Left: Statistics from the Kozle Basin bombing campaign reveal the density of potential hazards [3]. Right: The global context of the UXO crisis, highlighting the need for scalable detection solutions.

1.2 The Mission: Democratizing Subsurface Vision

Current humanitarian demining often relies on tools that have barely changed since the 1940s: prodding sticks and basic metal detectors. While effective for surface mines, they fail against deeply buried aircraft bombs. Conversely, the oil and gas industry uses sophisticated 'Crosshole Tomography' systems that offer incredible 3D resolution—but at a cost of $50,000 to $200,000 per unit.

The mission of the HIRT project is to bridge this gap. By utilizing modern microcontrollers, 3D printing, and open-source hardware, we have re-engineered the principles of crosshole tomography into a system that can be built for under $4,000. This places professional-grade imaging capabilities into the hands of university researchers, non-profits, and historical recovery teams who previously could only guess at what lay beneath the surface.

2. Physics and Measurement Principles

2.1 The Crosshole Geometry Advantage

The fundamental advantage of crosshole geometry lies in the physics of electromagnetic and electrical field propagation. Surface methods must send energy down to a target and receive the return signal—doubling the path length and exponentially increasing attenuation. In contrast, crosshole methods send signals horizontally through the target volume, with sensitivity concentrated precisely where targets are located. Figure 2 illustrates this geometric advantage.

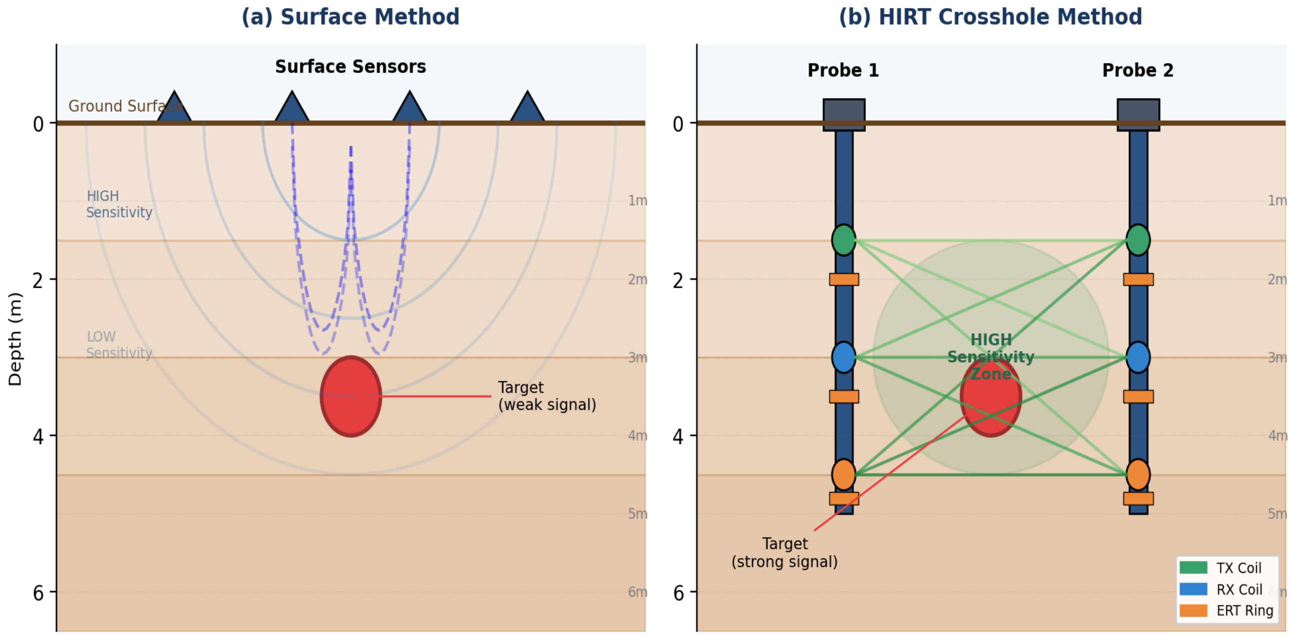

Figure 2. Comparison of (a) surface method versus (b) HIRT crosshole method. Surface sensors must contend with rapid sensitivity decay with depth ($1/r^2$ to $1/r^4$ falloff) and near-surface interference zones. Crosshole probes provide direct ray paths through the target volume with high sensitivity maintained at the investigation depth. The green ellipse in (b) indicates the zone of maximum sensitivity between probes.

The electromagnetic skin depth (δ) determines the effective penetration of MIT signals:

$$\delta = \sqrt{(2 / \omega\mu\sigma)}$$

where ω = angular frequency, μ = permeability, and σ = conductivity. At 10 kHz in typical soil (σ = 0.01 S/m), skin depth exceeds 50 meters. However, the practical limitation is coil coupling geometry, which scales as $1/r^3$ in near-field conditions. The effective MIT investigation depth is approximately 1-2x the probe spacing.

2.2 Dual-Channel Detection: MIT and ERT

HIRT employs two complementary sensing modalities. Magneto-Inductive Tomography (MIT) uses oscillating magnetic fields at 2-50 kHz to induce eddy currents in conductive targets, enabling detection of both ferrous and non-ferrous metals (including aluminum aircraft components that magnetometry cannot detect). Electrical Resistivity Tomography (ERT) injects small DC or low-frequency currents (0.5-2 mA) and measures voltage distribution, detecting resistivity contrasts from disturbed soil, moisture variations, voids, and grave shafts.

Parameter	MIT-3D	ERT-Lite
Operating Principle	TX coil magnetic field; RX measures eddy currents	Current injection; voltage measurement
Frequency Range	2-50 kHz	DC or 8-16 Hz
Detection Targets	Metal (incl. aluminum), conductivity anomalies	Disturbed fill, moisture, voids, grave shafts
Current Level	10-50 mA	0.5-2 mA
Key Advantage	Non-ferrous metal detection	Soil disturbance patterns
Resolution at 3m	0.75-1.5 m lateral	0.5-0.75 m vertical

Table 1. Comparison of MIT and ERT measurement methods. The dual-channel approach enables detection of targets that would be missed by either method alone.

3. System Architecture

The HIRT system follows an 'archaeologist brain first, engineer brain second' design philosophy, prioritizing minimal ground disturbance while maintaining measurement quality. The architecture employs passive micro-probes with centralized electronics. To address scalability for large arrays (20-50 probes), the system utilizes a 'Zone Wiring Strategy' where groups of 4 probes connect to passive Zone Hubs, which then feed back to the main unit via high-density trunk cables. Figure 3 shows the overall architecture.

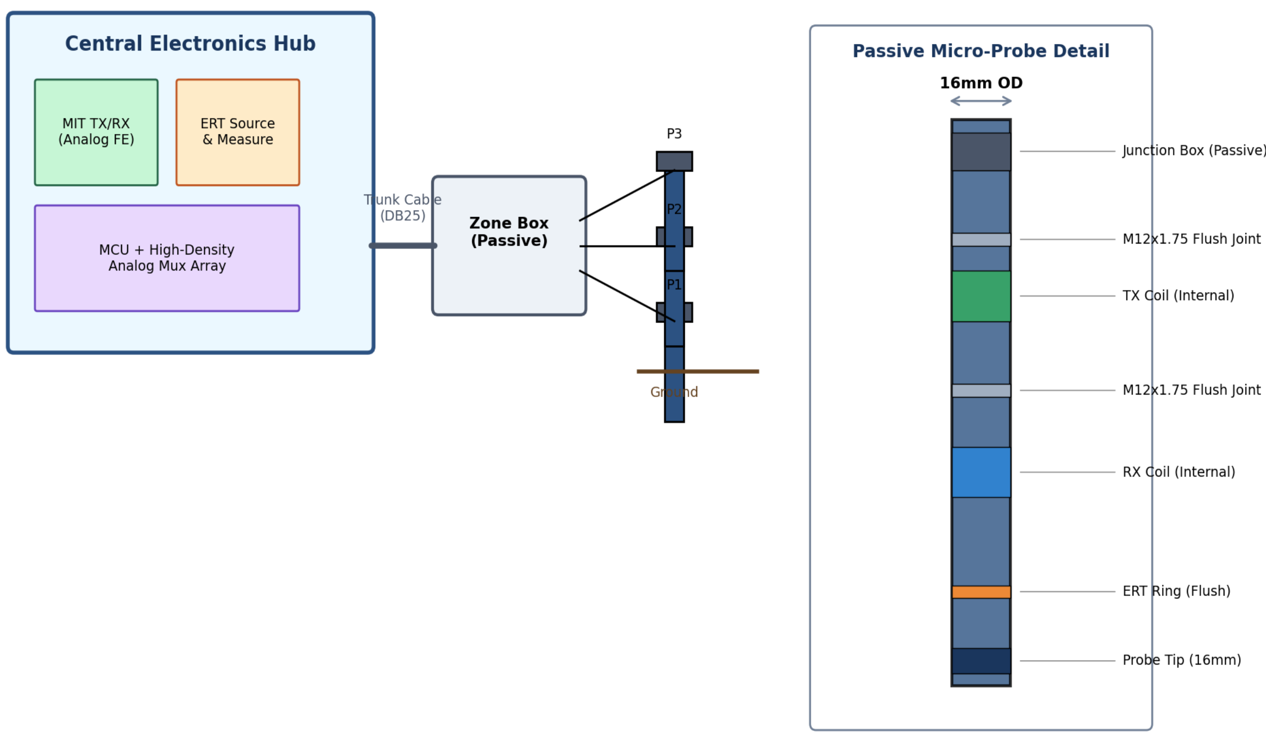

Figure 3. HIRT system architecture. Left: Central electronics hub connected to 'Zone Boxes' via high-density trunk cables. Each Zone Box aggregates 4 passive probes. Right: Detailed probe cross-section showing the flush 16mm OD profile, internal coils, and modular M12x1.75 threaded joints.

3.1 Micro-Probe Design

Each probe is a 16mm outer diameter fiberglass rod containing only passive sensors. The modular design uses **flush M12x1.75 threaded connectors** allowing field assembly of segments without creating snag points during insertion. This smooth 16mm profile ensures the probe can be inserted and removed with minimal force (~10x less disturbance than traditional geophysical probes).

Specification	Value	Notes
Rod Outer Diameter	16 mm	~10x less disturbance than traditional
Required Hole Size	18-20 mm	Hand auger or push-rod insertion
Material	Fiberglass (G10)	Non-conductive, RF transparent
Segment Lengths	50, 100 cm	Modular field assembly
Coil Inductance	1-2 mH	200-400 turns on ferrite core
ERT Ring Positions	0.5, 1.5, 2.5 m	From probe tip
Weight	~50-100 g/m	Lightweight for transport

Table 2. HIRT micro-probe physical specifications.

4. Performance Comparison

The crosshole geometry provides significant performance advantages over surface methods, particularly for targets at depths exceeding 1.5-2 meters. Research on crosshole ERT and electromagnetic tomography demonstrates 2-5x better resolution than surface methods at these depths [6,7]. Figure 4 compares the effective depth of investigation across common geophysical methods.

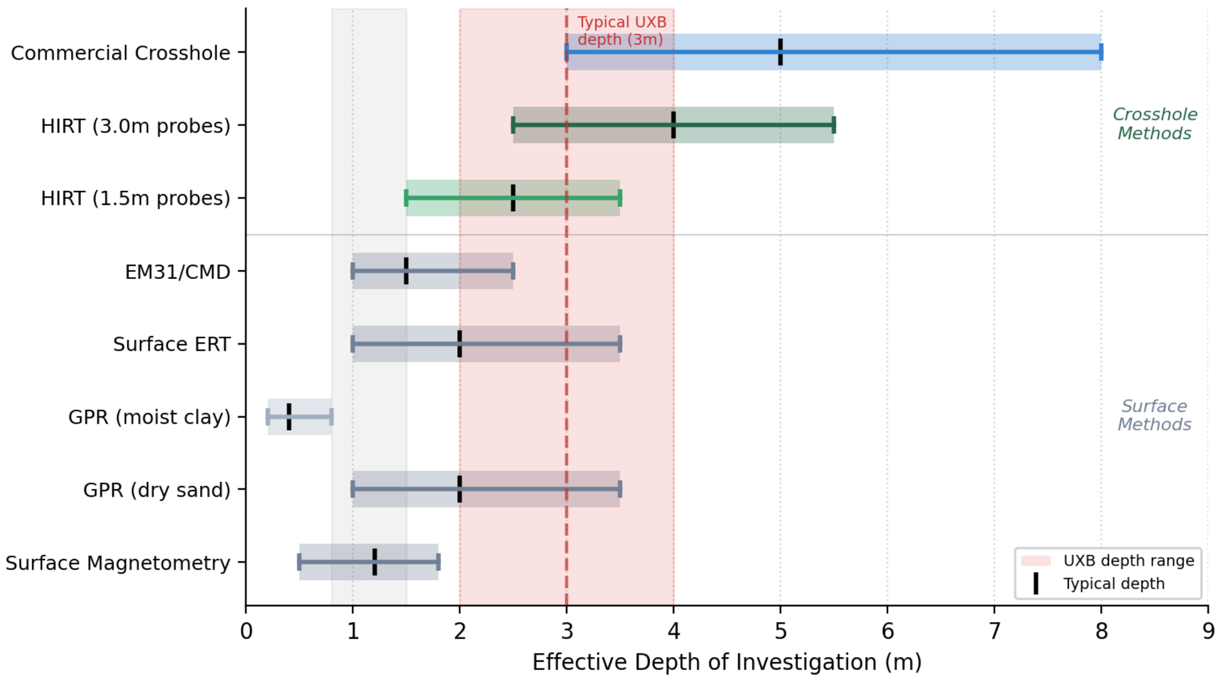

Figure 4. Effective depth of investigation comparison across geophysical methods. Horizontal bars show the range from minimum (poor conditions) to maximum (optimal conditions) depth, with vertical markers indicating typical performance. The red shaded zone indicates typical UXB burial depths (2-4m). HIRT crosshole methods maintain high-confidence detection throughout this critical range, while surface methods show significant degradation.

4.1 Cost-Effectiveness

A complete HIRT starter kit (25 probes, central electronics hub, cables, and tools) costs $1,800-3,900, representing a 95%+ reduction compared to commercial crosshole systems ($50,000-200,000+). This cost structure places professional-grade subsurface imaging within reach of research institutions, humanitarian organizations, and archaeological teams that could not otherwise afford crosshole tomography capabilities.

5. Application Scenarios

HIRT is optimized for three primary deployment scenarios, each with specific configuration recommendations. The system's dual-channel MIT+ERT approach enables comprehensive target characterization across diverse site conditions. Figure 5 illustrates the deployment strategies.

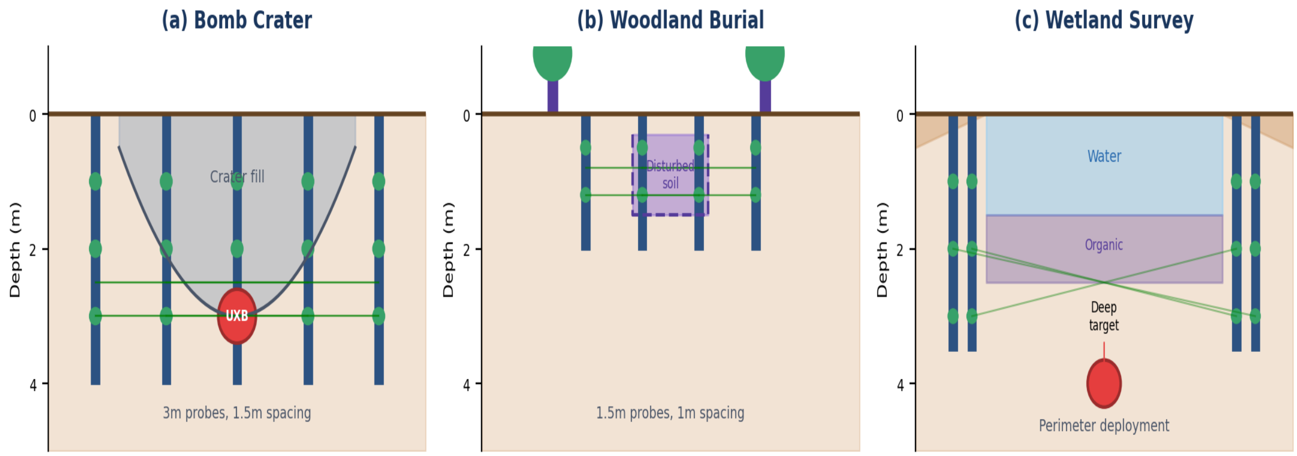

Figure 5. Primary HIRT application scenarios: (a) Bomb crater investigation uses perimeter probes (3m depth, 1.5m spacing) around suspected UXB locations with dense ray path coverage through the crater fill; (b) woodland burial search uses shallow dense arrays (1.5m probes, 1m spacing) to detect disturbed soil signatures; (c) wetland surveys deploy probes from accessible margins with long-baseline diagonal ray paths toward deep targets. Green lines indicate MIT measurement paths.

WWII Crash Sites and UXB Investigation: For craters 10-15m diameter with targets at 2-4m depth, use 3.0m probes at 1.5-2.0m spacing in a 5x5 or 6x6 array. MIT frequencies should emphasize lower ranges (2-10 kHz) for depth penetration. The combined MIT+ERT approach detects both metallic debris (MIT) and the disturbed fill boundaries of the crater (ERT).

Woodland Burials and Forensic Sites: For shallow targets (0.5-1.5m), use 1.5m probes at 1.0-1.5m spacing. Higher MIT frequencies (10-50 kHz) provide better near-surface detail. ERT excels at detecting the disturbed grave shaft signature while MIT identifies metallic artifacts such as belt buckles, buttons, or personal effects.

Wetland and Difficult-Access Sites: For targets exceeding 5m depth in areas with limited access, deploy probes from accessible margins. Use lowest MIT frequencies (2-5 kHz) with extended integration times (10-30 seconds). Diagonal ray paths from perimeter probes can interrogate central volumes that cannot be directly accessed.

6. Safety Considerations for UXO Sites

CRITICAL SAFETY REQUIREMENTS FOR UXO SITES

* Professional EOD clearance required before probe insertion
* No hammering or driving of pilot rods - soft insertion only
* Maintain 100m exclusion zone during insertion operations
* Perimeter-only deployment when UXB suspected at center
* Monitor groundwater conductivity: >5,500 uS/cm indicates elevated risk

Research by Waga et al. [3] documented a spontaneous UXB detonation in the Kozle Basin associated with elevated groundwater conductivity (>6,000 uS/cm) from industrial contamination. The electrochemical environment created by high-conductivity groundwater can accelerate corrosion of bomb casings and destabilize aging explosive fills. HIRT's ERT capability enables real-time monitoring of subsurface conductivity trends that may indicate elevated risk conditions.

7. Conclusions

The HIRT system addresses a critical gap between expensive commercial crosshole systems and limited-capability surface methods. By combining MIT and ERT sensing in a passive micro-probe architecture, HIRT achieves 2-5x better resolution than surface methods at depths exceeding 2 meters, while maintaining costs accessible to research institutions and humanitarian organizations.

The global unexploded ordnance crisis—affecting over 100 million people across 60+ countries—demands technological solutions that are both effective and deployable at scale. Traditional humanitarian demining methods clear only 10-20 square meters per day, a pace that would require centuries to address the existing backlog. HIRT offers a path toward more efficient detection and characterization of buried hazards, enabling prioritized clearance operations and reduced civilian casualties.

Key advantages of the HIRT approach include: (1) true 3D tomographic imaging rather than pseudo-depth estimation; (2) detection of non-ferrous metals that magnetometry cannot sense; (3) soil disturbance mapping independent of metallic content; (4) minimal ground disturbance (~10x less than traditional methods); (5) modular, field-serviceable design suitable for remote deployment; and (6) cost reduction of 95%+ compared to commercial alternatives.

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